A synthesis of Jurassic and Early Cretaceous crustal evolution along the southern margin of the Arctic Alaska–Chukotka microplate and implications for defining tectonic boundaries active during opening of Arctic Ocean basins

Alison B. Till
U.S. GEOLOGICAL SURVEY, 4210 UNIVERSITY DRIVE, ANCHORAGE, ALASKA 99508, USA

ABSTRACT

A synthesis of Late Jurassic and Early Cretaceous collision-related metamorphic events in the Arctic Alaska–Chukotka microplate clarifies its likely movement history during opening of the Amerasian and Canada basins. Comprehensive tectonic reconstructions of basin opening have been problematic, in part, because of the large size of the microplate, uncertainties in the location and kinematics of structures bounding the microplate, and lack of information on its internal deformation history. Many reconstructions have treated Arctic Alaska and Chukotka as a single crustal entity largely on the basis of similarities in their Mesozoic structural trends and similar late Proterozoic and early Paleozoic histories. Others have located Chukotka near Siberia during the Triassic and Jurassic, on the basis of detrital zircon age populations, and suggested that it was Arctic Alaska alone that rotated. The Mesozoic metamorphic histories of Arctic Alaska and Chukotka can be used to test the validity of these two approaches.

A synthesis of the distribution, character, and timing of metamorphic events reveals substantial differences in the histories of the southern margin of the microplate in Chukotka in comparison to Arctic Alaska and places specific limitations on tectonic reconstructions. During the Late Jurassic and earliest Cretaceous, the Arctic Alaska margin was subducted to the south, while the Chukotka margin was the upper plate of a north-dipping subduction zone or a zone of transpression. An early Aptian blueschist- and greenschist-facies belt records the most profound crustal thickening event in the evolution of the orogen. It may have resulted in thicknesses of 50–60 km and was likely the cause of flexural subsidence in the foredeep of the Brooks Range. This event involved northern Alaska and northeasternmost Chukotka; it did not involve central and western Chukotka. Arctic Alaska and Chukotka evolved separately until the Aptian thickening event, which was likely a result of the rotation of Arctic Alaska into central and western Chukotka. In northeastern Chukotka, the thickened rocks are separated from the relatively little thickened continental crust of the remainder of Chukotka by the oceanic rocks of the Kolyuchin-Mechigmen zone. The zone is a candidate for an Early Cretaceous suture that separated most of Chukotka from northeast Chukotka and Alaska. Albian patterns of magmatism, metamorphism, and deformation in Chukotka and the Seward Peninsula may represent an example of escape tectonics that developed in response to final amalgamation of Chukotka with Eurasia.

LITHOSPHERE; v. 8; no. 3; p. 219–237 | Published online 3 March 2016 doi:10.1130/L471.1

INTRODUCTION

Research in Arctic tectonics has blossomed in recent decades due to increased ease of access to the region and consequent interest in development of natural resources. Despite substantial progress, uncertainties and controversies persist regarding the tectonic mechanisms responsible for Mesozoic opening of the Amerasian Basin, a central feature of Arctic geography (Fig. 1). New geophysical and geologic data collected within the basin and its immediate borderlands have been used to update tectonic models (e.g., Grantz et al., 2011), but a broader geographic approach is required to account for all of the tectonic elements that were active during basin opening (e.g., Rowley and Lottes, 1988; Nokleberg et al., 2000; Shepherd et al., 2013). In many models, opening of the Amerasian Basin was accomplished by movement of a large continental block called the Arctic Alaska–Chukotka microplate or terrane (Fig. 1; Lawver et al., 2002; Grantz et al., 2011; Shepherd et al., 2013, and references therein). The processes responsible for movement of the microplate—via rotation, translation, or both—have been the subject of ongoing debate (e.g., Carey, 1955; Hamilton, 1970; Tailleur, 1973; Churkin and Trexler, 1980; Oldow et al., 1987; Smith, 1987; Grantz et al., 1990; Lane, 1997; Lawver et al., 2002; Miller et al., 2006, 2008).

The Canada Basin is the part of the Amerasian Basin adjacent to Canada and Arctic Alaska (Fig. 1). The results of modern geophysical and geologic studies of the Canada Basin summarized in Grantz et al. (2011), Shepherd et al. (2013), and Gottlieb et al. (2014) support the rotational model for basin opening. However, simple rigid rotation of the over 3000-km-long Arctic Alaska–Chukotka microplate results in significant overlap of the western end of the microplate with the continental crust of the Lomonosov Ridge (Fig. 1; Rowley and Lottes, 1988; Miller et al., 2006; Pease, 2011). Internal deformation of the microplate by crustal extension could account for some of the size discrepancy (Miller et al., 2006; Miller and Akinin, 2008; Miller and Verzhbitsky, 2009). Separate locations and tectonic histories for Chukotka and Arctic Alaska before basin opening have been proposed and help to address this issue,

Figure 1. Map of the Arctic region showing the location of the Amerasian and Canada basins and the Arctic Alaska–Chukotka microplate. Also shown are the location of Neoproterozoic and Lower Paleozoic rocks typically related to the Timanide orogen or Arctida (Kuznetsov et al., 2010) and the Timanide orogen itself (Pease, 2011). Location of the pole of rotation is from Grantz et al. (2011).

but no suture has been identified between the two (e.g., Miller et al., 2006; Shepherd et al., 2013; Amato et al., 2015).

Additional uncertainty regarding the process of basin opening and migration of the Arctic Alaska–Chukotka microplate arises from an incomplete understanding of the location and evolution of Mesozoic tectonic boundaries and associated collision zones on the south and west sides of the microplate (present coordinates; e.g., Moore et al., 1994; Sokolov et al., 2002, 2009; Amato et al., 2004, 2015; Pease, 2011). These subduction zones, collisional zones, and transform faults are important because they presumably accommodated closure of ocean basins south and west of the Arctic Alaska–Chukotka microplate as the Amerasian Basin opened. Evidence for subduction of the southern margin of Arctic Alaska (e.g., Till et al., 1988; Gottschalk, 1990) was used to constrain some tectonic models (e.g., Moore et al., 1994; Nokleberg et al., 2000; Amato et al., 2015). Amato et al. (2015) used geochronologic, structural, and seismic-reflection data as evidence for the existence of a subduction zone on the south side of Chukotka during the Mesozoic. Many unknowns persist; Shepherd et al. (2013) considered the absolute age and geometry of Mesozoic subduction zones on the Pacific side of the Arctic Alaska–Chukotka microplate to be critical factors that need to be constrained to improve tectonic reconstructions of the Arctic.

In light of these uncertainties and complications, the following outstanding questions about the Arctic Alaska–Chukotka microplate must be addressed to create better tectonic models for the opening of the Amerasian Basin:

(1) Were Arctic Alaska and Chukotka separate crustal entities during opening of the Amerasian Basin? Can a structure be identified within the Arctic Alaska–Chukotka microplate that delineates a boundary between the two crustal blocks?

(2) What information about crustal deformation can be used to constrain the size of the Arctic Alaska–Chukotka microplate during the process of Amerasian or Canada Basin opening?

(3) Can the metamorphic history of the southern Arctic Alaska–Chukotka microplate be used to constrain the age and character of major tectonic boundaries active during basin opening?

This paper addresses these three areas of uncertainty in two ways. First, I present a synthesis of the metamorphic and structural evolution of the southern margin of the Arctic Alaska–Chukotka microplate. The histories of regional metamorphic terranes are critical tools in tectonic reconstruction because they can be used to constrain the age, location, and tectonic character of crustal boundaries and the timing, geographic extent, and degree of thickening or thinning of continental crust.

Second, I present an outline of the Early Cretaceous tectonic evolution of Arctic Alaska and Chukotka that integrates their metamorphic histories with shallow crustal deformation events, magmatic events, and basin development. This outline reveals relationships that constrain the three areas of uncertainty outlined earlier and highlights areas needing further study.

REGIONAL GEOLOGY

Arctic Alaska–Chukotka Microplate

The Arctic Ocean basin is rimmed by blocks of continental crust that had similar Neoproterozoic and early Paleozoic histories, based on igneous ages, detrital zircon age populations, and affinities of early Paleozoic fauna (Fig. 1; Kuznetsov et al., 2010; Pease, 2011; Dumoulin et al., 2011). These blocks are considered by some to be pieces of a dismembered Neoproterozoic and earliest Paleozoic continent, such as Arctida (Shatskii, 1935; Kuznetsov, 2006; Kuznetsov et al., 2010; Filatova and Khain, 2010), while others consider them to be dispersed parts of a large accretionary margin related to the Timanide orogen of Baltica (Fig. 1; Patrick and McClelland, 1995; Dumoulin et al., 2002, 2011; Lorenz et al., 2008; Pease and Scott, 2009; Amato et al., 2009; Miller et al., 2010a).

The Arctic Alaska–Chukotka microplate has an area comparable to that of Greenland (Amato et al., 2015) and is the largest of these crustal blocks (Fig. 1). On the Russian side, it includes Chukotka, Wrangel Island, parts of the New Siberian Islands, and the adjacent continental shelf (Fig. 1). On the North American side, it includes Saint Lawrence Island, Seward Peninsula, the Brooks Range, and the North Slope of Alaska (Fig. 2). It is specifically the Neoproterozoic and early Paleozoic geology of the Seward Peninsula and the southern and western Brooks Range that are similar to Chukotka and the other crustal blocks in the Arctic (Churkin and Trexler, 1980; Natal'in et al., 1999; Dumoulin et al., 2002, 2011; Amato et al., 2014).

Notably, little shared history has been documented for Arctic Alaska and Chukotka between the Permian and the Cretaceous. For example, most of central and western Chukotka is underlain by voluminous Triassic turbidites (Tuchkova et al., 2009), while rocks of similar age in western Arctic Alaska are shale rich and were deposited in starved basins on a continental shelf (Moore et al., 2002).

The apparent continuity of structural trends related to Mesozoic collisional deformation along the Arctic Alaska–Chukotka microplate from west to east has resulted in the common interpretation that structures on both sides of the Bering Strait (Fig. 2) were part of a single Late Jurassic–Cretaceous orogen (e.g., Hamilton, 1970; Churkin and Trexler, 1980; Nokleberg et al., 2000). A closer examination of the timing and character of crustal shortening events yields a more complex picture. In the following text, the terms Arctic Alaska and Chukotka are used when history pertinent only to one part of the microplate is discussed.

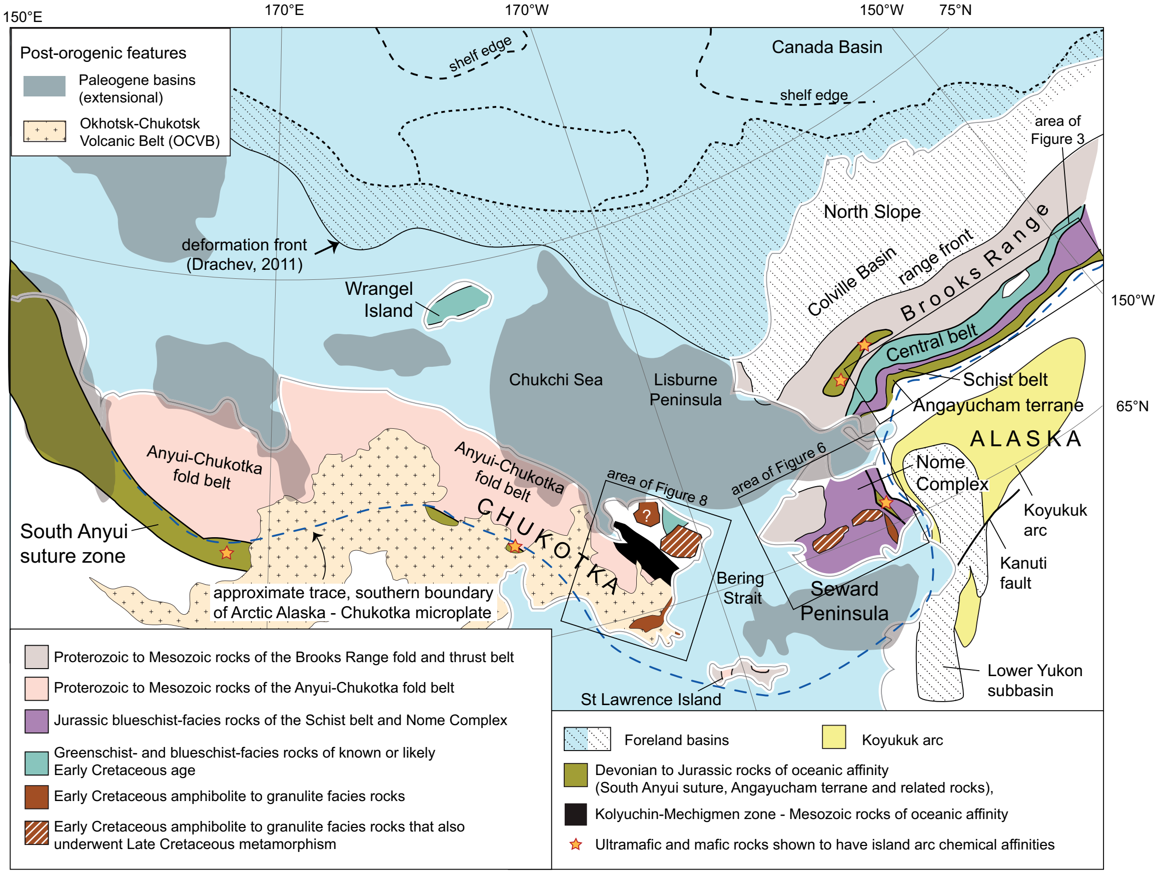

Figure 2. Map of northern Alaska and northeast Russia showing geographic names and major Mesozoic and Cenozoic geologic features. Map is modified from Drachev (2011), Houseknecht and Bird (2011), Till et al. (2008, 2011), and Beikman (1980).

Oceanic and Arc Rocks that Bounded the Southern Side of the Microplate

The southern boundary of the Arctic Alaska–Chukotka microplate is traced by exposures of Paleozoic and Mesozoic oceanic rocks (Fig. 2). These include rocks of the South Anyui suture zone on the west (Natal'in, 1984; Sokolov et al., 2002, 2009; Amato et al., 2015) and the Angayucham terrane and Koyukuk arc on the east (Patton et al., 1994; Box and Patton, 1989; Pallister et al., 1989). In eastern Chukotka, oceanic rocks of the Kolyuchin-Mechigmen zone occur within the microplate, flanked by continental crust.

In northern Alaska, the Angayucham terrane extends along the southern flank of the Brooks Range (Pallister et al., 1989) and is exposed in several klippe in the western part of a fold-and-thrust belt (Harris, 2004; shown as a single entity on Fig. 2). The Angayucham terrane is characterized by two structurally separate assemblages, the upper dominated by ultramafic rocks and the lower dominated by mafic rocks (Patton et al., 1994; Moore et al., 1994). Ultramafic and mafic rocks of the upper assemblage yielded U-Pb and $^{40}Ar/^{39}Ar$ hornblende ages of 170–162 Ma and originated in an arc or back-arc setting (Harris, 2004, and references therein). The lower assemblage is predominantly composed of pillow basalt and diabase with the chemical characteristics of within-plate or ocean-island basalts (Barker et al., 1988; Pallister et al., 1989; Karl, 1992). Fossils recovered from thin layers of limestone and chert associated with the mafic rocks yielded Devonian to Early Jurassic ages (Jones et al., 1988; Pallister et al., 1989).

Volcanic, volcaniclastic, and plutonic rocks of the Koyukuk arc are exposed over a broad area south of the Brooks Range and east of Seward Peninsula (Fig. 2). The oldest units in the Koyukuk arc are Middle Jurassic and older plutonic and sedimentary rocks that are located south of the Kanuti fault, more than 200 km south of the Brooks Range, and these represent a small volume relative to the arc as a whole (Fig. 2; Box and Patton, 1989). They are unconformably overlain by volcanic and volcaniclastic rocks that represent the main phase of Koyukuk arc activity, which spanned the period ca. 145–130 Ma (Box and Patton, 1989).

The South Anyui suture zone stretches from the New Siberian Islands in the west to the vicinity of the Bering Strait (Figs. 1 and 2). The geology of the complex, poorly exposed rocks of the zone was summarized in Natal'in (1984), Sokolov et al. (2002, 2009), and Amato et al. (2015). The suture zone contains mafic-ultramafic complexes that range in age from Carboniferous to Permian on the basis of $^{40}Ar/^{39}Ar$ and U-Pb zircon data (Ganelin et al., 2013; Sokolov et al., 2015), calc-alkaline and subalkaline volcanic and volcaniclastic rocks of the Nutesyn or Kulpolney arc that are Late Jurassic in age on the basis of fossils in associated sedimentary rocks (Natal'in, 1984; Sokolov et al., 2002), and Late Jurassic and Cretaceous deep- and shallow-water sedimentary rocks (Amato et al., 2015, and references therein).

Eastern Chukotka is transected by a tectonic assemblage of little-studied Permian, Triassic, and Jurassic oceanic rocks called the Kolyuchin-Mechigmen zone (Fig. 2; Natal'in et al., 1999; Sokolov et al., 2009; Ledneva et al., 2011, 2012). Some workers include Permian–Triassic(?) turbidite sequences that host basaltic sheet flows, pillow lava, and a 252 Ma diabase, interpreted as rift related (Ledneva et al., 2011), in the zone; others do not (e.g., Natal'in et al., 1999). The

more narrowly defined part of the Kolyuchin-Mechigmen zone (Fig. 2) consists of ultramafic rocks, gabbro, and terrigenous, siliceous, and volcanic deposits, mostly of unknown age, in a tectonic mélange (Sokolov et al., 2009). The ultramafic and mafic rocks may be arc-related cumulates crystallized at pressures typical of mature or Andean-style arcs (Ledneva et al., 2012). The sedimentary rocks include pyroclastic and tuffaceous sediments also thought to be arc related (Sokolov et al., 2009). The Kolyuchin-Mechigmen zone has been interpreted as a suture in some tectonic models (e.g., Sokolov et al., 2002), but its full extent and history are unknown.

Although the age, tectonic affinities, and structural histories of rocks in the South Anyui suture zone and the Angayucham terrane are not completely understood, there is general agreement that they are remnants of closed ocean basins (Patton et al., 1994; Amato et al., 2015; Sokolov et al., 2015). In several tectonic models, the rocks now exposed in the South Anyui suture zone and Angayucham terrane have been reconstructed as a single ocean basin (e.g., Nokleberg et al., 2000; Shepherd et al., 2013). They are considered separate elements in others (e.g., Amato et al., 2015). Continental crust of the Arctic Alaska–Chukotka microplate was deformed along its boundary with these ocean basins. The metamorphic and deformational histories of that continental crust, particularly in eastern Chukotka and northern Alaska, are the focus of this paper.

Metamorphic Rocks of the Southern Arctic Alaska–Chukotka Microplate

The characteristics of the deformational and metamorphic events that involved rocks along the southern margin of the Arctic Alaska–Chukotka microplate are outlined next. Most of the data presented are from the literature; data not previously published by the author are labeled as such.

Arctic Alaska

The Brooks Range orogen of northern Alaska stretches 1000 km from the Canadian border to the Lisburne Peninsula (Figs. 1 and 2). Both Mesozoic and Cenozoic periods of crustal shortening produced the topographic expression of the range (O'Sullivan et al., 1997; Moore et al., 2015). Mesozoic deformation was north vergent and resulted in deep deformation of crust along the southern part of the orogen and development of a fold-and-thrust belt and foreland basin to the north. Two metamorphic belts parallel the southern margin of the Brooks Range orogen (Fig. 2): the subduction-related blueschist- and greenschist-facies rocks of the Schist belt (Gottschalk, 1998) and the thrust-imbricated blueschist- and greenschist-facies rocks of the Central belt (Till et al., 1988), also known as the Hammond terrane (Moore et al., 1994) and Skajit allochthon (Oldow et al., 1998). The early metamorphic and deformational history of the Nome Complex of Seward Peninsula (Fig. 2) parallels that of the Schist belt.

St. Lawrence Island is situated south of the Bering Strait (Fig. 2) and is composed of unmetamorphosed Devonian and Mississippian carbonate rocks with strong similarities to those in the Nome Complex, Seward Peninsula; Devonian, Mississippian, and Triassic limestones and shales correlative with rocks in the Brooks Range; Permian to Triassic graywacke, shale, and associated gabbro and diabase possibly correlative with similar rocks on Chukotka; and Mesozoic to Cenozoic volcanic and plutonic rocks (Till and Dumoulin, 1994; Patton et al., 2011). Mid-Cretaceous alkalic plutonic rocks are similar in age and composition to plutonic rocks on Chukotka and the Seward Peninsula (Amato et al., 2003).

Schist belt and Nome Complex. The ages of meta-igneous rocks and lithologic and paleontologic characteristics of carbonate rocks tie the protoliths of the Schist belt and Nome Complex to the more shallowly deformed rocks of Arctic Alaska exposed in the Brooks Range (Moore et al., 1997a; Amato et al., 2009, 2014; Till et al., 2014). These rocks are the subducted and exhumed southern margin of Arctic Alaska (Patrick and Evans, 1989; Gottschalk, 1998). They are composed of penetratively deformed and recrystallized blueschist-facies rocks that reached peak pressure and temperature conditions of 1.0–1.3 GPa (Fig. 3A; equivalent to depths of 34–44 km assuming 0.34 km/GPa) and 450–500 °C (Patrick and Evans, 1989; Patrick, 1995; Gottschalk, 1998). The blueschist-facies minerals and fabric were variably overprinted by greenschist-facies assemblages (Patrick and Evans, 1989; Patrick, 1995; Gottschalk, 1990, 1998; Little et al., 1994; Hannula et al., 1995).

The age of the blueschist-facies metamorphism is not precisely known because the effects of the greenschist-facies overprint complicate interpretation of geochronologic data. On the basis of complicated $^{40}Ar/^{39}Ar$ age spectra from white mica, Gottschalk and Snee (1998) considered 142 Ma to be the minimum age for blueschist-facies metamorphism of the Schist belt. Little et al. (1994) reported similar spectra from an adjacent area. One white mica sample from the Schist belt yielded $^{40}Ar/^{39}Ar$ plateau and isochron ages of ca. 170–171 Ma (Christiansen and Snee, 1994); those authors concluded that this age represents cooling from a metamorphic event that predated greenschist-facies metamorphism.

Gottschalk (1990) interpreted the dominant fabric in the Schist belt as a greenschist-facies, exhumation-related fabric that overprinted the blueschist-facies, subduction-related metamorphic features; Hannula et al. (1995) identified similar relations in the Nome Complex. Shear sense indicators formed during greenschist-facies fabric development in the Schist belt near the Dalton Highway (Fig. 3B) record top-to-the-north shear (Gottschalk, 1990). A $^{40}Ar/^{39}Ar$ analysis of white mica associated with this fabric and similar fabrics to the west yielded a broad range of ages, from ca. 130 Ma to 110 Ma (Fig. 3A; Gottschalk and Snee, 1998; Christiansen and Snee, 1994). White mica samples from the Schist belt near the Dalton Highway with concordant plateau and isochron ages cooled through the closure temperature for argon in white mica between 130 and 120 Ma (Blythe et al., 1996; Fig. 3A). Nome Complex white micas yielded $^{40}Ar/^{39}Ar$ plateau ages of 129–116 Ma (Hannula and McWilliams, 1995; Werdon et al., 2005), similar to the range of ages from the Schist belt. Hannula and McWilliams (1995) interpreted these as minimum ages for blueschist-facies metamorphism. Sodic-calcic amphibole from a vein thought to have formed during decompression and heating of the Nome Complex produced a $^{40}Ar/^{39}Ar$ plateau age of 138.6 ± 1.0 Ma (Layer and Newberry, 2004).

Conservatively, these ages suggest that the blueschist-facies rocks of the Schist belt and Nome Complex were subducted and reached peak pressure before ca. 140 Ma, by which time they were partially exhumed. On the basis of available data, peak pressure could have occurred as early as 160–170 Ma. The exhumation-related greenschist-facies metamorphism and deformation, at ca. 130–120 Ma, was synchronous in the Nome Complex and Schist belt.

Central belt. The Central belt, immediately north of the Schist belt, contains blueschist-, greenschist-, and amphibolite-facies rocks metamorphosed during the Early Cretaceous (Figs. 2 and 3; Till and Snee, 1995; Toro et al., 2002; Vogl et al., 2002). Rocks in the Central belt reached pressures as high as 0.6–0.8 GPa during this period, corresponding to burial depths of 20–27 km (Fig. 3A; Patrick, 1995; Till and Snee, 1995; Vogl, 2003). At least two distinct metamorphic episodes affected Central belt rocks, one a regional event at blueschist and greenschist-facies conditions, and the other an amphibolite-facies event that affected a limited area in the central part of the range (Fig. 3B).

Deformation associated with the regional metamorphic event was not penetrative; rather, it was concentrated in high-strain zones. Geologic maps of the Central belt show classic fold-and-thrust structures (Dillon et al., 1986; Oldow et

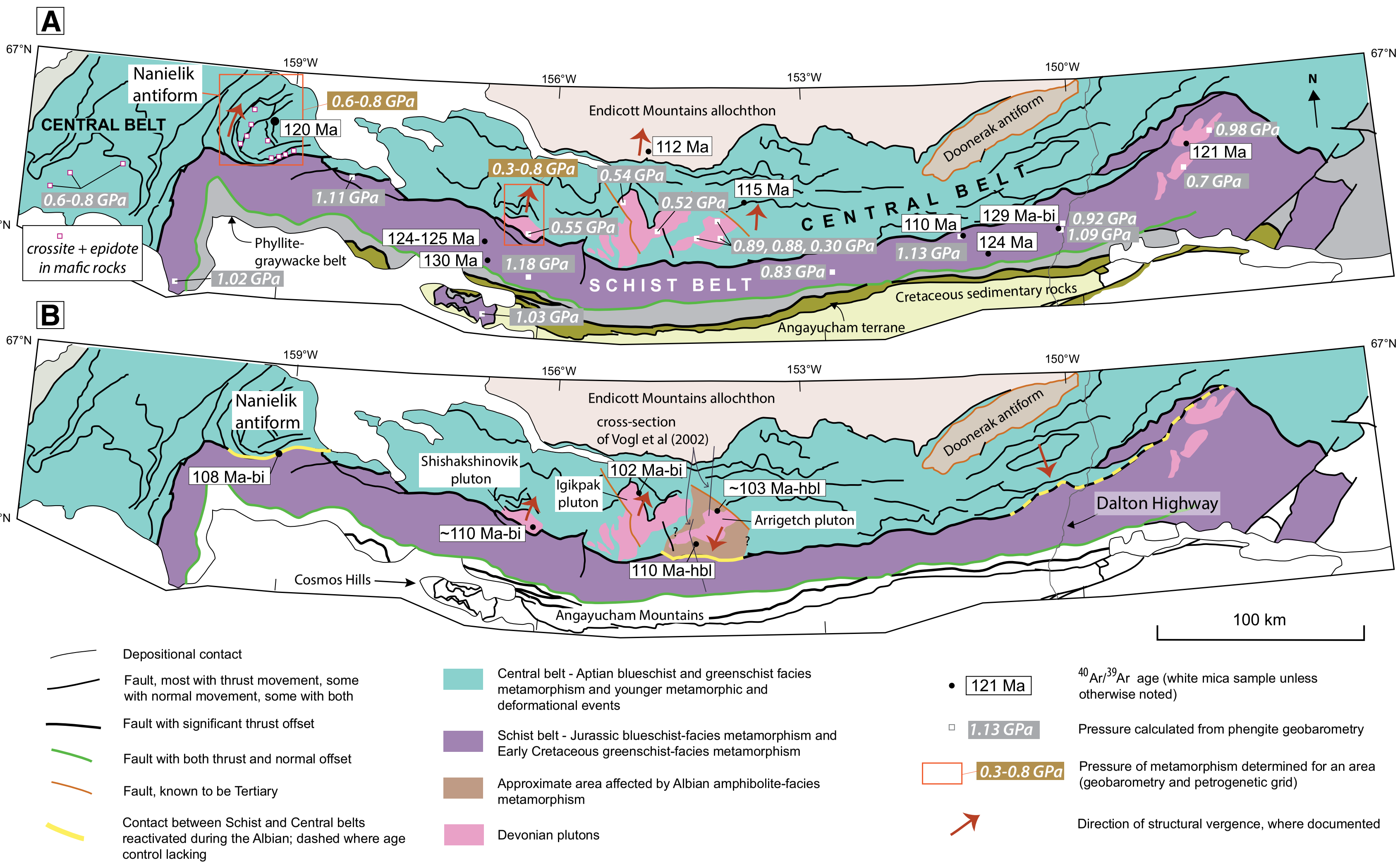

Figure 3. Maps of the southern Brooks Range illustrating major tectonic elements, select geochronologic and geobarometric data, and geographic names. (A) Features pertinent to pre-Albian Early Cretaceous metamorphism and deformation history; pressure estimates from phengite geobarometery have uncertainties of 0.1–0.15 GPa (Patrick, 1995). (B) Features pertinent to Albian metamorphism and deformation history. Most uncertainties reported for $^{40}Ar/^{39}Ar$ ages are less than 1.0 Ma; a few are in the range 1.0–1.5 Ma. Map is modified from Till et al. (2008). For location of figure, see Figure 2.

al., 1998; Till et al., 2008). However, the thrust surfaces, especially in the southern part of the belt, are ductile shear zones meters to tens of meters thick that contain well-developed stretching lineations (Till et al., 1988; Till and Snee, 1995; Toro et al., 2002). Primary features of the continental margin rocks—sedimentary, igneous, and metamorphic textures—were penetratively deformed in the shear zones but preserved in the core of thrust sheets (Till et al., 1988; Toro et al., 2002). In general, the intensity and ductile character of deformation in the shear zones decrease across the belt from south to north (Till et al., 1988); the structural contact of the Central belt with rocks to the north does not appear to be a major crustal boundary (Handschy, 1998).

Nanielik antiform. The blueschist-facies rocks of the Central belt are best exposed in the western Brooks Range at the Nanielik antiform (Fig. 3A). There, Neoproterozoic metamorphic basement was imbricated with Paleozoic rocks at blueschist-facies conditions during the Early Cretaceous (Fig. 4A; Till and Snee, 1995; Till et al., 1988, 2008). Mafic lithologies in the Neoproterozoic and Paleozoic sequences developed the diagnostic blueschist-facies assemblage crossite plus epidote during the thrusting event (Till and Snee, 1995). Mafic rocks within shear zones (thrust planes) and tear faults in this structure are crossite-epidote L-tectonites, whereas in the core of the thrust sheets, crossite and epidote statically overprinted primary igneous or earlier metamorphic textures (Till et al., 1988). Trends of stretching lineations formed in shear zones on thrust and tear faults, defined by crossite, actinolite, mica trains, and elongate clasts, indicate a north-south to northeast transport direction (Till and Snee, 1995). Pressures of 0.6–0.7 GPa (20–24 km) are typically required to generate crossite and epidote in mafic rocks (Brown, 1986; Evans, 1990). White mica from the tectonic fabric in a highly strained quartz-rich conglomerate in the lower part of this structure yielded concordant plateau and isochron $^{40}Ar/^{39}Ar$ ages of 120 Ma (Till and Snee, 1995).

The total area affected by this blueschist-facies event is not known due to several factors, including a paucity of mafic lithologies in the Central belt, younger metamorphic events that may have overprinted high-pressure assemblages, and a general lack of detailed field investigations. However, mafic dikes that cut Paleozoic carbonate rocks in a broad region up to 100 km southwest of the Nanielik antiform also contain the assemblage crossite plus epidote (Fig. 3A; Till et al., 2008). In addition, Patrick (1995), using the composition of phengitic white mica in granitic orthogneiss, calculated metamorphic pressures of 0.5–0.8 GPa (17–27 km depths) up to 240 km east of Nanielik antiform (Fig. 3A).

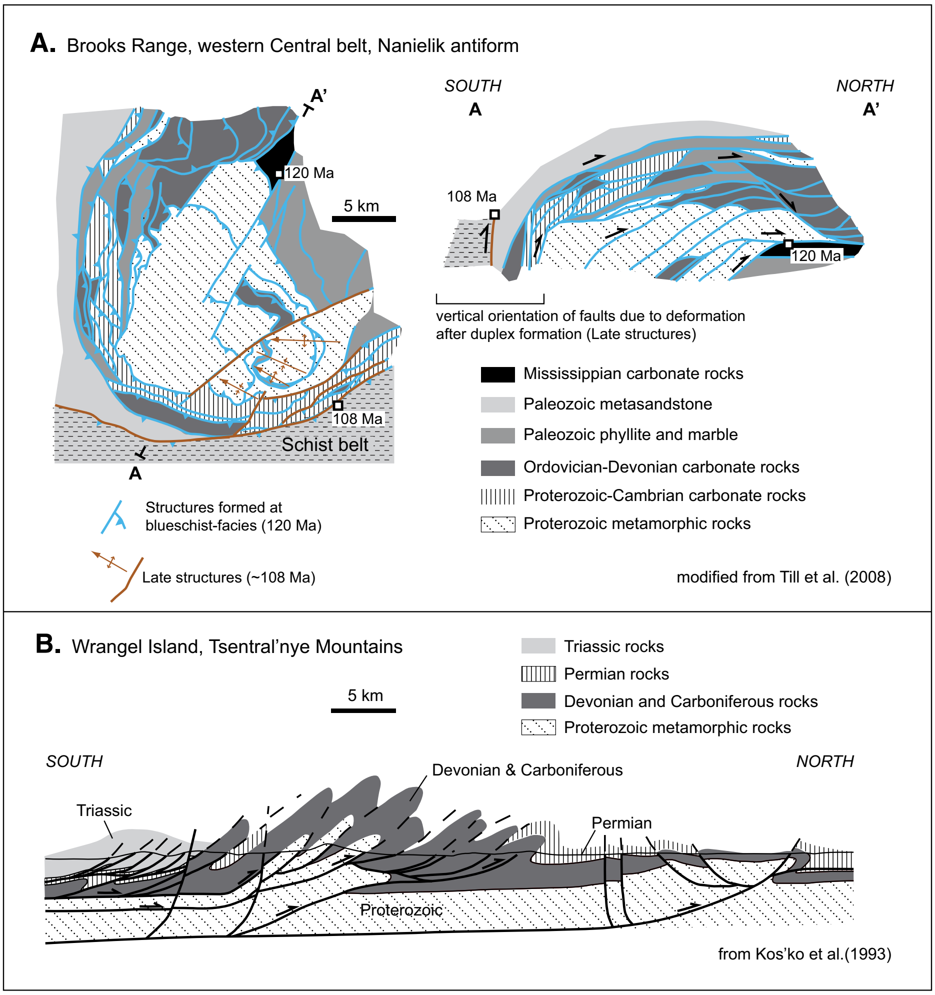

Figure 4. (A) Geologic map and cross section of Nanielik antiform, western Central belt, Brooks Range, modified from Till and Snee (1995). Uncertainties in $^{40}Ar/^{39}Ar$ ages are less than 1.0 Ma. (B) Geologic cross section of Tsentral'nye Mountains, Wrangel Island, from Kos'ko et al. (1993). Map and cross sections are shown at the same scale and with no vertical exaggeration.

These pressures overlap the likely peak pressure attained at the Nanielik antiform (Till and Snee, 1995). Thus, Early Cretaceous blueschist- to high-pressure greenschist-facies metamorphism apparently affected a zone at least 340 km long from west to east.

A later tectonic event focused along the contact of the Schist belt and Central belt resulted in deformation of shear zones in the southern part of the Nanielik antiform (Figs. 3A and 4A; Till and Snee, 1995). Late biotite from schist along the Schist belt–Central belt contact produced a $^{40}Ar/^{39}Ar$ age of 108.2 ± 0.2 Ma (Till and Snee, 1995), interpreted as an age of deformation along the contact between the Schist and Central belts.

Shishakshinovik and Mount Igikpak plutons, central Brooks Range. Greenschist-facies metamorphism and associated north-vergent deformation affected the area around the Devonian Shishakshinovik and Igikpak plutons (Figs. 3A and 3B). Near the Shishakshinovik pluton, the dominant greenschist-facies foliation contains aligned kyanite needles that define a N-S stretching lineation; small-scale kinematic indicators show a top-to-the-north sense of shear (Toro, 1998). Pelitic rocks contain the mineral assemblage quartz-muscovite-chloritoid-kyanite-biotite, which indicates conditions likely reached 0.3–0.8 GPa (depths of 10–27 km) and 400–540 °C (Toro, 1998). A pressure of 0.55 ± 0.15 GPa was obtained from the pluton (Patrick, 1995) and likely records the same event. Biotite from the pluton yielded a somewhat disturbed $^{40}Ar/^{39}Ar$ weighted mean age of ca. 110 Ma, interpreted by Toro (1998) as a minimum age for the regional greenschist-facies event.

Toro et al. (2002) documented north-vergent deformation and associated metamorphism in the vicinity of the Igikpak pluton in the Central belt and adjacent areas to the north in the

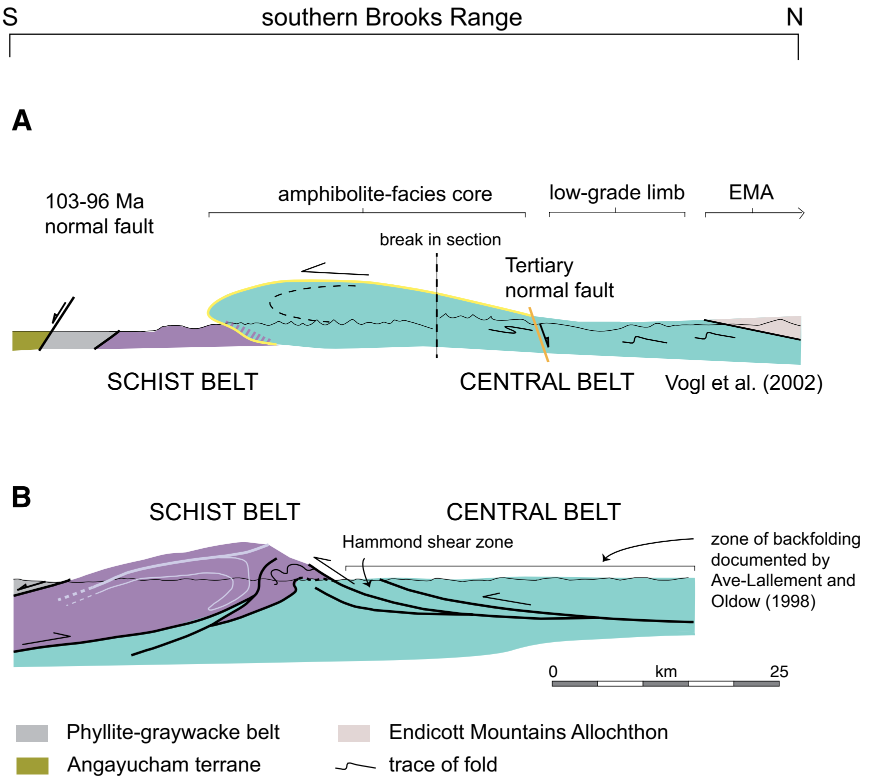

Figure 5. Cross sections drawn across the southern Brooks Range showing structures related to back thrusting on the contact between the Schist belt and the Central belt. Scale applies to both cross sections. (A) Cross section through Arrigetch pluton showing ductile back fold formed during Albian amphibolite-facies metamorphism (from Vogl, 2002; see Fig. 3 for location). Yellow line shows the mapped and projected trace of 500 °C isotherm and envelopes area that reached higher temperatures. Striped area represents part of Schist belt overprinted by amphibolite-facies metamorphic event. EMA—Endicott Mountains allochthon. (B) Cross section drawn along Dalton Highway (Fig. 3) showing south-vergent structures that formed during emplacement of Central belt rocks over the Schist belt. Structural relations are based on Till and Moore (1991), the geologic map of Till et al. (2008), and personal observation. Hammond River shear zone is equivalent to Hammond River phyllonite of Moore et al. (1997b).

Endicott Mountains allochthon (Figs. 3A and 3B). In an area of high strain adjacent to and north of the pluton, rocks were penetratively deformed and display two foliations (Toro et al., 2002). The younger foliation formed at lower-temperature greenschist-facies conditions and contains well-developed north-south–trending stretching lineations and small-scale kinematic indicators that consistently display top-to-the-north sense of shear (Toro et al., 2002). North of the pluton and the metamorphic rocks, less-deformed sedimentary rocks of the northern Central belt and southern Endicott Mountains allochthon also contain two foliations and north-vergent kinematic indicators, though metamorphic minerals are only weakly developed (Toro et al., 2002). White mica from the earlier-formed foliation in this area yielded $^{40}Ar/^{39}Ar$ weighted mean plateau and isochron dates of 112 and 111 Ma, interpreted by Toro et al. (2002) as the age of metamorphism and north-vergent deformation (Fig. 3A). The 0.54 ± 0.15 GPa pressure obtained from the Igikpak pluton (Fig. 3A) likely records the amount of tectonic burial that occurred at that time (~18 km; Patrick, 1995).

Arrigetch pluton, central Brooks Range. Greenschist-facies fabrics in the Central belt northeast of the Devonian Arrigetch pluton (Figs. 3A and 3B) formed during north-vergent contractional deformation (Vogl, 2002). The most deeply buried rocks that have these fabrics contain biotite that yielded plateau and isochron $^{40}Ar/^{39}Ar$ ages of 116–114 Ma (Vogl et al., 2002). Locally, kyanite porphyroblasts grew across the fabrics formed during this event. The kyanite-bearing and underlying biotite-bearing rocks reached pressures of at least 0.3 GPa (>10 km; Vogl, 2003).

In the vicinity of the Arrigetch pluton itself, a second crustal thickening event has been documented. There, the early structures associated with north-vergent thrust systems were folded and reoriented during large-scale south-vergent back folding and amphibolite-facies metamorphism (Fig. 5A; Vogl, 2002; Vogl et al., 2002). Amphibolite-facies rocks at the core of the back fold developed consistent N-S–oriented mineral streaks, elongate quartz and calcite grains, and porphyroblast strain shadows (Vogl et al., 2002). These rocks reached peak metamorphic pressures of at least 0.85–0.90 GPa (Vogl, 2003), corresponding to burial depths of 29–30.5 km. Hornblende $^{40}Ar/^{39}Ar$ cooling ages are complex, but they indicate that peak metamorphic conditions were reached before ca. 105–103 Ma (Vogl et al., 2002). Hornblende from the same area analyzed by Patrick et al. (1994) yielded concordant isochron and correlation diagram ages of 110 Ma.

Dalton Highway area, east-central Brooks Range. To the east, along the Dalton Highway (Fig. 3B), the Central belt is structurally above the Schist belt (Moore et al., 1997b). A cross section based on geologic map relations (Till et al., 2008), outcrop-scale structures in the vicinity of the contact (Till and Moore, 1991; Till, personal observation, 1989, 1990, 1992), and structural analysis by Avé Lallemant and Oldow (1998) shows that the Central belt was thrust to the south over the Schist belt (Fig. 5B). The timing of this event is not known.

Seward Peninsula—Kigluaik, Bendeleben, and Darby Mountains. Rocks in all three of the mountain ranges on the Seward Peninsula (Fig. 6) preserve evidence that amphibolite- and granulite-facies metamorphism overprinted the blueschist- to greenschist-facies fabrics of the Nome Complex (Thurston, 1985; Patrick and Lieberman, 1988; Calvert et al., 1999; Amato and Miller, 2004; Till et al., 2011). The Darby Mountains of southeast Seward Peninsula retain the clearest evidence of that overprint. Till et al. (2011) reported the locations of key metamorphic mineral assemblages and geochronologic data for the range; structural data and locations of isograds, as shown in Figure 7, have not been previously published. In the northern Darby Mountains, biotite-grade minerals statically overprinted blueschist-facies minerals that define a shallowly dipping fabric. In the central part of the range, foliations are steeper and defined by assemblages that contain staurolite plus kyanite. These minerals formed at pressures of least 0.65–0.7 GPa (Spear, 1993) or a depth of more than 22–24 km. In the southern part of the range, rocks that contain sillimanite- to second sillimanite–grade assemblages have steeply dipping foliations (Fig. 7; a fault-bounded block on the west side of the range contains similar rocks). Small bodies of anatectic biotite granite formed within the area that reached granulite facies (above the second sillimanite isograd; Fig. 7). These granites yielded a U-Pb zircon age

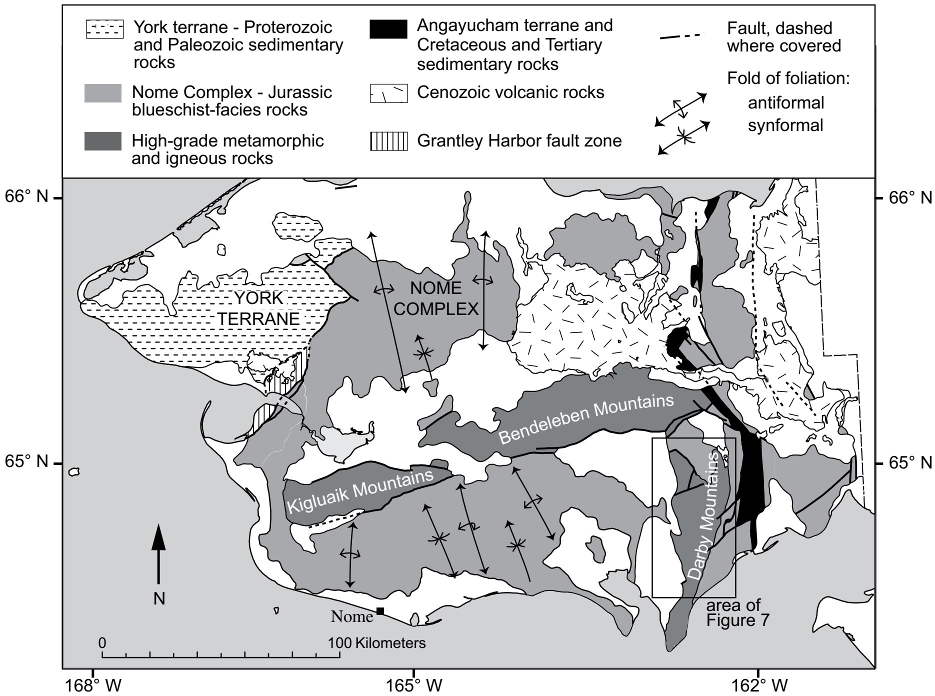

Figure 6. Simplified geologic map of the Seward Peninsula, modified from Till et al. (2011). Location and orientation of folds of foliation within the Nome Complex are shown. Plutonic rocks, which are most voluminous in the Kigluaik, Bendeleben, and Darby Mountain ranges, are not shown. For location of figure, see Figure 2.

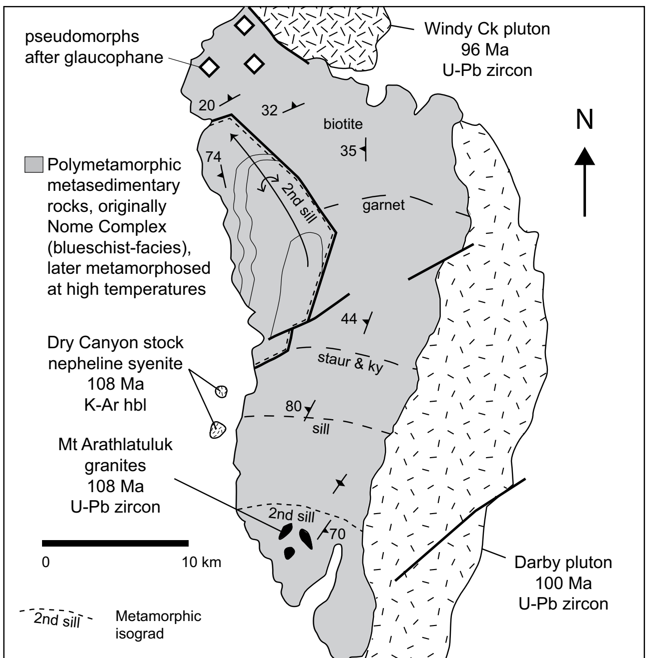

Figure 7. Geologic map of the Darby Mountains, southeast Seward Peninsula, showing foliations, previously unpublished metamorphic isograds, and select igneous rocks. Fault-bounded block in the northwest part of the range contains a map-scale fold of marble with a subvertical axial plane. All rocks within the block were metamorphosed at granulite facies (temperatures above the second sillimanite isograd). Reported uncertainties for the U-Pb zircon ages are less than 0.5 Ma; the uncertainty for the K-Ar biotite age is 1.4 Ma. For sources of geochronologic data, see text and Till et al. (2011). Map is modified from Till et al. (2011). For location of figure, see Figure 6. Abbreviations: sill—sillimanite; staur—staurolite; ky—kyanite; hbl—hornblende.

of 108 Ma and a biotite K-Ar age of ca. 102 Ma (Till et al., 2011). Decompression is recorded in highly aluminous rocks in the central part of the range, which preserve evidence of the reaction kyanite + orthoamphibole = cordierite + staurolite. This indicates that the rocks underwent decompression to pressures less than ~0.5 GPa (depths less than 17 km; Till et al., 2011). The kyanite-bearing assemblages predated or formed synchronously with the 108 Ma anatectic granites. The biotite age of ca. 102 Ma likely reflects cooling associated with decompression. The vertical foliations and axial planes in these rocks are consistent with E-W shortening, but they may have been rotated since they were formed. These data suggest that an episode of high-grade metamorphism, deformation, and anatexis affected the blueschist- to greenschist-facies rocks of the Nome Complex in eastern Seward Peninsula, starting around 108 Ma.

The earliest occurrence of high-grade metamorphism is challenging to identify and date in the Kigluaik and Bendeleben Mountains (Fig. 6), where multiple pulses of Early and Late Cretaceous magmatism and metamorphism complicate the effort (Amato et al., 1994; Akinin and Calvert, 2002; Gottlieb, 2008). Earliest-formed metamorphic assemblages in amphibolite-facies rocks of the Bendeleben Mountains contain kyanite and staurolite (Gottlieb, 2008). The kyanite-staurolite assemblages formed at 0.7–0.8 GPa (depths of 24–27 km) and temperatures over 600 °C based on the petrogenetic grid (Spear, 1993). North-vergent folds formed during this event, which is thought to be older than 104 Ma, based on the age of the oldest crosscutting granitic rock (Gottlieb, 2008).

Schists on the southern flank of the Kigluaik Mountains contain blueschist-facies mineral assemblages overprinted by upper-greenschist-facies assemblages (Thurston, 1985; Calvert et al., 1999). The core of the range is occupied by amphibolite- to granulite-facies metamorphic rocks that are 91 Ma or older, based on monazite ages (Amato et al., 1994). At the base of the section, kyanite inclusions in garnet in a granulite-facies gneiss and boudins of garnet lherzolite partially recrystallized to spinel lherzolite are remnants of a pre–91 Ma high-pressure history (Lieberman and Till, 1987; Lieberman, 1988). Garnet lherzolite is stable at pressures over 1.5–2.0 GPa, or approximate depths of 50–66 km (Garrido et al., 2011; Green et al., 2012).

Chukotka

Anyui-Chukotka fold belt, western Chukotka. The Anyui-Chukotka fold belt is a broad zone, locally more than 350 km wide perpendicular to its structural trend, that contains weakly metamorphosed and folded rocks

(Fig. 2). Within the belt, Neoproterozoic crystalline rocks, Devonian and Carboniferous continental margin sedimentary rocks, and voluminous Triassic turbidites were all deformed and locally overlain by Late Jurassic to Cretaceous sedimentary rocks (Natal'in et al., 1999; Miller et al., 2006; Amato et al., 2014). Most research on the deformational history of the fold belt was done in western Chukotka, north of the exposed portion of the South Anyui suture zone (Fig. 2). There, the Neocomian age of shortening is based in part on stratigraphic constraints, as synorogenic strata as old as latest Jurassic and as young as Valanginian were involved in deformation (Miller et al., 2009; Sokolov et al., 2009). The lower greenschist-facies metamorphism associated with these structures produced local mica growth and a weak metamorphic fabric (Tuchkova et al., 2007). Over 250 km to the north, near the coast, N-S to NE-SW shortening produced gentle to tight folds that have moderate to steep axial-plane cleavage (Miller and Verzhbitsky, 2009). Plutons as old as 117 Ma cut the deformed rocks in western Chukotka (Miller et al., 2009). In central Chukotka, Tikhomirov et al. (2008) noted that thick, 145 Ma caldera deposits are undeformed and rest unconformably on gently folded Upper Triassic sedimentary rocks, suggesting that deformation in that area occurred during the Jurassic rather than the Cretaceous.

Near the South Anyui suture zone, north-vergent thrusts emplaced oceanic crust, arc volcanic and volcaniclastic rocks, and related sedimentary rocks over the southern part of the Anyui-Chukotka fold belt (Sokolov et al., 2002, 2009). Below these thrusts, sedimentary rocks of the fold belt were also folded and thrust to the north. Sokolov et al. (2009, 2015) documented south-vergent structures within the South Anyui suture zone that formed synchronous with or after north-directed structures. Dextral strike-slip faults were the latest structures developed along the boundary between the South Anyui suture zone and the Anyui-Chukotka fold belt (Sokolov et al., 2002, 2009, 2015).

Offshore northern Chukotka. On Wrangel Island, north of central Chukotka (Fig. 2), Neoproterozoic, Paleozoic, and Triassic rocks were folded and thrusted during north-vergent shortening (Fig. 4B; Kos'ko et al., 1993; Verzhbitsky et al., 2015). In deeper parts of the deformed section, high strain produced L-S tectonites; primary features are preserved in sedimentary rocks deformed at shallower levels (Miller et al., 2010b). Mafic igneous and semipelitic sedimentary rocks contain greenschist-facies assemblages; temperatures of deformation were in the range of 350 °C to 450 °C (Kos'ko et al., 1993; Miller et al., 2014). Miller et al. (2014) considered the metamorphic assemblages and high-strain fabrics to be products of extension. The age of metamorphism and deformation is not known, but an apatite fission-track study revealed that the entire package of rocks was cooled to ~100 °C by 95 Ma (Dumitru and Miller, 2010).

Geophysical studies of the continental shelf west and east of Wrangel Island reveal north-vergent structures of probable Mesozoic age extending from the Chukotka shoreline to the northern edge of the shelf (Drachev, 2011; Verzhbitsky et al., 2015). Drachev (2011) identified a narrow foreland basin along the edge of the shelf from the New Siberian Islands to northern Alaska (Figs. 1 and 2). The width of the shelf has been modified by Late Cretaceous and Paleogene tectonics, so the original size of the offshore area underlain by contractional structures is difficult to reconstruct.

Senyavin uplift. The Senyavin uplift of southeastern Chukotka is south and west of the Kolyuchin-Mechigmen zone (Fig. 8). All of the information on the Senyavin uplift synthesized here is from Calvert (1999) and Akinin and Calvert (2002). The uplift is a 1500 km^2 area of metamorphic rocks directly overlain by thick volcanic and volcaniclastic rocks (Fig. 8). The metamorphic section in the Senyavin uplift is composed of oceanic and continental shelf rocks that were imbricated, buried to depths of 20–27 km (0.6–0.8 GPa), and recrystallized at amphibolite-facies conditions. High strain accompanied recrystallization and produced NE-SW–oriented stretching lineations defined by aligned kyanite, sillimanite, hornblende, and mica trains. Folds of the foliation and associated offset of leucocratic layers, formed at high temperatures, record north-vergent deformation. The $^{40}Ar/^{39}Ar$ weighted mean and plateau cooling ages from three metamorphic hornblendes indicate that peak metamorphism occurred before 132 Ma (Fig. 8). White mica cooling ages of 130–131 Ma record rapid cooling between 132 and 130 Ma. U-Pb zircon ages of ca. 135 Ma from amphibolite-facies gneissic granite exposed near the Senyavin uplift suggest that peak metamorphism in southeastern Chukotka occurred at or before 135 Ma and was accompanied by granitic magmatism (Pease et al., 2007; Pease, 2011).

Chegitun River area and Koolen dome, northeastern Chukotka. Greenschist-facies rocks of the Chegitun River area are exposed northeast of the Kolyuchin-Mechigmen zone in eastern Chukotka (Fig. 8). The Paleozoic sedimentary rocks of the Chegitun River area underwent greenschist-facies metamorphism and penetrative deformation around 120 Ma (Toro et al., 2003). Deformational fabrics in these rocks include NE-SW or N-S lineations defined by aligned minerals, stretched pebbles, and strain shadows on pyrite (Toro et al., 2003). The burial depth of these rocks is not known. The $^{40}Ar/^{39}Ar$ analyses of white mica from the earliest-formed fabric yielded weighted mean ages of 117–124 Ma (Toro et al., 2003). One of the three samples yielded concordant total fusion, isochron, and weighted mean ages of 121 Ma (Toro et al., 2003), which may closely approximate the age of metamorphism. The greenschist-facies rocks are in fault contact with the western flank of the Koolen dome (Fig. 8).

The Koolen dome, also northeast of the Kolyuchin-Mechigmen zone, is a large (3000 km^2) expanse of amphibolite- to granulite-facies and associated igneous rocks with a protracted history that spanned the Cretaceous (Fig. 8; BSGFP, 1997; Akinin and Calvert, 2002). Evidence for Early Cretaceous midcrustal metamorphism is preserved on its west flank, where the earliest-formed assemblages in amphibolite-facies pelitic rocks contain kyanite that crystallized before formation of the dominant foliation (Toro et al., 2003). The dominant foliation formed at a lower pressure, as the fabric contains the assemblage sillimanite plus cordierite (Toro et al., 2003). Minerals from the dominant foliation yielded concordant $^{40}Ar/^{39}Ar$ isochron and weighted mean ages of 108–109 Ma (hornblende; Fig. 8) and 105 Ma (biotite; Toro et al., 2003). The kyanite-bearing assemblages must be older than 109 Ma, and cooling associated with decompression was under way by 105–104 Ma. On the south flank of the Koolen dome, a $^{40}Ar/^{39}Ar$ hornblende age of 103 Ma also records cooling (Fig. 8; Akinin and Calvert, 2002).

Remnants of the midcrustal metamorphic event may be present near the core of the Koolen dome. There, amphibolite- to granulite-facies rocks record peak temperatures in excess of 700 °C and peak pressures of 0.6–0.8 GPa (20–27 km; Akinin and Calvert, 2002). It is likely these rocks traversed the kyanite stability field before reaching peak temperature (see fig. 3 of Akinin and Calvert, 2002). Small bodies of foliated leucogranite thought to be partial melts formed during this event and yielded U-Pb monazite ages, overlapping within error, of 104 Ma (BSGFP, 1997; Akinin and Calvert, 2002). Therefore, maximum burial of metamorphic rocks in the core of Koolen dome occurred before 104 Ma, likely synchronous with the pre–109 Ma maximum burial of rocks on the west flank. Toro et al. (2003) suggested that the kyanite-bearing assemblages on the west flank formed at about the same time as the greenschist-facies rocks in the Chegitun River valley (ca. 120 Ma). On the basis of this interpretation, maximum burial of rocks in both the Chegitun River valley and the entire Koolen dome was synchronous and occurred in the early Aptian.

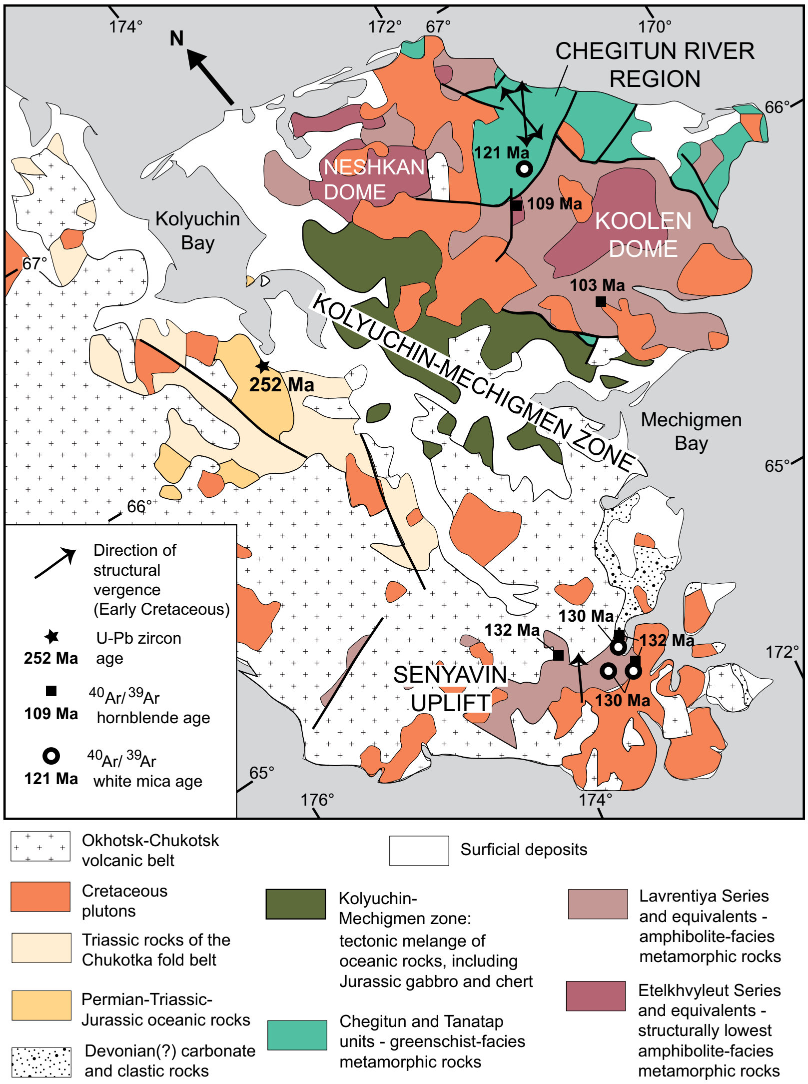

Figure 8. Geologic map of eastern Chukotka, modified from Natal'in et al. (1999) and Toro et al. (2002). Geochronologic data shown are from Calvert (1999), Ledneva et al. (2011), Toro et al. (2002), and Akinin and Calvert (2002). Reported uncertainties are less than 1 Ma. For location of figure, see Figure 2.

LATEST JURASSIC AND EARLY CRETACEOUS TECTONIC EVOLUTION

It is a goal of this paper to synthesize the metamorphic and deformational histories presented herein and put them in spatial and temporal context with concurrent shallow-level deformation, magmatism, and basin formation within the Arctic Alaska–Chukotka microplate. This information, together with that from the oceanic rocks of the South Anyui suture zone and the Angayucham terrane, provides a basis for reconstructing the tectonic evolution of the southern margin of the Arctic Alaska–Chukotka microplate during the latest Jurassic and Early Cretaceous.

Evolution of the Southern Margin of the Arctic Alaska–Chukotka Microplate

Southward subduction of the southern margin of Arctic Alaska is generally accepted as the first event that led to collisional orogenesis in the Brooks Range (Roeder and Mull, 1978; Moore et al., 1994; Gottschalk et al., 1998). The timing of subduction is unknown, due in part to the uncertain age of blueschist-facies metamorphism in the Schist belt and Nome Complex. Because Jurassic arc-related igneous rocks are present in the Brooks Range (Harris, 2004, and references therein) and several $^{40}Ar/^{39}Ar$ cooling ages from the blueschist-facies rocks of the Schist belt are 142 Ma or older (Christiansen and Snee, 1994; Gottschalk and Snee, 1998), the age of blueschist-facies metamorphism is assumed here to be latest Jurassic or to coincide with the Jurassic-Cretaceous boundary.

The status of the South Anyui suture zone and the nature of the tectonic boundary between Chukotka and the suture zone during the Late Jurassic are not well constrained. On the basis of detrital zircon ages from a Late Jurassic–Early Cretaceous basin on Chukotka, Miller et al. (2008) argued that the suture zone had closed by the Tithonian. Others contend that closure initiated in the Late Jurassic and was completed during the Early Cretaceous via north-dipping subduction under Chukotka (Amato et al., 2015; Nokleberg et al., 2000; Sokolov et al., 2002, 2009; Shepherd et al., 2013). Whether the Late Jurassic Nutesyn (or Kulpolney) arc (now exposed within the suture zone) developed on continental or oceanic crust is a key difference among these models. Tikhomirov et al. (2008) concluded that the geochemistry of a 146–144 Ma highly felsic caldera deposit in central Chukotka is consistent with its formation over an Andean-type subduction system. At the commencement of the tectonic scenario shown in Figure 9, a Late Jurassic–earliest Cretaceous north-dipping subduction zone is shown as the boundary between Chukotka and the South Anyui suture zone, which has yet to fully close.

Berriasian–Barremian (Neocomian: 145–126 Ma)

On the Arctic Alaska side, the locus of deformation shifted from the south-dipping subduction zone to the subjacent continental crust by earliest Neocomian time. Contractional deformation in the thin-skinned Brooks Range fold-and-thrust belt, and, by inference, deeper crustal shortening to the south in the Brooks Range hinterland, was well under way during the Neocomian (Fig. 9A). Zircon fission-track ages from the fold-and-thrust belt in the central and western Brooks Range indicate that crustal shortening commenced before ca. 138–130 Ma (Blythe et al., 1996; O'Sullivan et al., 2000). The zircon grain ages obtained require burial to depths of ~6–9 km before 138–130 Ma, and track lengths document rapid cooling at 138–130 Ma; both burial and cooling were accomplished by shortening episodes (Blythe et al., 1996; O'Sullivan et al. 2000). Berriasian–Valanginian (145–134 Ma) turbidite and debris-flow deposits are the oldest deposits of the Brooks Range foreland basin (Moore et al., 2015, and references therein). These proximal deposits contain heavy minerals and lithic fragments derived from a volcanic arc, mafic and ultramafic rocks, sedimentary rocks of the Arctic Alaska–Chukotka microplate, and metamorphic detritus, consistent with

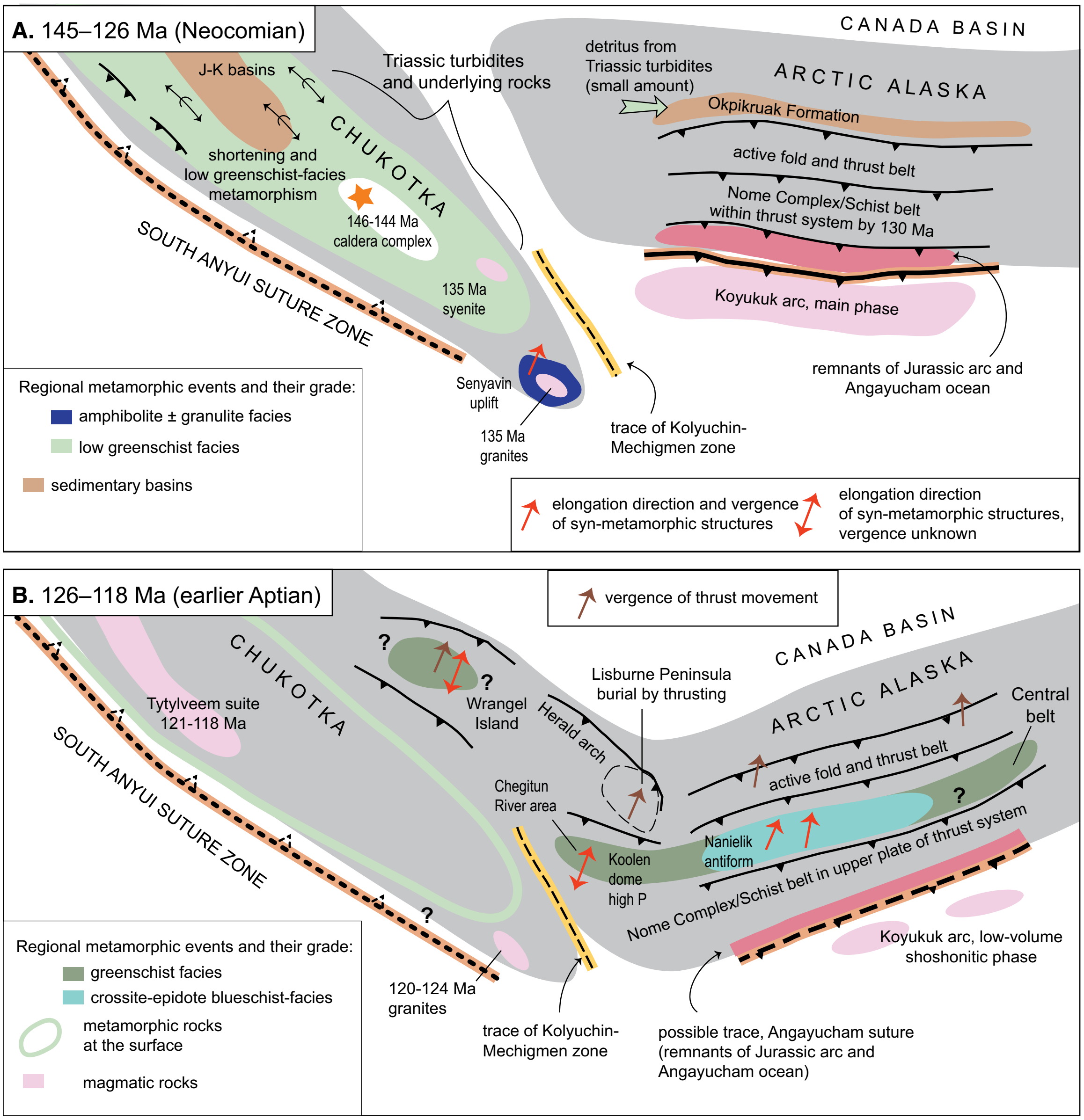

Figure 9. Four schematic maps that illustrate the spatial and temporal distribution of Early Cretaceous metamorphic events, major structural features, igneous events, and basin formation in the southern part of the Arctic Alaska–Chukotka microplate. The four maps illustrate events that occurred during Neocomian, earlier Aptian, later Aptian, and Albian time periods. Because the four periods of time are long relative to the pace of tectonic processes, each illustration contains multiple elements that may or may not have occurred synchronously. The schematic maps were not constructed in a way that fully reconstructs plate movements or accounts for the effects of Late Cretaceous and Paleogene extension. As a result, the relative positions of major crustal features are likely more accurate than the apparent distance between them. Fields shown as solid blues and greens signify areas of active metamorphism; open fields with blue or green boundaries indicate exposure of metamorphic rocks at the surface. Heavy lines highlighted in dark orange represent subduction zones. Fields shown as solid brown are sedimentary basins. (A) Berriasian–Barremian (Neocomian: 145–125 Ma); (B) early Aptian (126–118 Ma); (C) late Aptian (117–113 Ma); (D) Albian (113–100 Ma). Ages of magmatic rocks on Chukotka are from sources cited in the text as well as Akinin et al. (2012), Luchitskaya et al. (2013), and Tikhomirov et al. (2008, 2011). See text for discussion. J-K—Jurassic–Cretaceous. (*Continued on following page.*)

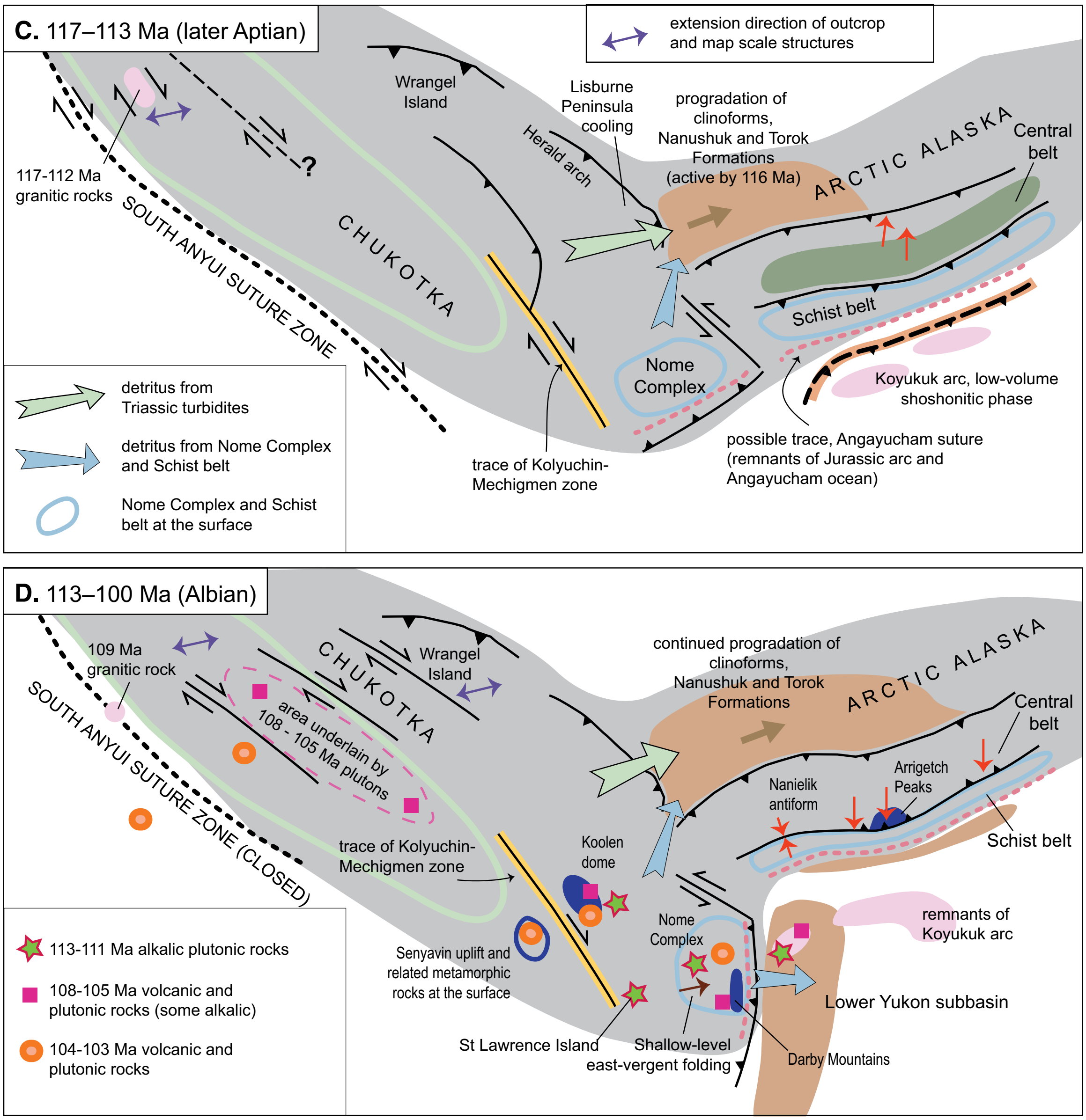

Figure 9 (*continued*).

deposition in an arc-continent collision setting (Toro et al., 1998; Moore et al., 2015). They also contain small numbers of detrital zircons likely derived from Triassic turbidites and sandstones similar to those exposed on Chukotka, Wrangel Island, and the Lisburne Peninsula of northwestern Alaska (Fig. 2; Moore et al., 2015).

Map-scale folding, development of cleavage, and lower-greenschist-facies metamorphism in the Anyui-Chukotka fold belt extend across a broad area (Tuchkova et al., 2007) and were more strongly developed in areas close to the South Anyui suture (Sokolov et al., 2002; Miller and Verzhbitsky, 2009). However, there are no metamorphic rocks that were buried to midcrustal depths adjacent to the South Anyui suture zone, as would be expected if significant amounts of crustal shortening had occurred along that boundary. Deformation was accompanied by deposition of synorogenic strata (Miller et al., 2009; Amato et al., 2015) and at least one period of magmatism (ca. 135 Ma; Pease, 2011; Luchitskaya et al., 2013).

Rocks in the Senyavin uplift, southeast Chukotka, record burial of oceanic and subjacent continental rocks to midcrustal depths, where they underwent high-grade metamorphism, incipient melting, and north-vergent deformation at ca. 135 Ma (Calvert, 1999; Fig. 9A). Senyavin is separated from other midcrustal metamorphic rocks in east Chukotka by the cryptic Kolyuchin-Mechigmen zone (Figs. 2 and 8), and no correlative metamorphic events further west on Chukotka have been identified. Thus, the tectonic setting of burial, granitic magmatism, and subsequent cooling is unknown.

Early Aptian (125–118 Ma)

The most significant period of metamorphism and crustal thickening in Arctic Alaska and eastern Chukotka was the earlier part of the Aptian. Crustal shortening and associated north-vergent deformation affected a broad area that included northeastern Chukotka, the Lisburne Peninsula, and the Brooks Range (Fig.

9B; Till and Snee, 1995; Toro et al., 2002, 2003; Moore et al., 2002; Vogl, 2003). Rocks of the Central belt in the Brooks Range were buried to depths of 20–27 km, and blueschist-facies mineral assemblages formed synchronously with north-vergent thrusting (Till and Snee, 1995; Toro et al., 2002; Vogl, 2003). High-pressure–low-temperature metamorphism affected an area extending at least as far to the east as the Igikpak pluton (Fig. 3B), based on phengite geobarometry (Patrick, 1995). Thus, the early Aptian blueschist-facies metamorphic belt in northern Alaska was at least 340 km long. In northern Alaska, the partially exhumed Nome Complex and Schist belt likely provided at least part of the tectonic load that produced the metamorphic rocks; $^{40}Ar/^{39}Ar$ cooling ages associated with exhumation-related greenschist-facies fabrics in the Nome Complex and Schist belt support this contention. Although numerous assumptions are required to estimate the total crustal thickness during this metamorphic event, it is possible that it would have been on the order of 50–60 km.

Greenschist-facies metamorphism of rocks along the Chegitun River, northeast Chukotka, was synchronous with the blueschist-facies metamorphism at the Nanielik antiform (ca. 120 Ma; Toro et al., 2003). Although burial depth of the Chegitun River rocks is unknown, Toro et al. (2003) suggested that metamorphism and burial of those rocks were synchronous with the early metamorphic history of rocks in the Koolen dome, which were buried to depths of 20–27 km (Akinin and Calvert, 2002). Toro et al. (2003) estimated that the thickness of the crust at the time of burial was ~59 km. This belt of thickening may have extended offshore (Drachev, 2011; Verzhbitsky et al., 2012). Metamorphism and north-vergent deformation of rocks on Wrangel Island may have been early Aptian events.

Although no early Aptian metamorphic event has been identified on Seward Peninsula, it is likely that rocks of the peninsula participated in this thickening event. The estimated total crustal thicknesses at Koolen dome and the Central belt are similar to the thickness required to produce garnet in lherzolite (Garrido et al., 2011; Green et al., 2012); the early high-pressure metamorphism recorded in the core of the Kigluaik Mountains could have occurred at this time, as well as the early north-vergent deformational event in the Bendeleben Mountains (Gottlieb, 2008).

No corresponding Aptian crustal thickening event is known in western and central Chukotka. Magmatism was under way in Chukotka during the first half of the Aptian. The 2.4-km-thick, mildly deformed, 121 Ma to 118 Ma andesites and trachytes of the Tytylveem suite are exposed in a northwest-trending trough in western Chukotka (U-Pb zircon ages; Tikhomirov et al., 2009a; Akinin and Miller, 2011; Tikhomirov, 2013, written commun.). Granitic rocks of similar age occur in eastern Chukotka (Pease et al., 2007), south of the Kolyuchin-Mechigmen zone (Fig. 9B). Pease et al. (2007) postulated that the magma mixing textures in these rocks are typical of those found in plutons formed in Andean-style collision zones, and that the 124–120 Ma rocks of eastern Chukotka may be remnants of an Aptian arc. Thus, there may have been a period of north-dipping subduction under Chukotka during the earlier part of the Aptian (as shown in Fig. 9B), but further geochemical study is needed to evaluate the possibility.

Late Aptian (117–113 Ma)

Two important events occurred during the middle to late Aptian (Fig. 9C). Sediments derived from Chukotka and northern Alaska began to pour into the Brooks Range foreland basin (Colville Basin of Fig. 2; Lease et al., 2014; Moore et al., 2015), and the overall style of deformation that affected western Chukotka changed from contractional to extensional or transtensional (Miller et al., 2009; Miller and Verzhbitsky, 2009).

Delivery of a huge volume of sediment to the Brooks Range foreland basin began in the middle to late Aptian (Lease et al., 2014; Moore et al., 2015). This sediment was deposited in a large sequence of clinoforms that prograded from west to east along the Colville Basin axis (Fig. 2; Nanushuk and Torok Formations; Houseknecht et al., 2009). The clinoform sequences are up to 2500 m thick, and the sediment dispersal system was ~300–500 km long. The volume of material in the clinoform sequence is larger than any comparable sequence in the world (Houseknecht et al., 2009). Detrital zircon studies of the Nanushuk-Torok system showed that progradation started around 116–115 Ma and progressed from west to east over the interval 116–104 Ma (Lease et al., 2014; Moore et al., 2015). Flexural subsidence created the deep trough into which the clinoform sequences prograded (Houseknecht et al., 2009; Houseknecht and Bird, 2011). That subsidence was likely caused by the same tectonic load that generated the regional blueschist- to greenschist-facies metamorphism in the Brooks Range Central belt and northeastern Chukotka at ca. 120 Ma.

Sediment was supplied to the Nanushuk-Torok system from at least two source areas (Fig. 9C). Detrital zircon studies confirm that Triassic turbidites in Chukotka and/or Wrangel Island were a source for sediments in the Nanushuk and Torok Formations (Lease et al., 2014; Moore et al., 2015). Heavy mineral studies show that the Nanushuk and Torok Formations contain the same assemblage of minerals that is typically found in the blueschist-facies rocks of the Nome Complex and Schist belt (muscovite + chloritoid + garnet ± glaucophane; Till, 1992). No blueschist-facies rocks are known from Chukotka. Till (1992) found muscovite + garnet + chloritoid in the oldest parts of the Nanushuk-Torok system that were sampled and suggested that exhumation of the metamorphic source terrane occurred before deposition of the clinoforms. Further support for this contention is present in western exposures of the Aptian Fortress Mountain Formation, which contain detrital muscovite and carbonate grains that must have been derived from a metamorphic source (Mull, 1985). The Fortress Mountain Formation underlies parts of the Torok Formation (Moore et al., 2015, and references therein). Presence of the diagnostic mineral assemblage muscovite + garnet + chloritoid ± glaucophane in the clinoform sequence and the presence of detrital muscovite in the underlying Fortress Mountain Formation are direct evidence that the Nome Complex and/or the Schist belt reached the surface during the Aptian (Fig. 9C).

Shortening in the Brooks Range fold-and-thrust belt was widespread during the Aptian, based on regional relations, deposition of orogenic clastic rocks, and backstripping models (Moore et al., 1994; Cole et al., 1997; Houseknecht and Wartes, 2013). The Aptian age of thrusting is directly documented on the Lisburne Peninsula, westernmost Brooks Range, where a contractional deformation front is exposed on and offshore (Moore et al., 2002; Fig. 2). Fifteen apatite fission-track samples yielded results that indicate tectonic burial between 132 and 115 Ma; rapid partial exhumation at ca. 115 Ma may have been accomplished by continued shortening (Fig. 9C; Moore et al., 2002).

In contrast, during the latter part of the Aptian, the Anyui-Chukotka fold belt was the site of shallow 117–112 Ma magmatism and associated ductile and brittle structures thought to have formed in an extensional or transtensional setting (Miller and Verzhbitsky, 2009; Miller et al., 2009). West-northwest–trending dextral strike-slip faults deformed the rocks in the South Anyui suture zone and in the adjacent Triassic turbidites (Sokolov et al., 2002, 2009). Offsets of at least 10 km have been observed, and flower structures are associated with some strands (Natal'in, 1984; Sokolov et al., 2009). The strike-slip faults deformed rocks as young as Barremian–Aptian (131–113 Ma) and ceased movement before the early phases of the Okhotsk-Chukotsk volcanic belt were deposited in the mid-Albian (Sokolov et al., 2002, 2009). On Figure 9C, strike-slip movement in the South Anyui suture is interpreted to be coeval with emplacement of the 117–112 Ma plutons.

Albian (113–100 Ma)

Contractional structures were active in the southern Brooks Range during the period 110–104 Ma. Deformation was concentrated along the Schist belt–Central belt contact at the Nanielik antiform in the west (Till and Snee, 1995); south-vergent back thrusting along that contact was accompanied by amphibolite-facies metamorphism at midcrustal depths in the Arrigetch area to the east (Fig. 3B; Vogl et al., 2002). Along the Dalton Highway (Fig. 3B), most of the Central belt was involved in south-vergent back thrusting (Avé Lallemant and Oldow, 1998).

By earliest Albian time, the tectonic evolution of eastern Chukotka, St. Lawrence Island, Seward Peninsula, and the area east of Seward Peninsula diverged from that of the Brooks Range. Around 113–111 Ma, each of these areas was intruded by alkalic plutons (Fig. 9D; Amato et al., 2003, and references therein). By 108 Ma, magmatism (some alkalic) was under way in a broad zone from western Chukotka to the area east of Seward Peninsula (Fig. 9D; Miller, 1989; Amato et al., 2003; Luchitskaya et al., 2014).

On Seward Peninsula, midcrustal metamorphism and shallow-level deformation accompanied 108 Ma alkalic plutonism. Structures associated with lode gold mineralization in southern Seward Peninsula formed during Albian east-west contraction (Pink and Rodgers, 2010). Vein mineralization is associated with regional north- to northwest-trending folds of the blueschist to greenschist foliation of the Nome Complex (Fig. 6; Pink and Rodgers, 2010; Till et al., 2011). Kinematic indicators associated with the folds and related low-angle faults show that they formed during northeast- to east-directed thrusting; dilational gold veins are kinematically related to these contractional structures (Pink and Rodgers, 2010). Two samples of late, undeformed muscovite from these veins produced $^{40}Ar/^{39}Ar$ plateau, isochron, and total gas ages of 104 Ma (Calvert, 2011, written commun.). Vein white mica from elsewhere in southern Seward Peninsula yielded plateau and total gas ages of ca. 106 Ma (Werdon et al., 2005) and 109 Ma (Ford and Snee, 1996). In short, brittle structures associated with shallow-level deformation and mineralization in the Nome Complex formed during the Albian (no later than 104 Ma) during an episode of NE-SW or E-W contraction.

Although this shallow-level deformational event did not result in significant shortening within the Nome Complex, its timing was roughly coeval with metamorphism and anatexis in the Darby Mountains and formation of a basin east of Seward Peninsula (Fig. 9D). Rocks in the Darby Mountains record midcrustal high-grade metamorphism, anatexis, and exhumation from ~20 km depths around 108–102 Ma. Detritus from the Nome Complex was shed eastward into the Albian–Cenomanian Lower Yukon subbasin (Fig. 2; Nilsen, 1989; Till et al., 2011). The west side of the basin contains shallow-marine, locally conglomeratic calcareous graywacke with Paleozoic meta-limestone cobbles derived from the Nome Complex (Fig. 9D; Nilsen, 1989; Till et al., 2011). Both the Colville Basin, north of the Brooks Range (Fig. 2), and the Lower Yukon subbasin, south of the Brooks Range, received detritus from the Nome Complex or similar metamorphic rocks during Albian–Cenomanian time.

During the Albian, magmatism and deformation affected a broad area in central and western Chukotka. In central Chukotka, 108–105 Ma plutons (Fig. 9D) were emplaced at shallow crustal levels (Miller and Verzhbitsky, 2009; Tikhomirov et al., 2009b; Kulyukina et al., 2013; Luchitskaya et al., 2014). The elongate shape of some plutons has been attributed to NW-SE extension related to right-lateral strike-slip faults (Luchitskaya et al., 2014). Brittle extensional structures in western Chukotka (Fig. 2), studied by Miller and Verzhbitsky (2009), have orientations consistent with formation in a NNW-SSE right-lateral wrench fault system. A system of dextral strike-slip faults, active during emplacement of plutons in western and central Chukotka, likely accommodated strain over a broad area from the South Anyui suture zone to Wrangel Island. This type of deformation may have started as early as 117 Ma (Miller et al., 2009).

During the middle to late Albian, a plate-boundary shift resulted in formation of the Okhotsk-Chukotsk volcanic belt, which extended 3250 km along the northwest Pacific margin over a north-dipping subduction zone (Fig. 2; Akinin and Miller, 2011). The South Anyui suture was closed by this time. Early deposits of the belt in the Chukotka region formed around 104–103 Ma (Fig. 9D; Akinin and Miller, 2011; Tikhomirov et al., 2012). Related magmatism might have extended as far east as Seward Peninsula and adjacent areas, where 104 Ma plutonic rocks with arc chemistry are known (Miller, 1989; Amato et al., 2003).

DISCUSSION

Although this synthesis and interpretation are built upon a limited amount of data, there is clear evidence for considerable Early Cretaceous crustal shortening within Arctic Alaska. The timing of the major period of shortening (early Albian, around 120 Ma) followed soon after the period of seafloor spreading in the Canada Basin (131–127.5 Ma; Grantz et al., 2011) and immediately preceded voluminous sedimentation in the Brooks Range foreland basin (116–115 Ma; Lease et al., 2014; Moore et al., 2015). Correspondingly, shortening in western and central Chukotka, based on the apparent absence of any deeply buried metamorphic rocks or thrusts with significant offset, appears to have been relatively limited.

Uncertainties remain, however, especially on the Chukotka side of the Bering Strait. The extent of Aptian crustal thickening in the offshore adjacent to northeast Chukotka and Wrangel Island is unknown (Drachev, 2011; Verzhbitsky et al., 2015). Identification of the offshore trace of the Kolyuchin-Mechigmen zone could lead to a more complete picture. Although the amount of Early Cretaceous shortening in the rest of Chukotka west of the Kolyuchin-Mechigmen zone appears to be limited, crustal shortening could have been concentrated on structures that are now offshore to the north.

Arctic Alaska and Chukotka—One Microplate or Two?

Arctic Alaska and Chukotka have late Proterozoic and Paleozoic rocks with similar igneous ages (Amato et al., 2014). Paleozoic sedimentary rocks as young as Carboniferous in northeastern Chukotka, Wrangel Island, Seward Peninsula, and the southern Brooks Range are similar in age and lithology; early Paleozoic rocks contain similar fauna (Natal'in et al., 1999; Dumoulin et al., 2002; Miller et al., 2010a). However, no geologic ties between Arctic Alaska and Chukotka have been established between the end of the Carboniferous and the beginning of the Cretaceous.

As noted by Miller et al. (2006, 2010a), the Triassic deposits of Chukotka and Arctic Alaska are markedly dissimilar. Detrital zircon ages from the voluminous Triassic sequences in Chukotka suggest that the Taimyr and Verkhoyansk regions were sources of sediment (Fig. 10; Miller et al., 2006, 2010a). Detrital zircon ages from Jurassic–Cretaceous sandstones from Chukotka and the New Siberian Islands indicate that Siberia was the likely source area for both regions (Miller et al., 2008). In contrast, Gottlieb et al. (2014) showed that the ages of detrital zircons from rare thin Triassic sandstones on the Lisburne Peninsula, western Alaska (Fig. 2), are more like those in Triassic–Jurassic sandstones of Axel Heiberg Island in the Canadian Arctic (Fig. 10) than those of Chukotka. Detrital zircons from Jurassic and Early Cretaceous deposits in the Brooks Range were locally sourced (Moore et al., 2015). Taken together, these detrital zircon studies support separate Triassic and Jurassic histories for Chukotka and Arctic Alaska.

The Early Cretaceous tectonic evolution outlined here shows that Arctic Alaska and

Chukotka could have been tectonically independent until the Aptian. The distribution of Aptian thickening is consistent with rotation of Arctic Alaska, northeastern Chukotka, and the adjacent offshore area as a block; central and western Chukotka, based on metamorphic information, may not have been involved in rotation.

If the Arctic Alaska–Chukotka microplate was two separate pieces of crust before Early Cretaceous collision, the Kolyuchin-Mechigmen zone is a candidate for the suture between those pieces (Fig. 10). The zone traces the boundary between the considerably thickened rocks of Arctic Alaska and northeast Chukotka and those less thickened in the Anyui-Chukotka fold belt. The pattern of Aptian crustal thickening suggests that the rocks of Chukotka north of the Kolyuchin-Mechigmen zone (including parts of the continental shelf) were part of Arctic Alaska before opening of the Canada Basin (Fig. 10). The Senyavin uplift, which sits south of the Kolyuchin-Mechigmen zone, is the one crustal element that cannot be fit into this model.

Little is known about the Kolyuchin-Mechigmen zone. It could be a closed suture and a focus of strike-slip deformation. The zone could represent part of the South Anyui suture that was enveloped by a transform fault system (Toro et al., 2002) or an independent suture that closed a short-lived Triassic–Middle Jurassic (?) ocean basin in earliest Aptian time (see fig. 6 of Sokolov et al., 2002). Alternatively, the oceanic rocks in the zone could be klippe of material emplaced on the Arctic Alaska–Chukotka microplate margin during arc-continent collision (Toro et al., 2002) and subsequently enveloped by strike-slip deformation. Whatever its origin and history, the Kolyuchin-Mechigmen zone now traces a significant boundary with respect to the crustal shortening histories of Alaska and Chukotka and therefore deserves further investigation.

Size of the Arctic Alaska–Chukotka Microplate before Rotation

In Arctic Alaska, both the burial depth of rocks metamorphosed during the Aptian and Albian and the amount of offset on crustal-scale structures indicate that a large amount of crustal shortening occurred. Therefore, the total area of Arctic Alaska considerably decreased. In particular, the boundary between the Brooks Range Schist and Central belts (Fig. 3) accommodated on the order of a hundred kilometers of crustal shortening. The Schist belt and correlative Nome Complex were subducted to depths in excess of 30 km during the Late Jurassic or Early Cretaceous (Patrick and Evans, 1989; Patrick, 1995); the Central belt was not. There is no evidence that the Central belt was metamorphosed before the Aptian; consequently, if it was part of the subducted crustal slab during the Jurassic or earliest Cretaceous, it only reached shallow depths. At subduction dip angles of 10°, which are reasonable for continental crust, thermobarometric data indicate the protoliths of the Schist belt traveled ~200 km down the subduction zone in the subducted slab. Allowing for subduction of the Central belt rocks to half the depth of the Schist belt, a section of crust 100 km wide would have separated protoliths of the two belts. The distance was likely greater, as the Central belt was probably not subducted to depths of 15 or 20 km during the Jurassic, and a minimum for peak pressure was used in the calculations (0.9 GPa). In short, at the time that the Schist belt reached peak pressure, the continental margin rocks that were to become the Central belt were a considerable distance up the slab, or not in the subduction zone at all. Therefore, during the Early Cretaceous, a major structure or set of structures cut out the section of continental crust that had separated the two belts and emplaced the Schist belt over the Central belt. The contact between the Schist and Central belts accommodated more shortening within the continental crust than any other collision-related structure in Arctic Alaska or Chukotka.

During the earlier part of the Albian, the southern margin of the Arctic Alaska–Chukotka microplate became structurally segmented as the character of deformation in Chukotka and Seward Peninsula diverged from that of the Brooks Range. The location of the Albian–Cenomanian Lower Yukon subbasin east of Seward Peninsula (Fig. 2) suggests that rocks of the Seward Peninsula migrated to the south and east relative to the western Brooks Range; the presence of detritus from Seward Peninsula in that basin indicates some crustal thickening occurred during that migration.

The magmatic histories of Chukotka and the Seward Peninsula link them together by the Albian (Miller, 1989; Amato et al., 2003). The crustal-scale deformational histories of the two areas are not well understood during this time period. In western and central Chukotka, transtension or some form of transcurrent boundary may have been active (Miller and Verzhbitsky, 2009; Miller et al., 2009; Tuchkova et al., 2014). Strike-slip faults, at least some of probable Albian age, have been noted in and adjacent to the South Anyui suture, in western Chukotka, and on Wrangel Island (Sokolov et al., 2002, 2009; Tuchkova et al., 2014; Verzhbitsky et al., 2015). In eastern Chukotka and Seward Peninsula, midcrustal high-grade metamorphism and anatexis, followed by rapid exhumation, overlapped in time with shallow-level east-vergent deformation (Calvert, 1999; Akinin and Calvert, 2002; Pink and Rodgers, 2010; this paper). Together, these complex patterns of magmatism and deformation in Chukotka and Seward Peninsula may record their eastward tectonic escape in response to final closure of the South Anyui suture. The escape could have been facilitated by a magmatically softened midcrust in Chukotka and the Seward Peninsula, where Albian plutons are commonly foliated (Gottlieb, 2008), and a lack of rigidity in the transitional crust east of Seward Peninsula (Arth et al., 1989).

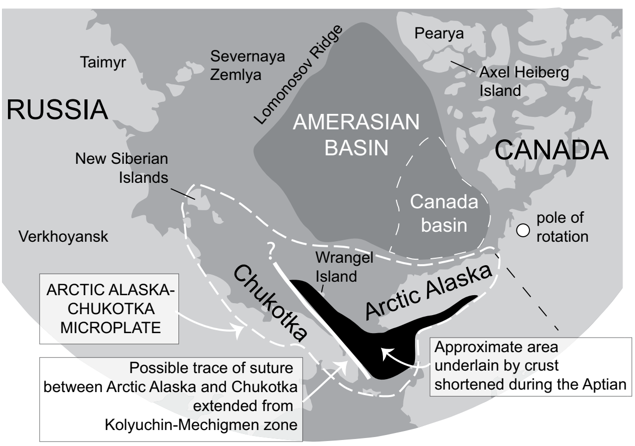

Figure 10. Map showing part of the Arctic region that shows the possible location of a suture zone or major tectonic boundary within the Arctic Alaska–Chukotka microplate. The boundary separates continental crust that was significantly shortened during the Aptian in Arctic Alaska and northeast Chukotka from rocks in central and western Chukotka that were not significantly shortened. The approximate extent of the significantly shortened rocks north of Chukotka in the vicinity of Wrangel Island is speculative.

Arc Systems

The combined strike length of the Nome Complex and Schist belt is 850 km. The existence of this large metamorphic belt requires that Arctic Alaska was subducted to the south during the early phases of collisional orogenesis under an arc system at least 850 km long. This is an important constraint on the tectonic evolution of Arctic Alaska, and it is potentially important as a driver for opening of the Canada Basin. Improved control on the age of blueschist-facies metamorphism of the Nome Complex and the Schist belt is needed in order to constrain the timing of subduction and identity of the related arc.

The arc that participated in the collision is thought by many to be the Koyukuk arc (Fig. 2; Moore et al., 1994; Nokleberg et al., 2000; Shepherd et al., 2013). The age of the Koyukuk arc is based on a small number of K-Ar and fossil ages from interlayered sedimentary rocks (Box and Patton, 1989). Apparently, a small part of the Koyukuk arc is Jurassic, and most is Early Cretaceous in age, spanning the period 145–130 Ma (Box and Patton, 1989). However, Middle Jurassic igneous rocks with arc or back-arc chemistry are preserved in the Brooks Range klippe (Harris, 2004). In addition, the oldest syntectonic sedimentary deposit in the Brooks Range is a Late Jurassic wacke composed largely of arc-derived detritus that was deposited on oceanic rocks of the Angayucham terrane (Moore et al., 2015). Detrital zircons from the wacke range in age from 180 to 140 Ma and have an age probability peak at ca. 155 Ma; a granodiorite clast analyzed in the same study produced a Late Jurassic age (Moore et al., 2015), consistent with the likelihood that remnants of a long-lived Middle to Late Jurassic arc are present within the Angayucham terrane. It is unclear whether the Koyukuk arc was built directly on the older Jurassic arc now contained in the Brooks Range klippe or Angayucham terrane (e.g., Moore et al., 1994; Fig. 2) or whether it was separated from the Angayucham terrane by a south-dipping subduction zone as shown in Figure 9A.

There is no known continental crust on Chukotka that underwent blueschist-facies metamorphism. Thus, the southern margin of Chukotka did not enter a south-dipping subduction zone along with Arctic Alaska. The nature of the plate boundary along southern Chukotka is difficult to identify on the basis of available data. Further investigation of the extent and petrogenesis of Late Jurassic–earliest Cretaceous magmatic rocks on Chukotka would contribute to resolution of this problem (Pease, 2011). Additional investigations along the northern side of the South Anyui suture zone would also be useful (Amato et al., 2015).

If the rotation hypothesis is correct, it would predict that the amount of shortening that occurred in response to rotation would be greater in the west (offshore Chukotka, northeast Chukotka, and the Nanielik antiform) than the east (Brooks Range Central belt near the Dalton Highway; Fig. 3B). Application of phengite geobarometry to granitic rocks on Wrangel Island might help to clarify its position during rotation and collision. No thermobarometry has been done in the Brooks Range Central belt near the Dalton Highway. Research on metamorphism during orogenesis in Arctic Alaska and Chukotka is in its infancy relative to other orogens around the globe; consequently, the interpretation presented here needs to be tested by further study.

CONCLUSIONS

The metamorphic histories of Chukotka and Arctic Alaska constrain Mesozoic tectonic reconstructions of the Arctic in the following ways:

(1) During the Late Jurassic and earliest Cretaceous, Arctic Alaska was subducted to the south; Chukotka was in the upper plate of a subduction system or was part of a transcurrent boundary. The two margins must have been separated by a transform or other crustal-scale structure that also separated the adjacent South Anyui and Angayucham oceans.

(2) The Early Cretaceous tectonic evolution of Chukotka and Arctic Alaska may have been independent until the earlier part of the Aptian, when rocks of northeastern Chukotka and Arctic Alaska simultaneously shortened, and material from the Triassic turbidites of Chukotka flowed into the foreland basin of the Brooks Range.

(3) The most profound period of crustal thickening that affected the Arctic Alaska–Chukotka microplate took place during the earlier part of the Aptian, around 120 Ma. The resultant metamorphic belt reached from northeast Chukotka along the length of the southern Brooks Range, and may have extended offshore northern Chukotka. Total crustal thickness may have reached 50 km. Thickening produced the flexural subsidence that accommodated the Brooks Range foreland basin.

(4) The western part of the zone of Aptian crustal thickening is located within the Arctic Alaska–Chukotka microplate in northeastern Chukotka. There, the thickened rocks are directly adjacent to a belt of oceanic rocks called the Kolyuchin-Mechigmen zone. If Arctic Alaska and Chukotka had separate tectonic histories until the Aptian, the Kolyuchin-Mechigmen zone is a candidate for the suture zone between them.

(5) During the Albian, internal deformation in the Arctic Alaska–Chukotka microplate continued, and its southern boundary was structurally segmented. Crustal thickening continued in the southern Brooks Range, while magmatism and a complex pattern of crustal deformation took place along a zone from western Chukotka to the area east of Seward Peninsula.

These conclusions are consistent with opening of the Canada Basin by rotation of Arctic Alaska and northeastern Chukotka away from the Canadian margin. The major Aptian thickening event, around 120 Ma, likely followed collision of the rotating block with what is now western and central Chukotka. The Albian internal deformation of the Arctic Alaska–Chukotka microplate and modification of its southern boundary may have resulted from final amalgamation of the collisional boundaries between Chukotka and Eurasia.

ACKNOWLEDGMENTS

Conversations over many years with Steve Boyer, Darrel Cowan, Brian Patrick, Sarah Roeske, Larry Snee, Dave Houseknecht, Andy Calvert, Richard Lease, Dwight Bradley, Jaime Toro, Paul O'Sullivan, and Jeff Amato stimulated my interest in synthesizing the big picture presented here. E-mail exchanges with Boris Natal'in and Peter Tikhomirov helped me improve my understanding of Chukotka. Reviews by Jamey Jones, Sarah Roeske, Jeff Amato, and E. Enkelmann resulted in significant improvement of the paper; Paul O'Sullivan's assistance in the review process is appreciated. I am grateful to Kurt Stüwe for responsive, constructive, and good-tempered editorial support.

REFERENCES CITED

Akinin, V.V., and Calvert, A.T., 2002, Cretaceous mid-crustal metamorphism and exhumation of the Koolen gneiss dome, Chukotka Peninsula, northeastern Russia, *in* Miller, E.L., Grantz, A., and Klemperer, S.L., eds., Tectonic Evolution of the Bering Shelf–Chukchi Sea–Arctic Margin and Adjacent Landmasses: Geological Society of America Special Paper 360, p. 147–165, doi:10.1130/0-8137-2360-4.147.

Akinin, V.V., and Miller, E.L., 2011, Evolution of calc-alkaline magmas of the Okhotsk-Chukotsk volcanic belt: Petrology, v. 19, no. 3, p. 237–277, doi:10.1134/S0869591111020020.

Akinin, V.V., Miller, E.L., Gottlieb, E., and Polzunenkov, G., 2012, Geochronology and geochemistry of Cretaceous magmatic rocks of Arctic Chukotka: An update: European Geological Union General Assembly 2012: Geophysical Research Abstracts, v. 14, abstract EGU2012-3876.

Amato, J.M., and Miller, E.L., 2004, Geologic map and summary of the evolution of the Kigluaik Mountain gneiss dome, Seward Peninsula, Alaska, *in* Whitney, D.L., and Siddoway, C.S., eds., Gneiss Domes in Orogeny: Geological Society of America Special Paper 380, p. 295–306.

Amato, J.M., Wright, J.E., Gans, P.B., and Miller, E.L., 1994, Magmatically-induced metamorphism and deformation in the Kigluaik gneiss dome, Seward Peninsula, Alaska: Tectonics, v. 13, p. 515–527, doi:10.1029/93TC03320.

Amato, J.M., Miller, E.L., Calvert, A.T., and Wright, J.E., 2003, Potassic magmatism on St. Lawrence Island, Alaska, and Cape Dezhnev, northeast Russia: Evidence for Early Cretaceous subduction in the Bering Strait region, *in* Clautice, K.H., and Davis, P.K., eds., Short Notes on Alaska Geology 2003: Alaska Division of Geological and Geophysical Surveys Professional Report 120, p. 1–20, doi:10.14509/2907.

Amato, J.M., Toro, J., and Moore, T.E., 2004, Origin of the Bering Sea salient, *in* Sussman, A.J., and Weil, A.B., eds., Orogenic Curvature: Geological Society of America Special Paper 383, p. 131–144.

Amato, J.M., Toro, J., Miller, E.L., Gehrels, G.E., Farmer, G.L., Gottlieb, E.S., and Till, A.B., 2009, Late Proterozoic–Paleozoic evolution of the Arctic Alaska–Chukotka terrane based on U-Pb igneous and detrital zircon ages: Implications for Neoproterozoic paleogeographic reconstructions: Geological Society of America Bulletin, v. 121, no. 9/10, p. 1219–1235, doi:10.1130/B26510.1.

Amato, J.M., Aleinikoff, J.N., Akinin, V.V., McClelland, W.C., and Toro, J., 2014, Age, chemistry, and correlations of Neoproterozoic–Devonian igneous rocks of the Arctic Alaska–Chukotka terrane: An overview with new U-Pb ages, *in* Dumoulin, J.A., and Till, A.B., eds., Reconstruction of a Late Proterozoic to Devonian Continental Margin Sequence, Northern Alaska, its Paleogeographic Significance, and Contained Base-Metal Sulfide Deposits: Geological Society of America Special Paper 506, p. 29–58.

Amato, J.M., Toro, J., Akinin, V.V., Hampton, B.A., Salnikov, A.S., and Tuchkova, M.I., 2015, Tectonic evolution of the Mesozoic South Anyui suture zone, eastern Russia: A critical component of paleogeographic reconstructions of the Arctic region: Geosphere, v. 11, no. 5, p. 1530–1564, doi:10.1130/GES01165.1.

Arth, J.G., Criss, R.E., Zmuda, C.C., Foley, N.K., Patton, W.W., Jr., and Miller, T.P., 1989, Remarkable isotopic and trace element trends in potassic through sodic Cretaceous plutons of the Yukon-Koyukuk basin, Alaska, and the nature of lithosphere beneath the Koyukuk terrane: Journal of Geophysical Research, v. 94, no. B11, p. 15,957–15,968, doi:10.1029/JB094iB11p15957.

Avé Lallemant, H.G., and Oldow, J.S., 1998, Antithetic shear and the formation of back folds in the central Brooks Range fold and thrust belt, *in* Oldow, J.S., and Avé Lallemant, H.G., eds., Architecture of the Central Brooks Range Fold and Thrust Belt, Arctic Alaska: Geological Society of America Special Paper 324, p. 253–259.

Barker, F., Jones, D.L., Budahn, J.R., and Coney, P.J., 1988, Ocean plateau–seamount origin of basaltic rocks, Angayucham terrane, central Alaska: The Journal of Geology, v. 96, p. 368–374, doi:10.1086/629227.

Beikman, H.M., compiler, 1980, Geologic Map of Alaska: Reston, Virginia, U.S. Geological Survey, scale 1:1,250,000, 2 sheets.

Bering Strait Geologic Field Party (BSGFP), 1997, Koolen metamorphic complex, NE Russia: Implications for the tectonic evolution of the Bering Strait region: Tectonics, v. 16, no. 5, p. 713–729, doi:10.1029/97TC01170.

Blythe, A.E., Bird, J.M., and Omar, G.I., 1996, Deformation history of the central Brooks Range, Alaska: Results from fission-track and $^{40}Ar/^{39}Ar$ analyses: Tectonics, v. 15, no. 2, p. 440–455, doi:10.1029/95TC03053.

Box, S.E., and Patton, W.W., Jr., 1989, Igneous history of the Koyukuk terrane, western Alaska: Constraints on the origin, evolution, and ultimate collision of an accreted island arc terrane: Journal of Geophysical Research, v. 94, no. B11, p. 15,843–15,867, doi:10.1029/JB094iB11p15843.

Brown, E.H., 1986, Geology of the Shuksan Suite, North Cascades, Washington, USA, *in* Evans, B.W., and Brown, E.H., eds., Blueschists and Eclogites: Geological Society of America Memoir 164, p. 143–154, doi:10.1130/MEM164-p143.

Calvert, A.T., 1999, Metamorphism and Exhumation of Mid-Crustal Gneiss Domes in the Arctic Alaska Terrane [Ph.D. thesis]: Santa Barbara, California, University of California, 198 p.

Calvert, A.T., Gans, P.B., and Amato, J.M., 1999, Diapiric ascent and cooling of a sillimanite gneiss dome revealed by $^{40}Ar/^{39}Ar$ thermochronology: The Kigluaik Mountains, Seward Peninsula, Alaska, *in* Ring, U., Brandon, M.T., Lister, G.S., and Willett, S.D., eds., Exhumation Processes: Normal Faulting, Ductile Flow and Erosion: Geological Society of London Special Publication 154, p. 205–232.

Carey, S.W., 1955, The orocline concept in plate tectonics, Part 1: Papers and Proceedings of the Royal Society of Tasmania, v. 89, p. 255–288.

Christiansen, P.P., and Snee, L.W., 1994, Structure, metamorphism, and geochronology of the Cosmos Hills and Ruby Ridge, Brooks Range schist belt, Alaska: Tectonics, v. 13, p. 193–213, doi:10.1029/93TC01545.

Churkin, M.J., Jr., and Trexler, J.H., Jr., 1980, Circum-Arctic plate accretion—Isolating part of a Pacific plate to form the nucleus of the Arctic basin: Earth and Planetary Science Letters, v. 48, p. 356–362, doi:10.1016/0012-821X(80)90199-5.

Cole, F., Bird, K.J., Toro, J., Roure, F., O'Sullivan, P.B., Pawlewicz, M., and Howell, D.G., 1997, An integrated model for the tectonic development of the frontal Brooks Range and Colville Basin 250 km west of the Trans-Alaska crustal transect: Journal of Geophysical Research, v. 102, no. B9, p. 20,685–20,708, doi:10.1029/96JB03670.

Dillon, J.T., Brosgé, W.P., and Dutro, J.T., Jr., 1986, Generalized Geologic Map of the Wiseman Quadrangle, Alaska: U.S. Geological Survey Open-File Report OF 86–219, 1 sheet, scale 1:250,000.

Drachev, S.S., 2011, Tectonic setting, structure and petroleum geology of the Siberian Arctic offshore sedimentary basins, *in* Spencer, A., Embry, A.F., Gautier, D.L., Stoupakova, A.F., and Sørenson, K., eds., Arctic Petroleum Geology: Geological Society of London Memoir 35, p. 369–394, doi:10.1144/M35.25.

Dumitru, T.A., and Miller, E.L., 2010, Preliminary apatite fission-track thermochronology of Wrangel Island, Arctic Russia: San Francisco, California, American Geophysical Union, 2010 Fall meeting supplement, abstract T31A–2131.

Dumoulin, J.A., and Harris, A.G., Gagiev, M., Bradley, D.C., and Repetski, J.E., 2002, Lithostratigraphic, conodont, and other faunal links between Lower Paleozoic strata in northern and central Alaska and northeastern Russia, *in* Miller, E.L., Grantz, A., and Klemperer, S.L., eds., Tectonic Evolution of the Bering Shelf–Chukchi Sea–Arctic Margin and Adjacent Landmasses: Geological Society of America Special Paper 360, p. 291–312, doi:10.1130/0-8137-2360-4.291.

Dumoulin, J.A., Till, A.B., and Bradley, D.C., 2011, Neoproterozoic–Paleozoic paleogeographic reconstruction of the Arctic Alaska–Chukotka terrane, *in* Stone, D.B., Clough, J.G., and Thurston, D.K., compilers, Geophysical Institute Report UAG-R-335: Fairbanks, Alaska, University of Alaska, p. 51–53 [extended abstract for ICAM VI (Sixth International Conference on Arctic Margins) in Fairbanks, Alaska, 30 May–2 June 2011].

Evans, B.W., 1990, Phase relations of epidote blueschists: Lithos, v. 25, p. 3–23, doi:10.1016/0024-4937(90)90003-J.

Filatova, N.I., and Khain, V.E., 2010, The Arctida craton and Neoproterozoic–Mesozoic orogenic belts of the circumpolar region: Geotectonics, v. 44, no. 3, p. 203–227, doi:10.1134/S0016852110030015.

Ford, R.C., and Snee, L.W., 1996, $^{40}Ar/^{39}Ar$ thermochronology of white mica from the Nome district, Alaska: The first ages of lode sources to placer gold deposits in the Seward Peninsula: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 91, p. 213–220, doi:10.2113/gsecongeo.91.1.213.

Ganelin, A.V., Sokolov, S.D., Layer, P., and Simonov, V.A., 2013, New isotopic age data on ophiolite complexes of western Chukotka (northeast Russia): Doklady Early Sciences, v. 451, no. 1, p. 679–683.

Garrido, C.J., Gueydan, F., Booth-Rea, G., Precigout, J., Hidas, K., Padron-Navarta, J.A., and Marchesi, C., 2011, Garnet lherzolite and garnet-spinel mylonite in the Ronda peridotite: Vestiges of Oligocene back-arc lithospheric extension in the western Mediterranean: Geology, v. 39, no. 10, p. 927–930, doi:10.1130/G31760.1.

Gottlieb, E.S., 2008, Geologic Mapping and Investigation of Cretaceous Magmatism and Deformation in the Bendeleben Metamorphic Complex, Seward Peninsula, Alaska [M.S. thesis]: Las Cruces, New Mexico, New Mexico State University, 176 p.

Gottlieb, E.S., Meisling, K.E., Miller, E.L., and Mull, C.G., 2014, Closing the Canada Basin: Detrital zircon geochronology relationships between the North Slope of Arctic Alaska and the Franklinian mobile belt of Arctic Canada: Geosphere, v. 10, no. 6, p. 1366–1384, doi:10.1130/GES01027.1.

Gottschalk, R.R., 1990, Structural evolution of the Schist belt, south-central Brooks Range fold and thrust belt, Alaska: Journal of Structural Geology, v. 12, p. 453–469, doi:10.1016/0191-8141(90)90034-V.

Gottschalk, R.R., 1998, Petrology of eclogite and associated high-pressure metamorphic rocks, south-central Brooks Range, Alaska, *in* Oldow, J.S., and Avé Lallemant, H.G., eds., Architecture of the Central Brooks Range Fold and Thrust Belt, Arctic Alaska: Geological Society of America Special Paper 324, p. 141–162.

Gottschalk, R.R., and Snee, L.W., 1998, Tectonothermal evolution of metamorphic rocks in the south-central Brooks Range, Alaska; constraints from $^{40}Ar/^{39}Ar$ geochronology, *in* Oldow, J.S., and Ave Lallemant, H.G., eds., Architecture of the Central Brooks Range Fold and Thrust Belt, Arctic Alaska: Geological Society of America Special Paper 324, p. 225–251.

Gottschalk, R.R., Oldow, J.S., and Avé Lallemant, H.G., 1998, Geology and Mesozoic structural history of the south-central Brooks Range, Alaska, *in* Oldow, J.S., and Avé Lallemant, H.G., eds., Architecture of the Central Brooks Range Fold and Thrust Belt, Arctic Alaska: Geological Society of America Special Paper 324, p. 195–223.

Grantz, A., May, S.D., Taylor, P.T., and Lawver, L.A., 1990, Canada Basin, *in* Grantz, A., Johnson, L., and Sweeney, J.F., eds., The Arctic Ocean Region: Boulder, Colorado, Geological Society of America, The Geology of North America, v. L, p. 379–402.

Grantz, A., Hart, P.E., and Childers, V.A., 2011, Geology and tectonic development of the Amerasia and Canada basins, Arctic Ocean, *in* Spencer, A., Embry, A.F., Gautier, D.L., Stoupakova, A.F., and Sørenson, K., eds., Arctic Petroleum Geology: Geological Society of London Memoir 35, p. 700–771, doi:10.1144/M35.50.

Green, E.C.R., Holland, T.J.B., Powell, R., and White, R.W., 2012, Garnet and spinel lherzolite assemblages in $MgO-Al_2O_3-SiO_2$ and $CaO-MgO-Al_2O_3-SiO_2$: Thermodynamic models and an experimental conflict: Journal of Metamorphic Geology, v. 30, p. 561–577, doi:10.1111/j.1525-1314.2012.00981.x.

Hamilton, W., 1970, The Uralides and the motion of the Russian and Siberian Platforms: Geological Society of America Bulletin, v. 81, p. 2553–2576, doi:10.1130/0016-7606(1970)81[2553:TUATMO]2.0.CO;2.

Handschy, J.W., 1998, Spatial variation in structural style, Endicott Mountains allochthon, central Brooks Range, Alaska, *in* Oldow, J.S., and Avé Lallemant, H.G., eds., Architecture of the Central Brooks Range Fold and Thrust Belt, Arctic Alaska: Geological Society of America Special Paper 324, p. 33–40.

Hannula, K.A., and McWilliams, M.O., 1995, Reconsideration of the age of blueschist facies metamorphism on the Seward Peninsula, Alaska, based on phengite $^{40}Ar/^{39}Ar$ results: Journal of Metamorphic Geology, v. 13, p. 125–139, doi:10.1111/j.1525-1314.1995.tb00209.x.

Hannula, K.A., Miller, E.L., Dumitru, T.A., Lee, J., and Rubin, C.M., 1995, Structural and metamorphic relations in the southwest Seward Peninsula, Alaska: Crustal extension and the unroofing of blueschists: Geological Society of America Bulletin, v. 107, no. 5, p. 536–553, doi:10.1130/0016-7606(1995)107<0536:SAMRIT>2.3.CO;2.

Harris, R., 2004, Tectonic evolution of the Brooks Range ophiolite, northern Alaska: Tectonophysics, v. 392, p. 143–163, doi:10.1016/j.tecto.2004.04.021.

Houseknecht, D.W., and Bird, K.J., 2011, Geology and petroleum potential of the rifted margins of the Canada Basin, *in* Spencer, A., Embry, A.F., Gautier, D.L., Stoupakova, A.F., and Sørenson, K., eds., Arctic Petroleum Geology: Geological Society of London Memoir 35, p. 509–526, doi:10.1144/M35.34.

Houseknecht, D.W., and Wartes, M.A., 2013, Clinoform deposition across a boundary between orogenic front and foredeep—An example from the Lower Cretaceous in Arctic Alaska: Terra Nova, v. 25, no. 3, p. 206–211, doi:10.1111/ter.12024.

Houseknecht, D.W., Bird, K.J., and Schenk, C.J., 2009, Seismic analysis of clinoform depositional sequences and shelf-margin trajectories in Lower Cretaceous (Albian) strata, Alaska North Slope: Basin Research, v. 21, p. 644–654, doi:10.1111/j.1365-2117.2008.00392.x.

Jones, D.L., Coney, P.J., Harms, T.A., and Dillon, J.T., 1988, Interpretive Geologic Map and Supporting Radiolarian Data from the Angayucham Terrane, Coldfoot Area, Southern Brooks Range, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-1993, scale 1:63,360.

Karl, S.M., 1992, Arc and extensional basin geochemical and tectonic affinities for Maiyumerak basalts in the western Brooks Range, *in* Bradley, D.C., and Ford, A.B., eds., Geological Studies in Alaska by the U.S. Geological Survey, 1990: U.S. Geological Survey Bulletin 1999, p. 141–155.

Kos'ko, M.K., Cecile, M.P., Harrison, J.C., Ganelin, V.G., Khandoshko, N.V., and Lopatin, B.G., 1993, Geology of Wran-

gel Island, between Chukchi and East Siberian Seas, Northeastern Russia: Geological Society of Canada Bulletin 461, 101 p.
Kulyukina, N.A., Tikhomirov, P.L., and Yapaskurt, V.O., 2013, New data on the metamorphic petrology of rocks from the Kuekvun uplift (northern Chukchi Peninsula): Moscow University Geology Bulletin, v. 68, no. 2, p. 89–95, doi:10.3103/S0145875213020063.
Kuznetsov, N.B., 2006, The Cambrian Baltica-Arctida collision, pre-Uralide Timanide orogeny, and its erosion products in the Arctic: Doklady Earth Sciences, v. 411A, no. 2, p. 1375–1380, doi:10.1134/S1028334X06090091.
Kuznetsov, N.B., Natapov, L.M., Belousova, E.A., O'Reilly, S.Y., and Griffin, W.L., 2010, Geochronological, geochemical and isotope study of detrital zircons suites from late Neoproterozoic clastic strata along the NE margin of the East European craton: Implications for plate tectonic models: Gondwana Research, v. 17, p. 583–601, doi:10.1016/j.gr.2009.08.005.
Lane, L.S., 1997, Canada basin, Arctic Ocean: Evidence against a rotational origin: Tectonics, v. 16, no. 3, p. 363–387, doi:10.1029/97TC00432.
Lawver, L.A., Grantz, A., and Gahagan, L.M., 2002, Plate kinematic evolution of the present Arctic region since the Ordovician, *in* Miller, E.L., Grantz, A., and Klemperer, S.L., eds., Tectonic Evolution of the Bering Shelf–Chukchi Sea–Arctic Margin and Adjacent Landmasses: Geological Society of America Special Paper 360, p. 333–358, doi:10.1130/0-8137-2360-4.333.
Layer, P.W., and Newberry, R.J., 2004, A Long-Term Effort to Determine $^{40}Ar/^{39}Ar$ Ages of Alaskan Mineral Deposits: Final report for U.S. Geological Survey MRERP grant 04HQGR0163, http://minerals.usgs.gov/mrerp/reports/Layer_Report-04HQGR0163.pdf (accessed May 2014).
Lease, R.O., Houseknecht, D.W., and Kylander-Clark, A., 2014, Detrital zircon constraints on Arctic Alaska foreland basin evolution: Chronostratigraphy, clastic progradation, provenance, and orogenic exhumation: Geological Society of America Abstracts with Programs, v. 46, no. 6, p. 784.
Ledneva, G.V., Pease, V.L., and Sokolov, S.D., 2011, Permo-Triassic hypabyssal mafic intrusions and associated tholeiitic basalts of the Kolyuchinskaya Bay, Chukotka (NE Russia): Links to the Siberian LIP: Journal of Asian Earth Sciences, v. 40, p. 737–745, doi:10.1016/j.jseaes.2010.11.007.
Ledneva, G.V., Bazylev, B.A., Kuzmin, D., Ishiwatari, A., Kononkova, N.N., and Sokolov, S.D., 2012, Plutonic mafic-ultramafic complexes of the Vel'may terrane, eastern Chukotka (Russia): First petrological results and preliminary geodynamic interpretations: Geophysical Research Abstracts, v. 14, abstract EGU2012-6195.
Lieberman, J.E., 1988, Metamorphic and Structural Studies of the Kigluaik Mountains, Western Alaska [Ph.D. thesis]: Seattle, Washington, University of Washington, 192 p.
Lieberman, J.E., and Till, A.B., 1987, Possible crustal origin of garnet lherzolite: Evidence from the Kigluaik Mountains, Alaska: Geological Society of America Abstracts with Programs, v. 19, no. 7, p. 746.
Little, T.A., Miller, E.L., Lee, J., and Law, R.D., 1994, Extensional origin of ductile fabrics in the Schist belt, central Brooks Range, Alaska—I. Geologic and structural studies: Journal of Structural Geology, v. 16, p. 899–918, doi:10.1016/0191-8141(94)90075-2.
Lorenz, H., Mannik, P., Gee, D., and Proskurnin, V., 2008, Geology of the Severnaya Zemlya archipelago and the north Kara terrane in the Russian High Arctic: International Journal of Earth Sciences, v. 97, p. 519–547, doi:10.1007/s00531-007-0182-2.
Luchitskaya, M.V., Sokolov, S.D., and Moiseev, A.V., 2013, Stages of late Mesozoic granitoid magmatism in Chukotka, northeast Russia: Doklady Earth Sciences, v. 450, no. 1, p. 479–483, doi:10.1134/S1028334X13050061.
Luchitskaya, M.V., Tikhomirov, P.L., and Shats, A.L., 2014, U-Pb ages and tectonic setting of mid-Cretaceous magmatism in Chukotka (NE Russia), *in* Stone, D.B., Grikurov, G.E., Clough, J.G., Oakey, G.N., and Thurston, D.K., eds., Proceedings of the International Conference on Arctic Margins VI: Fairbanks, Alaska, May, 2011: http://www2.gi.alaska.edu/icam6/proceedings/web/ (accessed October 2014).
Miller, E.L., and Akinin, V.V., 2008, Geology of the Bering Shelf region of Alaska-Russia: Implications for extensional processes in continental crust, *in* Spencer, J.E., and Titley, S.R., eds., Ores and Orogenesis: Circum-Pacific Tectonics, Geological Evolution, and Ore Deposits: Arizona Geological Society Digest, v. 22, p. 203–212.
Miller, E.L., and Verzhbitsky, V.E., 2009, Structural studies near Pevek, Russia: Implications for formation of the East Siberian Shelf and Makarov Basin of the Arctic Ocean, *in* Stone, D.B., ed., Origin of Northeastern Russia: Paleomagnetism, Geology, and Tectonics: European Geophysical Union, Stephan Mueller Publication 4, p. 223–241.
Miller, E.L., Toro, J., Gehrels, G., Amato, J.M., Prokopiev, A., Tuchkova, M., Akinin, V.V., Dumitru, T.A., Moore, T.E., and Cecile, M.P., 2006, New insights into Arctic paleogeography and tectonics from U-Pb detrital zircon geochronology: Tectonics, v. 25, TC3013, doi:10.1029/2005TC001830.
Miller, E.L., Soloviev, A., Kuzmichev, A., Gehrels, G., Toro, J., and Tuchkova, M., 2008, Jurassic and Cretaceous foreland basin deposits of the Russian Arctic: Separated by birth of the Makarov basin?: Norwegian Journal of Geology, v. 88, p. 201–226.
Miller, E.L., Katkov, S.M., Strickland, A., Toro, J., Akinin, V.V., and Dumitru, T.A., 2009, Geochronology and thermochronology of Cretaceous plutons and metamorphic country rocks, Anyui-Chukotka fold belt, northeast Arctic Russia, *in* Stone, D.B., ed., Origin of Northeastern Russia: Paleomagnetism, Geology, and Tectonics: European Geophysical Union, Stephan Mueller Publication 4, p. 157–175.
Miller, E.L., Gehrels, G.E., Pease, V., and Sokolov, S., 2010a, Stratigraphy and U-Pb detrital zircon geochronology of Wrangel Island, Russia: Implications for Arctic paleogeography: American Association of Petroleum Geologists Bulletin, v. 94, no. 5, p. 665–692, doi:10.1306/10200909036.
Miller, E.L., Dumitru, T.A., and Seward, G., 2010b, Structural geology and microstructures of Wrangel Island Arctic Russia: San Francisco, California, American Geophysical Union, 2010 fall meeting, abstract T31A–2131.
Miller, E.L., Dumitru, T.A., and Meisling, K.E., 2014, Structural geology of Wrangel Island, Arctic Russia: Geological Society of America Abstracts with Programs, v. 46, no. 6, p. 786.
Miller, T.P., 1989, Contrasting plutonic suites of the Yukon-Koyukuk basin and the Ruby geanticline, Alaska: Journal of Geophysical Research, v. 94, no. B11, p. 15,969–15,987, doi:10.1029/JB094iB11p15969.
Moore, T.E., Wallace, W.K., Bird, K.J., Karl, S.M., Mull, C.G., and Dillon, J.T., 1994, Geology of northern Alaska, *in* Plafker, G., and Berg, H.C., eds., The Geology of Alaska: Boulder, Colorado, Geological Society of America, The Geology of North America, v. G-1, p. 49–140.
Moore, T.E., Aleinikoff, J.N., and Harris, A.G., 1997a, Stratigraphic and structural implications of conodont and detrital zircon U-Pb ages from metamorphic rocks of the Coldfoot terrane, Brooks Range, Alaska: Journal of Geophysical Research, v. 102, no. B9, p. 20,797–20,820, doi:10.1029/96JB02351.
Moore, T.E., Wallace, W.K., Mull, C.G., Adams, K.E., Plafker, G., and Nokleberg, W.J., 1997b, Crustal implications of bedrock geology along the Trans-Alaska crustal transect (TACT) in the Brooks Range, northern Alaska: Journal of Geophysical Research, v. 102, no. B9, p. 20,645–20,684, doi:10.1029/96JB03733.
Moore, T.E., Dumitru, T.A., Adams, K.E., Witebsky, S.N., and Harris, A.G., 2002, Origin of the Lisburne Hills–Herald Arch structural belt: Stratigraphic, structural and fission-track evidence from the Cape Lisburne area, northwest Alaska, *in* Miller, E.L., Grantz, A., and Klemperer, S.L., eds., Tectonic Evolution of the Bering Shelf–Chukchi Sea–Arctic Margin and Adjacent Landmasses: Geological Society of America Special Paper 360, p. 77–109, doi:10.1130/0-8137-2360-4.77.
Moore, T.E., O'Sullivan, P.B., Potter, C.J., and Donelick, R.A., 2015, Provenance and detrital zircon geochronologic evolution of Lower Brookian foreland basin deposits of the western Brooks Range, Alaska, and implications for early Brookian tectonism: Geosphere, v. 11, no. 1, p. 93–122, doi:10.1130/GES01043.1.
Mull, C.G., 1985, Cretaceous tectonics, depositional cycles, and the Nanushuk Group, Brooks Range and the Arctic Slope, Alaska, *in* Huffman, T.S., ed., Geology of the Nanushuk Group and Related Rocks, North Slope, Alaska: U.S. Geological Survey Bulletin 1614, p. 7–36.
Natal'in, B.A., 1984, Early Mesozoic Eugeosynclinal Systems in the Northern Circum-Pacific: Moscow, Nauka, 135 p. [in Russian.]
Natal'in, B.A., Amato, J.M., Toro, J., and Wright, J.E., 1999, Paleozoic rocks of northern Chukotka Peninsula, Russian Far East: Tectonics, v. 18, no. 6, p. 977–1003, doi:10.1029/1999TC900044.
Nilsen, T.H., 1989, Stratigraphy and sedimentology of the mid-Cretaceous deposits of the Yukon-Koyukuk basin, west central Alaska: Journal of Geophysical Research, v. 94, no. B11, p. 15,925–15,940, doi:10.1029/JB094iB11p15925.
Nokleberg, W.J., Parfenov, L.M., Monger, J.W.H., Norton, I.O., Khanchuk, A.I., Stone, D.B., Scotese, C.R., Scholl, D.W., and Fujita, K., 2000, Phanerozoic Tectonic Evolution of the Circum-North Pacific: U.S. Geological Survey Professional Paper 1626, 122 p.
Oldow, J.S., Seidensticker, C.M., Phelps, J.C., Julian, F.E., Gottschalk, R.R., Boler, K.W., Handschy, J.W., and Avé Lallement, H.G., 1987, Balanced Cross-Sections through the Central Brooks Range and North Slope, Arctic Alaska: Tulsa, Oklahoma, American Association of Petroleum Geologists Special Publication, 19 p., 8 plates, scale 1:200,000.
Oldow, J.S., Boler, K.W., Avé Lallement, H.G., Gottschalk, R.R., Julian, F.E., Seidensticker, C.M., and Phelps, J.C., 1998, Stratigraphy and paleogeographic setting of the Skajit allochthon, central Brooks Range, Arctic Alaska, *in* Oldow, J.S., and Avé Lallemant, H.G., eds., Architecture of the Central Brooks Range Fold and Thrust Belt, Arctic Alaska: Geological Society of America Special Paper 324, p. 109–125, doi:10.1130/0-8137-2324-8.109.
O'Sullivan, P.B., Murphy, J.M., and Blythe, A.E., 1997, Late Mesozoic and Cenozoic thermotectonic evolution of the central Brooks Range and adjacent North Slope foreland basin, Alaska: Including fission track results from the Trans-Alaska crustal transect (TACT): Journal of Geophysical Research, v. 102, no. B9, p. 20,821–20,845, doi:10.1029/96JB03411.
O'Sullivan, P.B., Kelley, K.D., and Jennings, S., 2000, Post-mineralization thermotectonic evolution of the region of the Red Dog Pb-Zn-Ag mine, northwest Alaska, *in* Noble, W.P., O'Sullivan, P.B., and Brown, R.W., eds., 9th International Conference on Fission Track Dating and Thermochronology, Lorne, Australia, 2000: Geological Society of Australia Abstracts, v. 58, p. 255–257.
Pallister, J.S., Budahn, J.R., and Murchey, B.L., 1989, Pillow basalts of the Angayucham terrane: Oceanic plateau and island crust accreted to the Brooks Range: Journal of Geophysical Research, v. 94, p. 15,901–15,923, doi:10.1029/JB094iB11p15901.
Patrick, B., 1995, High-pressure–low-temperature metamorphism of granitic orthogneiss in the Brooks Range, northern Alaska: Journal of Metamorphic Geology, v. 13, no. 1, p. 111–124, doi:10.1111/j.1525-1314.1995.tb00208.x.
Patrick, B.E., and Evans, B.W., 1989, Metamorphic evolution of the Seward Peninsula blueschist terrane, Alaska: Journal of Petrology, v. 30, p. 531–556, doi:10.1093/petrology/30.3.531.
Patrick, B.E., and Lieberman, J.E., 1988, Thermal overprint on blueschists of Seward Peninsula: The Lepontine in Alaska: Geology, v. 16, p. 1100–1103, doi:10.1130/0091-7613(1988)016<1100:TOOBOT>2.3.CO;2.
Patrick, B.E., and McClelland, W.C., 1995, Late Proterozoic granitic magmatism on Seward Peninsula and a Barentian origin for Arctic Alaska–Chukotka: Geology, v. 23, no. 1, p. 81–84, doi:10.1130/0091-7613(1995)023<0081:LPGMOS>2.3.CO;2.
Patrick, B., Till, A.B., and Dinklage, W.S., 1994, An inverted metamorphic field gradient in the central Brooks Range, Alaska, and implications for exhumation of high pressure/low temperature metamorphic rocks: Lithos, v. 33, p. 67–83, doi:10.1016/0024-4937(94)90054-X.
Patton, W.W., Jr., Box, S.E., and Grybeck, D.J., 1994, Ophiolites and other mafic-ultramafic complexes in Alaska, *in* Plafker, G., and Berg, H.C., eds., The Geology of Alaska: Boulder, Colorado, Geological Society of America, The Geology of North America, v. G-1, p. 671–686.
Patton, W.W., Jr., Wilson, F.H., and Taylor, T.A., 2011, Geologic Map of Saint Lawrence Island, Alaska: U.S. Geological Survey Scientific Investigations Map 3146, 9 p., scale 1:250,000 [http://pubs.usgs.gov/sim/3146/].
Pease, V., 2011, Eurasian orogens and Arctic tectonics: An overview, *in* Spencer, A.M., Embry, A.F., Gautier, D.L.,

Stoupakova, A.V., and Sorenson, K., eds., Arctic Petroleum Geology: Geological Society of London Memoir 35, p. 311–324.

Pease, V., and Scott, R.A., 2009, Crustal affinities in the Arctic Uralides, northern Russia: Significance of detrital zircon ages from Neoproterozoic and Paleozoic sediments in Novaya Zemlya and Taimyr: Journal of the Geological Society of London, v. 166, p. 517–527, doi:10.1144/0016-76492008-093.

Pease, V., Miller, E.L., and Sokolov, S., 2007, New age relationships from Chukotka, Russia, and implications for opening of the Amerasian basin, *in* Geological Society of Norway, Arctic Conference Days 2007, Tromsø, Norway, Abstracts and Proceedings: Geological Society of Norway, p. 113.

Pink, C.L., and Rodgers, D.W., 2010, Structural controls on gold mineralization at the Rock Creek deposit, Nome, Alaska; implications for middle Cretaceous lode emplacement on the southwest Seward Peninsula: Geological Society of America Abstracts with Programs, v. 42, no. 5, p. 476.

Roeder, D., and Mull, C.G., 1978, Tectonics of Brooks Range ophiolites, Alaska: American Association of Petroleum Geologists Bulletin, v. 62, no. 9, p. 1696–1713.

Rowley, D.B., and Lottes, A.L., 1988, Plate-kinematic reconstructions of the North Atlantic and Arctic: Late Jurassic to present: Tectonophysics, v. 155, p. 73–120, doi:10.1016/0040-1951(88)90261-2.

Shatskii, N., 1935, On the Tectonics of the Arctic: Geology and Mineral Resources in the North of the USSR: Leningrad, Glavsevmorput, p. 149–165 [in Russian].

Shepherd, G.E., Muller, R.D., and Seton, M., 2013, The tectonic evolution of the Arctic since Pangea breakup: Integrating constraints from surface geology and geophysics with mantle structure: Earth-Science Reviews, v. 124, p. 143–183.

Smith, D.G., 1987, Late Paleozoic to Cenozoic reconstruction of the Arctic, *in* Tailleur, I.L., and Weimer, P., eds., Alaskan North Slope Geology: Pacific Section, Society of Economic Paleontologists and Mineralogists, Field Trip Guidebook 50, p. 785–795.

Sokolov, S.D., and Bondarenko, G.Ye., Morozov, O.L., Shekhovtsov, V.A., Glotov, S.P., Ganelin, A.V., and Kravchenko-Berezhnoy, I.R., 2002, South Anyui suture, northeast Arctic Russia: Facts and problems, *in* Miller, E.L., Grantz, A., and Klemperer, S.L., eds., Tectonic Evolution of the Bering Shelf–Chukchi Sea–Arctic Margin and Adjacent Landmasses: Geological Society of America Special Paper 360, p. 209–224, doi:10.1130/0-8137-2360-4.209.

Sokolov, S.D., Bondarenko, G.Ye., Layer, P.W., and Kravchenko-Berezhnoy, I.R., 2009, South Anyui suture: Tectono-stratigraphy, deformations, and principal tectonic events, *in* Stone, D.B., ed., Origin of Northeastern Russia: Paleomagnetism, Geology, and Tectonics: European Geophysical Union, Stephan Mueller Publication 4, p. 201–221.

Sokolov, S.D., Tuchkova, M.I., Ganelin, A.V., Bondarenko, G.Ye., and Layer, P.W., 2015, Tectonics of the South Anyui suture, northeast Asia: Geotectonics, v. 49, no. 1, p. 3–26, doi:10.1134/S0016852115010057.

Spear, F.S., 1993, Metamorphic Phase Equilibria and Pressure-Temperature-Time Paths: Washington, D.C., Mineralogical Society of America, 799 p.

Tailleur, I.L., 1973, Possible mantle-derived rocks in the western Brooks Range, Arctic Alaska, *in* Geological Survey Research 1973: U.S. Geological Survey Professional Paper 850, p. 64–65.

Thurston, S.P., 1985, Structure, petrology, and metamorphic history of the Nome Group blueschist terrane, Salmon Lake area, Seward Peninsula, Alaska: Geological Society of America Bulletin, v. 96, p. 600–617, doi:10.1130/0016-7606(1985)96<600:SPAMHO>2.0.CO;2.

Tikhomirov, P.L., Akinin, V.V., and Nakamura, E., 2008, Mesozoic magmatism in the central Chukotsk Peninsula: New U-Pb geochronological data and their geodynamic interpretation: Doklady Earth Sciences, v. 419, no. 1, p. 261–265, doi:10.1134/S1028334X08020165.

Tikhomirov, P.L., Kalinina, E.A., Kobayashi, K., and Nakamura, E., 2009a, Tytylveem volcano-plutonic belt, the Early Cretaceous magmatic province of NE Asia, *in* The Geology of Polar Regions of the Earth, Abstracts of the XLII Conference on Tectonics: Moscow, GEOS, v. 2, p. 239–241 [in Russian].

Tikhomirov, P.L., Luchitskaya, M.V., and Kravchenko-Berezhnoy, I.R., 2009b, Comparison of Cretaceous granitoids of the Chaun tectonic zone to those of the Taigonos Peninsula, NE Asia: Rock chemistry, composition of rock-forming minerals, and conditions of formation, *in* Stone, D.B., ed., Origin of Northeastern Russia: Paleomagnetism, Geology, and Tectonics: European Geophysical Union, Stephan Mueller Publication 4, p. 289–311.

Tikhomirov, P.L., Luchitskaya, M.V., and Shats, A.L., 2011, Age of granitoid plutons, north Chukotka: Problem formation and new SHRIMP U-Pb datings: Doklady Earth Sciences, v. 440, no. 2, p. 1363–1366, doi:10.1134/S1028334X11100060.

Tikhomirov, P.L., Kalinina, E.A., Moriguti, T., Makashima, A., and Kobayashi, K., 2012, The Cretaceous Okhotsk-Chukotsk volcanic belt (NE Russia): Geology, geochronology, magma output rates, and implications on the genesis of silicic LIPs: Journal of Volcanology and Geothermal Research, v. 221–222, p. 14–32, doi:10.1016/j.jvolgeores.2011.12.011.

Till, A.B., 1992, Detrital blueschist-facies metamorphic mineral assemblages in Early Cretaceous sediments of the foreland basin of the Brooks Range, Alaska, and implications for orogenic evolution: Tectonics, v. 11, p. 1207–1223, doi:10.1029/92TC01104.

Till, A.B., and Dumoulin, J.A., 1994, The Seward Peninsula—Seward and York terranes, *in* Plafker, G., and Berg, H.C., eds., Geology of Alaska: Boulder, Colorado, Geological Society of America, The Geology of North America, v. G-1, p. 141–152.

Till, A.B., and Moore, T.E., 1991, Tectonic relations of the schist belt, southern Brooks Range, Alaska: Eos, Transactions, American Geophysical Union, v. 72, no. 44, p. 295–296.

Till, A.B., and Snee, L.W., 1995, $^{40}Ar/^{39}Ar$ evidence that deformation of blueschists in continental crust was synchronous with foreland fold and thrust belt deformation, western Brooks Range, Alaska, *in* Patrick, B.E., and Day, H.W., eds., Special Issue on Cordilleran High-Pressure Metamorphic Terranes: Journal of Metamorphic Geology, v. 13, p. 41–60.

Till, A.B., Schmidt, J.M., and Nelson, S.W., 1988, Thrust involvement of metamorphic rocks, southwestern Brooks Range, Alaska: Geology, v. 16, p. 930–933, doi:10.1130/0091-7613(1988)016<0930:TIOMRS>2.3.CO;2.

Till, A.B., Dumoulin, J.A., Harris, A.G., Moore, T.E., Bleick, H.A., and Siwiec, B., 2008, Bedrock Geologic Map of the Southern Brooks Range, Alaska, and Accompanying Conodont Data: U.S. Geological Survey Open-File Report 2008–1149, 88 p., 2 sheets, sheet 1 scale 1:500,000, sheet 2 scale 1:600,000.

Till, A.B., Dumoulin, J.A., Werdon, M.B., and Bleick, H.A., 2011, Bedrock Geologic Map of Seward Peninsula, Alaska, and Accompanying Conodont Data: U.S. Geological Survey Scientific Investigations Map 3131, 2 sheets, scale 1:500,000, 75 p.

Till, A.B., Dumoulin, J.A., Ayuso, R.A., Aleinikoff, J.N., Amato, J.M., Slack, J.F., and Shanks, W.C., III, 2014, Reconstruction of an early Paleozoic continental margin based on the nature of protoliths in the Nome Complex, Seward Peninsula, Alaska, *in* Dumoulin, J.A., and Till, A.B., eds., Reconstruction of a Late Proterozoic to Devonian Continental Margin Sequence, Northern Alaska, its Paleogeographic Significance, and Contained Base-Metal Sulfide Deposits: Geological Society of America Special Paper 506, p. 1–28. doi:10.1130/2014.2506(01).

Toro, J., 1998, Structure and Thermochronology of the Metamorphic Core of the Central Brooks Range, Alaska [Ph.D. thesis]: Palo Alto, California, Stanford University, 200 p.

Toro, J., Cole, F., and Meier, J.M., 1998, $^{40}Ar/^{39}Ar$ ages of detrital minerals in Lower Cretaceous rocks of the Okpikruak formation: Evidence for Upper Paleozoic metamorphic rocks in the Koyukuk arc, *in* Gray, J.E., and Riehle, J.R., eds., Geologic Studies in Alaska by the U.S. Geological Survey, 1996: U.S. Geological Survey Professional Paper 1595, p. 169–182.

Toro, J., Gans, P.B., McClelland, W.C., and Dumitru, T.A., 2002, Deformation and exhumation of the Mount Igikpak region, central Brooks Range, Alaska, *in* Miller, E.L., Grantz, A., and Klemperer, S.L., eds., Tectonic Evolution of the Bering Shelf–Chukchi Sea–Arctic Margin and Adjacent Landmasses: Geological Society of America Special Paper 360, p. 111–132, doi:10.1130/0-8137-2360-4.111.

Toro, J., Amato, J.M., and Natal'in, B., 2003, Cretaceous deformation, Chegitun River area, Chukotka Peninsula, Russia: Implications for the tectonic evolution of the Bering Strait region: Tectonics, v. 22, no. 3, p. 5-1–5-19, doi:10.1029/2001TC001333.

Tuchkova, M.I., Bondarenko, G.E., Buyakaite, M.I., Golovin, D.I., Galuskina, I.O., and Pokrovskaya, E.V., 2007, Deformation of the Chukchi microcontinent: Structural, lithologic, and geochronologic evidence: Geotectonics, v. 41, no. 5, p. 403–421.

Tuchkova, M.I., Sokolov, S.D., and Kravchenko-Berezhnoy, I.R., 2009, Provenance analysis and tectonic setting of the Triassic clastic deposits in western Chukotka, northeast Russia, *in* Stone, D.B., ed., Origin of Northeastern Russia: Paleomagnetism, Geology, Tectonics: European Geophysical Union, Stephan Mueller Publication 4, p. 177–200.

Tuchkova, M.I., Sokolov, S.D., Khudoley, A.K., Verzhbitsky, V.E., Hayasaka, Y., and Moiseev, A.V., 2014, Permian and Triassic deposits of Siberian and Chukotka passive margins: Sedimentation setting and provenances, *in* Stone, D.B., Grikurov, G.E., Clough, J.G., Oakey, G.N., and Thurston, D.K., eds., ICAM VI: Proceedings of the International Conference on Arctic Margins VI, Fairbanks, Alaska, May 2011: Press VSEGEI, p. 61–96, http://www2.gi.alaska.edu/icam6/ (accessed October 2014).

Verzhbitsky, V.E., Sokolov, S.D., Tuchkova, M.I., Frantzen, E.M., Little, A., and Lobkovsky, L.I., 2012, The south Chukchi sedimentary basin (Chukchi Sea, Russian Arctic): Age, structural pattern, and hydrocarbon potential, *in* Gao, D., ed., Tectonics and Sedimentation: Implications of Petroleum Systems: American Association of Petroleum Geologists Memoir 100, p. 267–290.

Verzhbitsky, V.E., Sokolov, S.D., and Tuchkova, M.I., 2015, Present-day structure and stages of tectonic evolution of Wrangel Island, Russian eastern Arctic region: Geotectonics, v. 49, no. 3, p. 165–192, doi:10.1134/S001685211503005X.

Vogl, J.J., 2002, Late-orogenic backfolding and extension in the Brooks Range collisional orogeny, northern Alaska: Journal of Structural Geology, v. 24, p. 1753–1776, doi:10.1016/S0191-8141(01)00155-9.

Vogl, J.J., 2003, Thermal-baric structure and *P-T* history of the Brooks Range metamorphic core, Alaska: Journal of Metamorphic Geology, v. 21, p. 269–284, doi:10.1046/j.1525-1314.2003.00440.x.

Vogl, J.J., Calvert, A.T., and Gans, P.B., 2002, Mechanisms and timing of exhumation of collision-related metamorphic rocks, southern Brooks Range, Alaska: Insights from $^{40}Ar/^{39}Ar$ thermochronology: Tectonics, v. 21, no. 3, p. 2-1–2-17, doi:10.1029/2000TC001270.

Werdon, M.B., Stevens, D.S.P., Newberry, R.J., Szumigala, D.J., Athey, J.E., and Hicks, S.A., 2005, Explanatory Booklet to Accompany Geologic, Bedrock, and Surface Maps of the Big Hurrah and Council Areas, Seward Peninsula, Alaska: Alaska Division of Geological and Geophysical Surveys Report of Investigations 2005-1, 24 p.

MANUSCRIPT RECEIVED 6 JUNE 2015
REVISED MANUSCRIPT RECEIVED 27 JANUARY 2016
MANUSCRIPT ACCEPTED 8 FEBRUARY 2016

Printed in the USA