First bedrock samples dredged from submarine outcrops in the Chukchi Borderland, Arctic Ocean

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ABSTRACT

The Chukchi Borderland, a prominent bathymetric feature within the Arctic Ocean, has been interpreted as a fragment of an undeformed continental platform sequence rifted from the passive margin of Arctic Canada. Dredges collected for the U.S. Extended Continental Shelf project aboard the icebreaker U.S. Coast Guard Cutter Healy (cruise number HLY0905) recovered hundreds of kilometers of broken crystalline basement lithologies consisting of mylonitically deformed biotite-bearing amphibolite, garnet-bearing feldspathic gneiss, and augen-bearing orthogneiss from the Chukchi Borderland. Metamorphic zircon within the amphibolite and associated leucogranitic seams within these rocks yielded U-Pb zircon ages between ca. 480 and 530 Ma. Garnet-bearing feldspathic gneisses contain variably discordant Mesoproterozoic zircon, ca. 600 Ma igneous zircon, and ca. 485–505 Ma metamorphic overgrowths. While we interpret these gneisses as deformed and metamorphosed granitoids, they could, instead, have a very immature sedimentary protolith. The youngest rocks sampled were K-feldspar augen orthogneiss from the Chukchi Borderland. The nature and geologic history of the intrabasinal features is important in defining the area’s continental character and for Extended Continental Shelf (ECS) submissions will have far-reaching implications for future marine science research in the Arctic Ocean and consequences for scientific studies monitoring and exploring this important region.

INTRODUCTION

The Arctic Ocean consists of two subbasins, the Eurasia and Amerasia Basins (Fig. 1). The Eurasia Basin is floored by oceanic crust and is the northernmost continuation of the mid-Atlantic Rift (Heezen and Ewing, 1961). Magnetic anomalies within the Eurasia Basin indicate that seafloor spreading began at ca. 60 Ma, separating the Lomonosov Ridge from the Barents Shelf (Ostenson and Wold, 1973; Herron et al., 1974). In contrast, the crustal character and plate tectonic history of the adjacent Amerasia Basin is very poorly understood. The Amerasia Basin includes a number of intrabasinal bathymetric highs including the Chukchi Borderland that appear to represent continental crust (Fig. 1). The nature and geologic history of the bathymetric features in the Arctic Ocean have implications for both natural resource exploration and for Extended Continental Shelf (ECS) submissions of Arctic states under Article 76 of the United Nations Convention on the Law of the Sea (UNCLOS). The geologic make up of bathymetric features is important in defining the “natural prolongation” of land territory for the purpose of defining an Extended Continental Shelf under UNCLOS. The final and binding international boundaries that result from these submissions will have far-reaching implications for future marine science research in the Arctic Ocean and consequences for scientific studies monitoring and exploring this important region.

GEOLOGICAL BACKGROUND

The Chukchi Borderland

The Chukchi Borderland is a bathymetric high of presumed continental affinity that is physiographically connected to the Alaska margin...
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The borderland covers ~420,000 km² and is deformed and extended by major north-south–trending normal faults (Hall, 1990; Brumley, 2009). The geologic and tectonic history of the Chukchi Borderland has been controversial. Grantz et al. (1998) sampled talus-slope fragments from sites along the Northwind Ridge in the Chukchi Borderland (red X, Fig. 1) using sediment piston cores and box cores. The lithologies represented within the sediment core samples were interpreted to resemble the Franklinian Neoproterozoic–early Paleozoic passive margin sequence of northern Canada (described below). Grantz et al. (1998) concluded that the rock samples appeared to correlate most closely to shelf strata situated between the north end of the Mackenzie Delta and Melville Island with an assumed attachment point of the Chukchi Borderland to the Banks Island area (striped region, Fig. 1). Based upon preliminary analysis of the HLY0905 dredge results, Brumley et al. (2013) alternatively proposed that the Chukchi Borderland was related to peri-Laurentian orogenic terranes similar to southwestern Svalbard and the Pearya terrane of northern Ellesmere Island.

Timing of Deformation in the Arctic Region

The Grenville orogeny affected northern Laurentia during assembly of the supercontinent Rodinia from 1200 to 950 Ma (Davidson, 2008). Evidence for Grenville age deformation, meta-
morphism, and magmatism occurs in north-
eastern Greenland (e.g., Higgins and Leslie, 2008; Kalsbeek et al., 2008), the assembled ter-
rane of Svalbard (e.g., Johansson et al., 2005),
and the Pearya terrane of northern Ellesmere
Island (e.g., Trettin, 1987) leading Johannson
et al. (2005), to argue for a northern arm of the
Grenville orogen in the Arctic (Fig. 1). Amal-
gamation of the composite terrane of Pearya
is attributed to collision of a continental frag-
ment with an island arc during the Cambro-
Ordovician M’Clintock orogeny. This orogenic
event involved thrusting of calc-alkaline vol-
canic rocks, deep marine sediments, and a dis-
membered ophiolite over the Proterozoic base-
ment of Pearya (Trettin, 1987; Trettin et al.,
1992). M’Clintock orogenesis is coeval with
subduction-related collision in Cambro-
Ordovician time (Ohta et al., 1989; Gee and
Page, 1994; Harland, 1997; Gee and Teben’kov,
2004; Gee et al., 2008; Labrousse et al., 2008).
Closure of the early Paleozoic Iapetus Ocean
led to the collision of eastern Laurentia (North
America) and Greater Baltica (Eurasia) result-
ing in the Silurian to Early Devonian Caledo-
nian orogeny (e.g., Leslie and Higgins, 2008).
The Caledonian orogen, which straddles both
conjugate margins of the Atlantic, continues
into the high Arctic, where it is truncated at the
shelf edges of the modern Arctic Ocean (Fig. 1).
The Scandian phase of the Caledonian orogeny
affected northeastern Greenland, Norway, and
parts of Svalbard between ca. 435 and 415 Ma
(Fig. 1; Harland, 1997; Mckerrow et al., 2000;
Johansson et al., 2005; Gee et al., 2008; Leslie
and Higgins, 2008). The Ellesmerian orogeny
created a south-verging fold belt that affected
Arctic Alaska, Pearya, northern Greenland, and
parts of western Svalbard (Fig. 1; e.g., Trettin
and Norford, 1994). This deformation is thought
to reflect collision of an unknown landmass with
the northern margin of Laurentia from Devonian
to earliest Carboniferous time (Embry, 1993;
Trettin and Norford, 1994; Colpron and Nelson,
2006). This landmass was subsequently rifted
away by the opening of the Amerasia Basin and
may exist as rifted fragments around the Arctic
shelf margins and within the Arctic Ocean itself
(Beranek et al., 2010).

The Northern Laurentian Passive Margin

The Franklinian margin of northern Laurentia
consisted of an uninterrupted latest Neo-
proterozoic–Devonian continental platform that
formed along the Arctic edge of Laurentia and
created associated slope and deep-water basin
deposits (Trettin, 1991; Henricksen and Hig-
gins, 1998). On the platform, carbonate deposi-
tion predominated over this lengthy period, con-
structing a thick pericratonic wedge (Harrison
et al., 1991). Lower Paleozoic sedimentation on
the Arctic platform and within the Franklinian
basin continued until Devonian uplift, deforma-
tion, and foreland subsidence associated with
the Ellesmerian orogeny (Haimila et al., 1990;
discussed below).

The bedrock geology exposed on Banks
Island in the Canadian Arctic Islands, to which
the Chukchi Borderland has been correlated
(Grantz et al., 1998), includes undeformed Meso-
and Neoproterozoic dolostones and sandstones
(Trettin, 1989) with rift-related diabase sills and
extrusive basaltic rocks (ca. 723 Ma; Heaman et al., 1992). Cambrian to
Devonian strata of the Arctic platform and
Franklinian basin are overlain by shallow
marine and fluvial deltaic clastic sediments of
the Ellesmerian foreland basin (Trettin, 1991;
Hadlari et al., 2012).

Peri-Laurentian Terranes Potentially
Correlative with the Chukchi Borderland

Pearya Terrane

The crystalline basement of the Pearya terrane
(Fig. 1) consists of Mesoproterozoic metavol-
canics, orthogneisses, and metasedimentary
rocks that were affected by late Mesoprotero-
zic to early Neoproterozoic (ca. 1100–960
Ma) deformation and magmatism attributed to
Grenville orogenesis as expressed in the North
Atlantic region (Succession I of Trettin, 1987).
These rocks are overlain by Neoproterozoic to
Ordovician age platform strata and volcanic
rocks that are interpreted to have been deposi-
ted in an extensional tectonic setting (Succes-

Figure 2. Central Chukchi Borderland dredge site location: (A) Multibeam bathymetric
image of HLY0905 dredge site #5 (red X on inset map of the Chukchi Borderland; see Fig. 1
for location) showing steep scarp with over 2000 m of relief. Slope angles are almost 62°
at the steepest point between ~2000 and 1500 m water depth where the dredge was collected.
Average slope along the profile is 39°. Red line is track of multichannel seismic line (B) inter-
preted in Brumley (2009) showing thin sediment drape in dredged interval and normal fault
geometry in the subsurface. V.E.—vertical exaggeration.
Geosphere, February 2015

Sylvia II of Trettin, 1987). Additional mafic volcanic and sedimentary rocks occur adjacent to the platform sequence and represent deposits that formed during collision of the continental platform with an island arc during the Cambro-Ordovician M’Clintock orogeny (Succession III of Trettin, 1987). The subduction-related rocks associated with this collision are unconformably overlain by Middle Ordovician calc-alkaline volcanic rocks (Succession IV of Trettin, 1987, 1991) and Late Ordovician to Silurian clastic rocks that record continuous subsidence without volcanism or deformation (Trettin, 1987).

Pearya was adjacent to the northern edge of Laurentia by Late Silurian time as demonstrated by clastic rocks that record proximity to the Laurentian margin and subsequent Late Silurian to Early Carboniferous accretion-related deformation (Succession V of Trettin, 1991; Churkin and Trexler, 1980; Trettin, 1987). The transpressional accretion of Pearya resulted in the development of the Clements-Markham fold belt on northern Ellesmere Island (Fig. 1; Piepjohn et al., 2007).

**Western Terranes of Svalbard**

The Pearya Terrane has been correlated to the southwestern terranes of Svalbard (e.g., Trettin, 1987; Harland, 1997). Like Pearya, southwestern Svalbard consists of Proterozoic basement with deformation, metamorphism, and anatectic magmatism between 1160 and 940 Ma associated with the Grenville orogeny (Ohta et al., 1989; Harland, 1997; Johansson et al., 2005). Parts of southwestern Svalbard experienced metamorphism and magmatism between ca. 650 and 620, and ca. 620–540 Ma (Peucat et al., 1989; Majka et al., 2008, 2012). Ediacaran tillites record rift-associated uplift and glaciation (Harland, 1997). Cambro-Ordovician lithotectonic units along the western coast of Svalbard include a subduction complex with high-pressure metamorphic and oceanic volcanic rocks that are thought to represent a collision of an island arc along the northern Laurentian margin (Ohta et al., 1989). The subduction complex is unconformably overlain by Late Ordovician through Early Silurian island arc and shelf sedimentary sequences (Ohta et al., 1989; Ohta, 1994; Harland, 1997; Mazur et al., 2009).

Neither Pearya nor southwestern Svalbard record evidence for Silurian (Scandian) Caledonian metamorphism (Gasser and Andresen, 2013). The translation and accretion of western Svalbard and Pearya along the northern edge of Laurentia is coeval with late Caledonian orogenesis along the northeastern edge of Laurentia and was probably completed by Early Devonian time (Trettin, 1987; von Gosen et al., 2012).

**Sampling and Experimental Methods**

Deformed and metamorphosed amphibolite-grade igneous rocks including biotite-bearing amphibolites, garnet-bearing feldspathic gneisses, and potassium feldspar augen-orthogneisses were dredged from a steep normal fault scarp in central Chukchi Borderland. When dredging in ice-covered water, it is essential to maximize the chance that dredged rock samples are from submarine bedrock exposures by avoiding locations dominated by ice-raftered debris (IRD). To avoid collecting the thick pelagic mud and IRD that is ubiquitous across the seafloor of the Arctic Ocean, only very steep slopes (>35°) were chosen as dredge sites (Fig. 2). Hundreds of kilograms of angular broken rock fragments collected from the central Chukchi Borderland were plucked from outcrop as recorded by high-tension pulls on the dredge line. High tension on the dredge line occurs when the dredge basket becomes stuck on hard bottom seafloor (Fig. 3A).

To check the conclusion that rock fragments in the dredge were broken from the submarine outcrops during high-tension pulls, we carried out a detailed lithologic comparison of the fragments with the gravel through boulder-size IRD that was also collected during normal dredging. We classify IRD after Huggett and Kidd (1983) by their wedge shape, the presence of glacial striations and polish, roundness, and manganese stain development. Rocks we infer have been broken from outcrop have approximately uniform thicknesses of manganese crust on surfaces exposed to seawater (white arrow, Fig. 3B), while broken surfaces are fresh and free of manganese precipitate. In contrast, manganese staining on IRD is either nonexistent or of heterogeneous thicknesses due to variable time exposed to seawater after deposition by ice rafting (Fig. 3C). No IRD lithology matched any of the angular and broken rocks that were dredged from outcrop (Fig. 3D).

**Sample Descriptions**

The high-tension dredge pulls achieved in dredge HLY0905-DS5 yielded broken fragments of mafic amphibolite, garnet-bearing feldspathic gneiss, and potassium feldspar (K-feldspar) augen-orthogneiss. Despite the range of lithologies represented within the central Chukchi Borderland dredge haul, all of the rock fragments have been variably mylonitized and share a lower amphibolite-facies overprint. This observation supports our conclusion that the rocks reported on here were indeed collected from submarine outcrops.

**Amphibolites**

Mafic rocks make up about a quarter of the HLY0905-DS5 dredge haul. Amphibolite samples are blocky and dark gray to blackish green in hand specimens with iron-oxide staining on fractured surfaces (Figs. 4A and 4C). Many samples have deformed quartz veins or quartzofeldspathic-rich bands (Fig. 4C).

**Garnet-Bearing Feldspathic Gneisses**

Garnet-bearing gneisses make up about half of the HLY0905-DS5 dredge haul. These rocks are very finely layered with mm-size altered garnet in hand samples (Fig. 4E). Most of the samples are also fractured at high angles to the compositional banding.

Sample #5-019 (IGSN ECS008044) (Fig. 4F) is composed of strongly recrystallized quartz (35%) with grain sizes that range from ~100 µm down to 10–40 µm. Thin dark bands are composed of biotite variably altered to chlorite. Feldspars include highly sericitized, 200–400 µm plagioclase phenocrysts (40%) and subordinate microcline (10%). There are trace amounts of chloritized garnet (2%), small
amounts of zoisite, secondary muscovite, abundant apatite, and some zircon. Spaced fractures are filled with chlorite.

Sample #5-020 (IGSN ECS008045) is less deformed with overall larger grain sizes relative to the sample described above. Quartz (30%) varies from coarse grained down to a grain size between 20 and 40 µm. The rock also includes highly sericitized plagioclase (40%), potassium feldspar (5%), chloritized biotite (15%), muscovite (2%), and zoisite (2%). Large garnets (1–3 mm) are tabular or fragmental and altered to chlorite. Accessory titanite, apatite, and zircon are visible in the thin section.

The protolith of these quartzofeldspathic rocks is uncertain due to their highly deformed and metamorphosed nature. However, the size...
and abundance of feldspar, as well as aspects of the U-Pb analysis discussed below, suggest that the protolith of the garnet-bearing feldspathic gneiss was an igneous rock of intermediate composition, although an immature sedimentary protolith cannot be ruled out.

**Potassium Feldspar Augen-Orthogneiss Samples**

We selected two representative coarse-grained orthogneiss samples from the approximately 20 K-feldspar augen-orthogneiss fragments collected from the HLY0905-DS5 dredge haul. Both samples displayed large (>1 cm) K-feldspar augen visible in hand sample (Fig. 4G). Sample #5-001b (IGSN ECS008094) is composed of recrystallized quartz (35%) with subgrain development and grain boundary migration textures with grain sizes between 50 and 200 μm. Variably sericitized plagioclase (30%) makes up most of the augen with lesser amounts of microcline (15%). The largest augens (>1 cm) are potassium feldspars. Variably chloritized biotite (15%) is aligned and defines the foliation. Abundant zircon was visible in this sample along with large euhedral titanite (250 μ) and apatite.

Sample #5-002a (IGSN ECS008095) is similar in composition, but quartz (30%) is more deformed with grain sizes between ~50 and 100 μm. The proportion of plagioclase (15%) is subordinate to large K-feldspar augen (35%). There is some chloritization of biotite (10%), which is aligned in a preferred orientation that defined the foliation. Trace epidote, allanite, and abundant apatite and zircon are present.

**Experimental Methods**

**Ion Microprobe U-Pb Analysis**

We employed the sensitive high-resolution ion microprobe–reverse geometry (SHRIMP-RG) located at the Stanford University–U.S. Geological Survey (USGS) Micro Analysis Center to determine U-Pb crystallization ages of zircons in the three lithologies from the HLY0905-DS5 dredge haul. Zircons were concentrated by standard heavy-mineral separation processes and were hand selected and mounted on double-sided adhesive tape on glass plates. Mounts were cast in epoxy, lightly sectioned by grinding with 1500 grit carbide, and ultimately polished using 1-micron polycrystalline diamond. Zircon grains were imaged with a cathodoluminescence (CL) detector mounted within a JEOL 5600 scanning electron microscope (SEM) to identify internal compositional zoning to select spots for U-Pb analyses.

We followed ion microprobe analytical routines modified after Williams (1998). Primary beam tuning produced 4–6 nA O2-ion beam that created a 25–30 μm diameter, 1–2-μm-deep sputter pit depending upon analysis duration. Both trace elements and U-Pb ion intensities were generally measured in the same run (some trace-element analyses were performed separately on the same mounts, and several samples lacked trace-element data). Analysis times included pre-sputtering of the analysis surface to minimize surface Pb contamination.
Data reduction utilized the SQUID program of Ludwig (2005). Concentration data for U, Th, and all of the measured trace elements were standardized against a well-characterized, homogeneous in-house zircon standard (MAD-green zircon). Measured Pb/U ratios from unknown zircons were standardized using equivalent measurements for R33 standard zircon (Black et al., 2004). Primary beam drift corrections were applied. Zircon U-Pb ages younger than 1 Ga were based on $^{206}\text{Pb}^{238}\text{U}$ ages calculated from ratios corrected for common lead using age corrected $^{206}\text{Pb}$ as a proxy. Ages older than 1 Ga are based on $^{207}\text{Pb}^{206}\text{Pb}$ ages calculated from ratios corrected for common Pb using measured $^{204}\text{Pb}$. Common Pb isotopic compositions were estimated from Stacey and Kramers (1975). Age calculations and Tera-Wasserburg diagrams were generated with the Isoplot/Ex program of Ludwig (2003). Zircon U-Pb ages and trace-element data appear in Supplemental Tables A.1–A.5 in the Supplemental File1.

Whole-Rock Major- and Trace-Element Geochemistry

Whole-rock major- and trace-element compositions were measured for both K-feldspar augen-orthogneiss samples (#5-001b and #5-002a) at the Washington State University (WSU) GeoAnalytical Lab. The samples were crushed, and unaltered rock chips were hand selected for analysis. These chips were pulverized to a very fine powder using an agate bowl at the WSU facility. The rock powder was mixed with di-lithium tetraborate flux (2:1 flux:rock) and fused at 1000 °C in a muffle oven. The resulting bead was reground, refused, and polished on diamond laps to provide a smooth flat analysis surface. The beads were analyzed using the ThermoARL Advant’X+ sequential X-ray fluorescence spectrometer at the WSU GeoAnalytical Lab. Ten major elements and 19 trace elements were determined. A split of the powder was dissolved using high-strength acids (HF, HCl, and H$_2$NO$_3$). The solution was analyzed for trace elements and rare-earth elements (REEs) using the high-resolution, single-collector, inductively coupled plasma mass spectrometer (HR-SC-ICP MS), a Finnigan Element 2, capable of analyzing elements in solution at concentrations as low as parts per quadrillion at the WSU GeoAnalytical Lab.

Results

Whole-rock trace-element analyses of K-feldspar augen-orthogneiss show an overall enrichment in large ion lithophile elements (LILEs), relative to high field strength elements (HFSE); this enrichment is commonly attributed to the high solubility of LILE in the aqueous fluid abun-https://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/11/1/76/3334623/76.pdfdance in subduction zones (e.g., Rogers and Greenberg, 1990). Dehydration of subducting oceanic crust releases fluids with high concentrations of LILE relative to HFSE, enriching subduction-related magmas in LILE (e.g., Zindler and Hart, 1986). The trace-element patterns of the K-feldspar augen-orthogneisses are similar to I-type granites (Fig. 5A; Supplemental Table A.8 [see footnote 1]). The Chukchi Borderland rocks demonstrate depletions in Ta, Nb, and Ti, relative to trace elements of similar geochemical behavior, which is also a hallmark of subduction zone magmatism.

Nd and Sr Isotopic Measurements

K-feldspar augen-orthogneiss #5-001b and #5-002a were processed at the Stanford University ICP-MS/thermal ionization mass spectrometer (TIMS) facility using the procedures described in Konstantinou et al. (2013a, 2013b). Primary beam drift corrections were applied. Zircon U-Pb ages younger than 1000 Ma are $^{207}\text{Pb}$ corrected 206Pb/238U ages. Analyses over 1000 Ma are $^{204}\text{Pb}$ corrected 207Pb/206Pb ages. Sample #5-001b was mounted on one zircon mount (KJB002) but run in two different sessions. Blue bars outline analyzed spots on CL images. Table A.4. Zircon U-Pb lead geochronologic data and apparent ages from Chukchi Borderland orthogneiss samples 5-002a (IGSN ECS008095), 5-001b (IGSN ECS008094) were analyzed seven times and yielded an average age of 0.710144 ± 52 [2σ]; accepted value of $^{143}\text{Nd}^{144}\text{Nd}$ = 0.512986 ± 18 (2σ) from Weis et al. (2005). The results of the Sr and Nd isotope analyses, together with the values used to calculate $^{87}\text{Sr}^{86}\text{Sr}$ and eNd(t) values, are reported in Supplemental Table A.6 (see footnote 1).

RESULTS

Major- and Trace-Element Geochemistry

Whole-rock normalized major elements of the studied K-feldspar augen-orthogneiss (#5-001b and #5-002a) revealed intermediate SiO$_2$ concentrations (65%–67%), enrichment of Na$_2$O (3.4%–3.8%), and low K$_2$O/Na$_2$O (1.0–1.4; Table 1). Calculated CIPW norms classify samples #5-001b (IGSN ECS008094) as a monzogranite (Q$_2$A$_1$P$_5$) and #5-002a (IGSN ECS008095) as a granodiorite (Q$_2$A$_1$P$_3$) (Supplemental Table A.7 [see footnote 1]). Whole-rock trace-element analyses of K-feldspar augen-orthogneiss are shown in Supplemental Table A.9: Table A.1. Zircon U-Pb lead geochronologic data and apparent ages from Chukchi Borderland amphibolite samples 5-009 (IGSN ECS008102), 5-043b (IGSN ECS008136) were processed at the Stanford University ICP-MS/thermal ionization mass spectrometer (TIMS) facility using the procedures described in Konstantinou et al. (2013a, 2013b). The sample analyses were compared and normalized to 43 analyses of Standard Reference Material (SRM) 987 (accepted value of 0.703483 ± 14 [2σ]). A secondary standard of BHVO-1 was analyzed seven times and yielded an average age of 0.710144 ± 52 [2σ]; accepted value of $^{143}\text{Nd}^{144}\text{Nd}$ = 0.512986 ± 18 (2σ) from Weis et al. (2005). The results of the Sr and Nd isotope analyses, together with the values used to calculate $^{87}\text{Sr}^{86}\text{Sr}$ and eNd(t) values, are reported in Supplemental Table A.6 (see footnote 1).

Nd isotopic ratios, sample ratios were multiplied by a normalization factor determined from Ndi corrections to a value of $^{143}\text{Nd}^{144}\text{Nd} = 0.512115 ± 10$ (2σ; Tanaka et al., 2000); 26 analyses of Ndi resulted in an average $^{143}\text{Nd}^{144}\text{Nd}$ value of 0.512087 ± 22 (2σ). A secondary standard of BHVO-1 was analyzed three times and yielded an average $^{143}\text{Nd}^{144}\text{Nd}$ value of 0.512969 ± 20 (2σ). This compares to the value for BHVO-1 of $^{143}\text{Nd}^{144}\text{Nd} = 0.512986 ± 18$ (2σ) from Weis et al. (2005). The results of the Sr and Nd isotope analyses, together with the values used to calculate $^{87}\text{Sr}^{86}\text{Sr}$ and eNd(t) values, are reported in Supplemental Table A.6 (see footnote 1).

For the Nd isotope analyses, sample ratios were multiplied by a normalization factor determined from Ndi corrections to a value of $^{143}\text{Nd}^{144}\text{Nd} = 0.512115 ± 10$ (2σ; Tanaka et al., 2000); 26 analyses of Ndi resulted in an average $^{143}\text{Nd}^{144}\text{Nd}$ value of 0.512087 ± 22 (2σ). A secondary standard of BHVO-1 was analyzed three times and yielded an average $^{143}\text{Nd}^{144}\text{Nd}$ value of 0.512969 ± 20 (2σ). This compares to the value for BHVO-1 of $^{143}\text{Nd}^{144}\text{Nd} = 0.512986 ± 18$ (2σ) from Weis et al. (2005). The results of the Sr and Nd isotope analyses, together with the values used to calculate $^{87}\text{Sr}^{86}\text{Sr}$ and eNd(t) values, are reported in Supplemental Table A.6 (see footnote 1).

Keck-laser Raman Spectroscopy

Raman spectra were measured for a subset of the zircons from samples 5-001b and 5-002a using a Renishaw InVia Raman Spectrometer with a 785 nm laser. The spectra were analyzed using the PeakFit software to identify the Raman bands associated with different minerals. The results of the Raman spectroscopy are shown in Supplemental Table A.10: Table A.1. Raman Spectral Data for Zircons from Chukchi Borderland Orthogneiss Samples 5-001b and 5-002a.

Sr and Nd Isotope Geochemistry

Based on radiogenic isotopic analyses, the Chukchi Borderland K-feldspar augen-orthogneiss samples have an eNd value of −4.8 and $^{87}\text{Sr}^{86}\text{Sr}$ ratios of 0.707. These values are typical of granites emplaced in a continental arc setting or I-type granites (Fig. 5B; Zindler and Hart, 1986) and are not as evolved as typical anatectic S-type granites. Continental arc magmas...
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with \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios in the range 0.704 to 0.708 are often interpreted to indicate interaction of mantle-derived melts with continental crust above continental margin subduction zones (Table 1; White, 1979; Pearce, 1983).

**U-Pb Zircon Geochronology**

**Amphibolites**

Zircon U-Pb results were obtained from two representative Chukchi Borderland amphibolite samples (#5-009 and #5-043). Zircons were also analyzed from the leucocratic seam (#5-043L) discussed above. Zircons from both the amphibolites and leucocratic seam were between ~150 and 250 µm long, generally anhedral, and yellow to brown on ion probe mounts. Many were highly fractured and contained inclusions. The CL images of zircons from both amphibolites (#5-009 and #5-043) revealed weakly planar, patchy or chaotic zoning, or no zoning (Figs. 6A–6C). These characteristics are typical of metamorphic zircon (Corfu et al., 2003; Yuanbao and Yongfei, 2004).

Ion microprobe U-Pb age results from both amphibolite samples yielded a broad, uniform age distribution (Figs. 6D–6F; Supplemental Table A.1 [see footnote 1]). Using all measured ages, we calculated weighted mean \(^{206}\text{Pb}/^{238}\text{U}\) ages of 508 ± 5 Ma for sample #5-009 (n = 27; Figs. 6D–6G) and 486 ± 20 Ma for sample #5-043 (n = 20; Figs. 6E–6H). Uncertainties are quoted at 95% confidence. The leucocratic seam (#5-043L) also contained zircons exhibiting patchy, planar, or chaotic CL zoning (Fig. 6C). Zircon U-Pb results from the leucocratic seam overlapped those from the amphibolite samples and yielded a weighted mean age of 489 ± 15 Ma (n = 30; Figs. 6F–6I). U-Pb weighted mean ages of all three samples overlap at 95% confidence.

**Garnet-Bearing Feldspathic Gneisses**

Zircons yielded by the two finely banded garnet-bearing feldspathic gneiss samples ranged from 50 to 250 µm in length and generally exhibit subhedral to prismatic forms with rounded terminations. Some zircon grains were highly rounded. Zircons ranged in color from yellowish to reddish brown. The most rounded zircons tended to be more reddish color, although this was not consistent throughout. Cathodoluminescence imaging revealed some consistent relationships between zircon shape and internal structure. For example, subhedral grains had oscillatory-zoned cores with dark overgrowths, while prismatic crystals had bright cores and patchy zoned overgrowths (Figs. 7A and 7B). Smaller rounded zircons show patchy or chaotic zoning with no visible core/rim relationships (Figs. 7A and 7B). The U-Pb age distributions for both samples are very similar in that they exhibit age clusters at ca. 480–545 Ma (black and dark red ellipses, Fig. 7D) and 560–650 Ma (red and blue ellipses, Fig. 7D) and older ages between 1100 and 1700 Ma (Fig. 7C; Supplemental Table A.3 [see footnote 1]).

**Potassium Feldspar Augen-Orthogneisses**

Zircon CL images reveal that most grains extracted from the K-feldspar augen-orthogneiss samples (#5-001b and #5-002a) are euhedral and exhibit oscillatory zonation with
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a few texturally distinct cores (Figs. 8A and 8B). Analysis of the oscillatory-zoned regions yielded a range of 206Pb-corrected 206Pb/238U ages for both samples of between 403 and 465 Ma (Supplemental Table A.4 [see footnote 1]). The broad spread of concordant ages in these samples yields a mean square of weighted deviates (MSWD) that is inconsistent with a homogeneous population. The youngest age determinations (between ca. 415 and 403 Ma) are discordant and/or have large errors (Fig. 8C, dashed ellipses). The youngest zircons yield trace-element patterns that show enrichment of light rare-earth elements (LREE; Supplemental Table A.5 [see footnote 1]) that are indicative of hydrothermally altered zircon (Fig. 9C; Hoskin and Schaltegger, 2003). Because these young ages represent a post-crystallization process, they were excluded from calculations of mean ages. All highly discordant analyses were also discarded (Supplemental Table A.4 [see footnote 1]). After filtering these results, we calculated weighted mean 206Pb/238U ages of 432 ± 3.8 Ma and 430 ± 3.6 Ma for #5-001b and #5-002a, respectively (Fig. 8C). Nine targeted cores yielded U-Pb ages between ca. 860 and 980, 1100 and 1450, and 1650 and 1825 Ma (Fig. 8D).

INTERPRETATION OF IGNEOUS AND METAMORPHIC ZIRCON U-PB AGES

Amphibolites

Zircon trace-element patterns are controlled by the equilibrium phase assemblage during zircon growth. Garnet is absent from
Figure 7. Zircon U-Pb results from garnet-bearing feldspathic gneisses: (A) cathodoluminescence (CL) images of representative zircons from sample #5-020 and (B) sample #5-019. Red circles are analysis spots with spot numbers; ages are $^{207}$Pb/$^{206}$Pb corrected $^{206}$Pb/$^{238}$U ages for zircons younger than 1000 Ma. For zircons older than 1000 Ma, $^{206}$Pb-corrected $^{207}$Pb/$^{206}$Pb ages are shown. (C) Tera-Wasserberg concordia diagram with analyses from both #5-019 (dark red ellipses) and #5-020 (black ellipses). Call-out of younger ages (D) shows analyses taken from prismatic zircon and zircon cores (red and blue ellipses) as well as analyses of metamorphic zircon and overgrowths (black and dark red ellipses in gray region). Data ellipses are 2$\sigma$.

the Chukchi Borderland amphibolites, and feldspar is the stable aluminous phase. The zircon trace-element characteristics of the dredged amphibolite samples are consistent with Eu being preferentially partitioned in plagioclase in that they yield negative Eu anomalies (Fig. 9A; Supplemental Table A.2 [see footnote 1]). Most zircons recovered from the amphibolite samples appear to have crystallized as new metamorphic grains (see Corfu et al., 2003, for criteria). A few zircons exhibit CL zoning patterns, but these are age equivalent within error of the ages measured from light-colored rims. We thus regard the CL patterns as planar zoning established during metamorphic zircon growth (Figs. 6A–6C). Overall, we interpret the amphibolite U-Pb zircon results in terms of metamorphic recrystallization during a protracted period of deep crustal residence between ca. 508 and 486 Ma.
Garnet-Bearing Feldspathic Gneisses

The strong deformation fabric of the garnet-bearing feldspathic gneisses obscures the nature of their protolith. While their distribution of U-Pb zircon ages is consistent with that expected from detrital zircons from an immature sedimentary protolith, closer inspection of the CL images and zircon trace-element data suggests a more complicated history for these highly deformed rocks.

All of the oldest ages (1100–1700 Ma; Fig. 7C) in both samples (#5-020 and #5-019) are from analyses taken from oscillatory-zoned cores in subhedral grains with rounded terminations suggesting that these ages are inherited from an older protolith (Figs. 7A and 7B). The discordance of many of the Proterozoic U-Pb results (Fig. 7C) is attributed to metamorphic overprinting at ca. 500 Ma (see below).

In contrast, the ca. 600 Ma ages were obtained from analyses of either prismatic zircon grains or bright cores and suggest a genetic relationship. We interpret results from the prismatic zircon as recording the crystallization age of a plutonic protolith for the garnet-bearing feldspathic gneisses but acknowledge that the gneisses could have been derived from an immature sedimentary protolith. Weighted mean ^206Pb/238U zircon crystallization ages of 610 ± 24 Ma and 580 ± 20 Ma can be calculated for samples #5-020 and #5-019, respectively (red and blue ellipses in callout, Fig. 7D). Trace-element characteristics of zircon cores and from the prismatic zircons within both garnet-bearing feldspathic gneiss samples display a significant Eu anomaly and HREE enrichment typical of igneous zircon (Fig. 9B; Rubatto, 2002; Hoskin and Schaltegger, 2003; Yuanbao and Yongfei, 2004) (Supplemental Table A.2 [see footnote 1]).

Finally, all of the 480–545 Ma zircon ages are from either rounded patchy zoned grains or
Bedrock samples from submarine outcrops in the Chukchi Borderland

from obvious zircon overgrowth rims that we interpret as metamorphic zircon (gray region, Fig. 7D). These analyses show depletion of HREE, which is consistent with an interpretation of zircon crystallized in equilibrium with garnet (Fig. 9B; Supplemental Table A.2 [see footnote 1]). The trace-element pattern and ages of the metamorphic zircon overgrowths suggest that these rocks were probably later subjected to the same Cambro-Ordovician metamorphic event that affected the amphibolites collected in the same dredge discussed above.

Potassium Feldspar Augen-Orthogneisses

Zircons from the K-feldspar augen-orthogneiss samples yielded concordant U-Pb ages between ca. 420 and 465 Ma that may represent inheritance from earlier plutonic rocks within a long-lived and deep magmatic system (Fig. 8C). We interpret the mean ages of 432 ± 3.8 Ma and 430 ± 3.6 Ma as approximating the crystallization ages of the K-feldspar augen-orthogneiss samples. Zircons from the augen-orthogneiss samples contain cores that yield ages between ca. 860 and 980, 1100 and 1450, and 1650 and 1825 Ma that we interpret as inherited zircon from a sedimentary protolith (Fig. 8D). These inherited zircon cores have similar ages to the metasedimentary basement in Pearya and western Svalbard (see sections on Pearya Terrane and Western Terrane of Svalbard).

DISCUSSION

Basement samples dredged from the central Chukchi Borderland (dredge HLY0905-DS5) preserve a record of late Neoproterozoic–Silurian metamorphism and igneous activity that conflicts with previously advanced models that the Chukchi Borderland shared the tectonically quiescent late Neoproterozoic and early Paleozoic passive margin evolution of Arctic Canada (Grantz et al., 1998). Grantz et al.’s (1998) hypothesis was based upon sediment piston-core and box-core samples that were collected along the Northwind Ridge (red X, Fig. 1) of the Chukchi Borderland. There are several possible explanations to account for the discrepancy in geologic history inferred from samples recovered from the two separate locations of the Chukchi Borderland: (1) The unmetamorphosed sedimentary rocks described by Grantz et al. (1998) were deposited atop the basement rocks discovered in the present study, but faulting has caused exposure of different crustal levels across the Chukchi Borderland; (2) an undetected large displacement fault between the two collection sites has juxtaposed genetically unrelated materials; or (3) the Grantz et al. (1998) samples rep-

Figure 9. Normalized rare-earth element abundances relative to chondrite (Supplemental Table A.2 [see footnote 1]) for (A) amphibolite sample #5-009 and (B) garnet-bearing gneiss sample 5-019. Aqua data points were from analysis of older zircon cores, while black data points represent analyses of metamorphic zircon and overgrowths. (C) Zircon trace-element abundance pattern of K-feldspar augen-orthogneiss shows that the zircons with the youngest ages have an enrichment in light rare-earth elements (LREEs), which is typical of hydrothermal zircon growth (see text for discussion). HREE—heavy rare-earth element.
resent distally derived, ice-rafted debris that has no relationship to the Chukchi Borderland.

While it is not at present possible to conclusively select between these possibilities, there are some important considerations. First, the average slope at the collection sites of the Grantz et al. (1998) piston-core study (997–3720 m water depth) was only 7°–9°. Such gentle slopes are problematic in that they primarily yield IRD when dredged (Figs. 3B and 3C). Second, the samples described by Grantz et al. (1998) were unmetamorphosed. Although this paper only reports on a single dredge haul from the central Chukchi Borderland, four more ECS dredges were collected from the Chukchi Borderland, all of which yielded metamorphic rock from submarine outcrops (Mayer and Armstrong, 2008, 2012). For instance, one ESC dredge haul (cruise number HLY1202; Mayer and Armstrong, 2012) encountered bedrock exposures along a >40° cliff face at the base of the Northwind Ridge less than 35 km north of the sites reported on by Grantz et al. (1998). This HLY1202 dredge yielded ~300 kg of deformed and metamorphosed manganese-encrusted calcareous sandstones and phyllites (O’Brien et al., 2013). Third, the piston-core samples described by Grantz et al. (1998) contained many of the same lithologies that are present within IRD collected during our dredging operations (Fig. 3D). Finally, features such as manganese crusts were seldom described by Grantz et al. (1998) for the clasts that they studied. Based upon these observations, we speculate that the piston-core samples described by Grantz et al. (1998) consisted primarily of IRD. Consequently, correlation of the Chukchi Borderland to the unmetamorphosed Franklinian passive margin is unsupported by the piston-core sampling.

Below we discuss how the intrusive and metamorphic history of the central Chukchi Borderland basement bears a strong similarity to the history recorded by basement rocks present in the Pearya terrane of northern Ellesmere Island and the western terranes of Svalbard (Brumley et al., 2013) (Fig. 1). This is supported by a growing body of evidence suggesting that these terranes were all likely subjected to late Mesoproterozoic–Neoproterozoic deformation and anatexis possibly associated with the Grenville orogeny (e.g., Johansson et al., 2005) followed by Neoproterozoic–Cambrian deformation and tectonothermal activity (e.g., Peucat et al., 1989; Manbeck et al., 1998; Majka et al., 2008, 2012). Zircons from felsic dikes in southwestern Svalbard have yielded U-Pb ages of 1100–1700 Ma. Inherited zircon cores measured in the K-feldspar augen-orthogneiss are 880–980 and 1100–1825 Ma. The inherited zircon cores found in both of these dredged rock types are consistent with derivation from basement rocks similar to those of Pearya and western Svalbard (Fig. 10).

Proterozoic Basement

Both Pearya and the western terranes of Svalbard are thought to record a northern continuation of the Grenville orogen from Greenland into the Arctic region (Trettin, 1991; Johansson et al., 2005; Higgins and Leslie, 2008; Kalsbeek et al., 2008). Metasedimentary rocks of this age in East Greenland were deposited between ca. 1100 and 950 Ma and underwent high-grade metamorphism between ca. 950 and 890 Ma (Strachan et al., 1995). While the protolith ages of the metamorphic rocks are not well known in western Svalbard, they probably mainly consist of Neoproterozoic metasedimentary rocks and intercalated basalts (Gasser and Andreassen, 2013). Deformation, metamorphism, and crustal anatexis of these Proterozoic sediments occurred between 1160 and 930 Ma (Peucat et al., 1989; Johansson et al., 2005).

In the Pearya terrane, Proterozoic sedimentary and volcanic rocks were deformed, metamorphosed, and intruded by granitic plutons between ca. 1100 and 956 Ma (Trettin and Parrish, 1987). In the Chukchi Borderland dredge samples, zircon cores present within the garnet-bearing feldspathic gneisses are interpreted to be inherited from an older sedimentary and/or metasedimentary protolith and yield U-Pb ages of 1100–1700 Ma. Inherited zircon cores measured in the K-feldspar augen-orthogneisses are 880–980 and 1100–1825 Ma. The inherited zircon cores found in both of these dredged rock types are consistent with derivation from basement rocks similar to those of Pearya and western Svalbard (Fig. 10).

Cambro-Ordovician Metamorphic Event

The significance of the ca. 600 Ma U-Pb ages from the garnet-bearing feldspathic gneisses of the Chukchi Borderland is more difficult to interpret but do suggest another tie to western Svalbard, where Neoproterozoic tectonothermal activity has also been reported (Fig. 7; Peucat et al., 1989; Manbeck et al., 1998; Majka et al., 2008, 2012). Zircons from felsic dikes in southwestern Svalbard have yielded U-Pb ages of ca. 670–620 Ma that are speculated to be rift related (Peucat et al., 1989; Gromet and Gee, 1998). Pegmatites of western Svalbard (Majka et al., 2012) are also within error of zircon ages from the garnet-bearing feldspathic gneisses of the Chukchi Borderland. 40Ar/39Ar step heating of mineral separates yielded a 616 Ma age for hornblende from the Eimfjellt Group and 585–575 Ma ages for biotite and muscovite from the Isbjørnhamna Group, both from western Svalbard (Manbeck et al., 1998). An age of 643 ± 9 Ma was obtained for metamorphic monazite (Majka et al., 2008) providing direct evidence of Neoproterozoic metamorphism in western Svalbard. Majka et al. (2012) also studied zircons and monazite from a pegmatite in southwestern Svalbard, which were dated by U-Pb methods and found to be 651 ± 88 Ma and 675 ± 25 Ma, respectively. Ediacaran ages deduced from U-Pb data on zircons from western Svalbard high-grade rocks (Peucat et al., 1989) have been interpreted as a magmatic age and Cambrian ages (560–500 Ma) as the age of recrystallization near the eclogite facies (Dallmeyer et al., 1989). All of the Neoproterozoic ages from western Svalbard overlap in age with zircon crystallization ages in the dredged garnet-bearing feldspathic gneiss samples from the Chukchi Borderland (600–660 Ma), many of which also displayed Cambrian metamorphic overgrowths. This suggests that the Chukchi Borderland had a Neoproterozoic–Cambrian history similar to that of western Svalbard (Fig. 10). Late Neoproterozoic detrital zircons (630–650 Ma) are also present in Ordovician volcanic sandstone deposits within Pearya (Malone, 2012; Hadliari et al., 2013), which could indicate a connection to source rocks of that age in Svalbard and/or the Chukchi Borderland.

Metamorphic zircon crystallization that occurred between ca. 520 and 470 Ma in the dredged amphibolites and garnet-bearing gneisses of the Chukchi Borderland (Figs. 6 and 7) overlaps in age with tectonothermal events on both Pearya and Svalbard (Fig. 10; Trettin, 1987). On Pearya, Early Ordovician ultramafic rocks, arc-type metavolcanic rocks, and associated metasedimentary rocks of the M’Clintock orogeny are interpreted to represent amalgamation of an arc terrane that was accompanied by metamorphism between ca. 485 and 450 Ma (Trettin, 1987; Trettin et al., 1992; McClelland et al., 2012). In western Svalbard, 40Ar/39Ar cooling ages dating micas and whole-rock fractions from blueschists give a Middle Ordovician age (461–475 Ma) for the peak metamorphism, with exhumation dated by an unconformity of Ordovician age (Dallmeyer et al., 1989; Ohta, 1994). This unconformity defines the Eidehbremen tectonothermal event of Svalbard (Harland, 1997), which is coeval with the M’Clintock orogeny of Pearya. These ages overlap with analyses of metamorphic zircon from the dredged amphibolites and metamorphic zircon overgrowths from the garnet-bearing gneiss samples from the Chukchi Borderland (Fig. 10), and suggest a possible relationship to the M’Clintock and Eidehbremen tectonothermal events.
Bedrock samples from submarine outcrops in the Chukchi Borderland

Figure 10. Tectonostratigraphic comparisons between southwest Svalbard, Pearya, and the Chukchi Borderland: Generalized correlations of tectonic, metamorphic, and magmatic events in southwestern Svalbard, Pearya, and the Chukchi Borderland (modified from Gee and Teben’kov, 2004). Colored horizontal bars signify time span of regional tectonic events. Black boxes signify zircon analysis of metamorphic events, white ellipses are dated intrusive bodies, and the 476 Ma is age of crosscutting mafic intrusive body in southwest Svalbard. The far-right column shows probability density plots of zircon U-Pb analysis from this study with ages that correspond to events in SW Svalbard events, white ellipses are dated intrusive bodies, and the 476 Ma is age of crosscutting mafic intrusive body in southwest Svalbard. The far-right column shows probability density plots of zircon U-Pb analysis from this study with ages that correspond to events in SW Svalbard.

Ordovician-Silurian Arc Magmatism

The dredged K-feldspar augen-orthogneisses from the Chukchi Borderland provide further links to Pearya. Isotopically, the Chukchi Borderland orthogneisses are I-type granitoids and have much lower ⁸⁷Sr/⁸⁶Sr ratios than S-type granitoids (0.720–0.740) typical of collisional settings (Fig. 5B; Pearce, 1983; Rogers and Greenberg, 1990; Chappell and White, 2001; Johansson et al., 2005). The existence of I-type plutons in the basement of the Chukchi Borderland demonstrates that arc magmatism was active in this region during Silurian time. The broad U-Pb age range of concordant zircon exhibited by the orthogneiss samples can be explained by inheritance from wall rocks of a long-lived (Late Ordovician–Silurian) magmatic system (ca. 430–465 Ma). I-type granitic plutons that overlap this age range are present on Pearya (ca. 462–481 Ma; Trettin, 1987). Detrital zircon studies indicate that a magmatic arc continued to be a sediment source in Pearya during Silurian time (Hadlari et al., 2013). Thus the Chukchi Borderland and Pearya both record evidence of Ordovician and Silurian calc-alkaline magmatism. Farther south, younger (ca. 430–410 Ma) S-type granites intruded the Caledonian orogen within East Greenland, Norway, and eastern Svalbard (white dots, Fig. 11). Ordovician-age I-type granitoids (ca. 466 Ma yellow dots, Fig. 11) reappear below latitude 72°N in southeastern Greenland (Kalsbeek et al., 2001; Higgins and Leslie, 2008). We correlate the Late Ordovician I-type granitoids of southeastern Greenland with the Late Ordovician–Silurian I-types of Pearya and the Chukchi Borderland and conclude that Late Ordovician–Silurian arc terranes extended north of the
main Caledonian orogen prior to and during the collision of Baltica and Greenland (see Gee and Teben’kov, 2004; Labrousse et al., 2008; McClelland et al., 2012).

Ellesmerian Deformation

All basement rocks dredged from the Chukchi Borderland were variably mylonitized and underwent lower amphibolite-facies metamorphism subsequent to the ca. 430 Ma crystallization ages of the orthogneisses. Large offset strike-slip faults are thought to have translated Pearya and southwestern Svalbard away from the Caledonian collision zone to eventually be amalgamated to the northern margin of Laurentia during Silurian time (Trettin, 1987; Mazur et al., 2009; McClelland et al., 2012). Pearya was accreted to the northern margin of Laurentia in Late Silurian to Early Devonian time (Trettin, 1987; Harland, 1997; McClelland et al., 2012). While some models have suggested that Pearya was previously exotic to Laurentia (Churkin and Trexler, 1980; Trettin, 1987), other reconstructions have preferred a peri-cratonic origin for Pearya (Hadlari et al., 2013 and references therein). Following accretion of Pearya and western Svalbard to northern Laurentia, accounts of contractional deformation in the Yukon (e.g., Lane 2007), the Canadian Arctic (e.g., Piepjohn et al., 2008), north Greenland (e.g., Soper and Higgins, 1990), and Svalbard (e.g., Piepjohn, 2000) have been attributed to the Ellesmerian orogeny. The deformation in this region is thought to have been caused by collision with an unknown northern landmass that has since been rifted away due to the opening of the Amerasia Basin (Embry, 1993). The deformation that produced the mylonitic fabrics in the basement rocks of the Chukchi Borderland may have been related to this younger Ellesmerian orogenic event that postdated the arc-related plutonism in both Pearya and the Chukchi Borderland.

CONCLUSIONS

1. The first dredged samples from the Chukchi Borderland were collected during the U.S. Extended Continental Shelf project aboard the icebreaker USCGC Healy (cruise number HLY0905) and offer clear evidence that the borderland is underlain by continental crust. This is important for establishing natural prolongation of the landmass for Extended Continental Shelf claims of Arctic states. Rock samples dredged from the central Chukchi Borderland site include biotite amphibolites, garnet-bearing feldspathic gneisses, and K-feldspar augen-orthogneisses.

2. Amphibolites and associated leucocratic lenses contain only metamorphic zircon, based on their rounded morphology and patchy or chaotic zonation seen in CL images. Zircon U-Pb ages of the metamorphic zircon yield mean $^{206}\text{Pb}/^{238}\text{U}$ ages of 508 ± 5 Ma and 486 ± 20 Ma. A leucogranitic seam extracted from the latter amphibolite yielded an indistinguishable mean U-Pb zircon age of 489 ± 15 Ma. This metamorphic event correlates with the coeval M’Clintock orogeny of Pearya and Eidembreen tectonothermal event of western Svalbard and suggests a genetic relationship of the Chukchi Borderland to these terranes.

3. Two garnet-bearing feldspathic gneisses contain zircon populations of 474–545 Ma, ca. 560–650 Ma, and 1100–1750 Ma. Examination of zircon morphology, internal structure, and trace-element abundances, as well as the abundant large feldspars present, suggest that the protoliths of the two gneisses analyzed were intermediate plutonic rocks that crystallized at 610 ± 24 Ma and 580 ± 20 Ma, respectively. An immature sedimentary origin for the proto-
lith of the gneisses, however, cannot be ruled out. The inherited U-Pb ages from zircon cores that range from 1100 to 1750 Ma suggest an affinity with the late Mesoproterozoic to early Neoproterozoic basement rocks of the Pearya terrane of northern Ellesmere Island and the western terranes of Svalbard. U-Pb age analyses of metamorphic zircon and overgrowths (ca. 486–525 Ma) indicate that the gneisses were involved in the same Cambro-Ordovician metamorphic event as the one that affected the amphibolites from the same dredge.

4. The two K-feldspar augen-orthogneisses sampled yield weighted mean zircon $^{206}\text{Pb} / ^{238}\text{U}$ crystallization ages of 432 ± 3.8 and 430 ± 3.6 Ma. Based on their geochemistry, they are interpreted as subduction-related (I-type) intrusions.

5. Most tectonic reconstructions of the Amerasia Basin return Chukchi Borderland to a pre-rift position proximal to the northwestern edge of the Canadian Arctic Islands (see Lawver and Scotese, 1990; Embry, 1998; Grantz et al., 1998). We alternatively propose that the Chukchi Borderland was part of an active peri-Laurer- iant arc terrane(s) that included Pearya and southwest Svalbard that lay outboard of the Franklinian passive margin. If correct, Cretaceous tectonic reconstruction models of the Amerasia Basin should position the pre-rift location of Chukchi Borderland much closer to the Lomonosov Ridge and the Pearya terrane of northern Ellesmere Island (Fig. 11).

ACKNOWLEDGMENTS

The authors would like to thank the United States Geological Survey, Stanford University, and BP for their generous support of this project. The work was also partly supported by NSF Grant No. EAR 0948673. We would like to say thank you to the crew of the USCGC Healy who provided help and support throughout dredging operations, and to Dale Chayes for his diving expertise. Special thanks to Max Lloyd for his detailed descriptions of the dredged ice rafted debris. We would also like to thank the anonymous reviewers for their constructive suggestions that greatly improved the manuscript. Portions of this study have been presented at the American Geophysical Union annual meeting on 5–9 December 2011 and 9–13 December 2013.

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