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# *Paleozoic evolution of the northern Laurentian margin: Evaluating links between the Caledonian, Ellesmerian, and Cordilleran orogens*

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## ABSTRACT

**The passive margins of Laurentia that formed during Neoproterozoic–Cambrian breakup of the supercontinent Rodinia record subsequent histories of contraction and translation. This contribution focuses on the northern margin of Laurentia, where recent geologic and geochronologic data have provided new insight into the evolution of northern North America. The Laurentian margin in East and North-East Greenland records synorogenic sedimentation and deformation associated with the Caledonian orogeny—the Silurian to Devonian continent-continent collision between Baltica and Laurentia that followed closure of the northern tract of the Iapetus Ocean. The timing of ultrahigh-pressure metamorphism and simultaneous sinistral and dextral strike-slip faulting in North-East Greenland indicates that the Himalayan-style orogen persisted through the Devonian. In contrast, the Franklinian margin further west records sinistral strike-slip translation of allochthonous crustal blocks and arc fragments starting in the Ordovician–Silurian and culminating with the Devonian–Carboniferous Ellesmerian orogeny, the origin of which remains enigmatic. We suggest that Ellesmerian deformation was related to widespread transpression associated with northward motion of Laurentia during Acadian and Neo-Acadian deformation along the Appalachian margin rather than orthogonal ocean basin closure and microcontinent-continent collision. The Pearya terrane and North Slope subterrane of the Arctic Alaska terrane, separated from the Franklinian passive margin by the Petersen Bay fault and Porcupine shear zone, respectively, best preserve the Paleozoic**

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**translational and transpressional history of the northern Laurentian margin. These two major structures record a complex history of terrane accretion and translation that defines the Canadian Arctic transform system, which truncated the Caledonian suture to the east and ultimately propagated early Paleozoic subduction to the Cordilleran margin of western Laurentia.**

## INTRODUCTION

The northern margin of Laurentia (Fig. 1) is broadly similar to the eastern and western continental margins in that they all represent rifted passive margins that subsequently experienced a long history of terrane accretion and translation. Northeastern Laurentia preserves a record of the Caledonian orogeny—the Cambrian to Devonian closure of the Iapetus Ocean between Laurentia and Baltica (McKerrow et al., 2000). Passive-margin sedimentation on the northwestern margin of Laurentia was disturbed in the Late Devonian by subduction initiation that ultimately led to terrane translation and accretion along the length of the Cordilleran orogen (Nelson et al., 2013). The history of terrane accretion on the northern Laurentian margin is preserved by the Pearya terrane outboard of the Franklinian passive margin on northern Ellesmere Island and the North Slope subterrane of Arctic Alaska. Elsewhere, Neoproterozoic–early Paleozoic units of the passive margin are buried beneath Carboniferous and younger sedimentary rocks (e.g., Sverdrup Basin) but are inferred to be truncated at their northernmost extent by steep structures with a poorly understood history (e.g., McClelland et al., 2021). The end of passive-margin deposition on Ellesmere Island and North Greenland appears to have resulted from Ordovician–Silurian deformation (Trettin, 1987; Soper and Higgins, 1991). Sedimentation on the Franklinian margin was terminated by the Ellesmerian orogeny, which is represented by Devonian–Carboniferous deformation (e.g., Lane, 2007; Piepjohn et al., 2013) and Middle–Late Devonian foreland basin sedimentation (Thorsteinsson and Tozer, 1970; Embry, 1988) that profoundly impacted the composition of younger sediments across much of North America (Patchett et al., 1999). The nature and timing of the transition from a passive to active margin along northern Laurentia that might link orogenic activity on the northeastern and western margins remain poorly known. New geochronologic data and observations summarized herein improve our understanding of the tectonic evolution of northern Laurentia.

The Northwest Passage model of Colpron and Nelson (2009) predicts that large-scale translation of terranes occurred along the Canadian Arctic margin in the Paleozoic. This translation was accommodated by a set of faults collectively referred to as the Canadian Arctic transform system (McClelland et al., 2021). Some of the displaced fragments have basement signatures consistent with a Laurentian origin (e.g., Pearya terrane and North Slope subterrane of Arctic Alaska) and are best modeled either

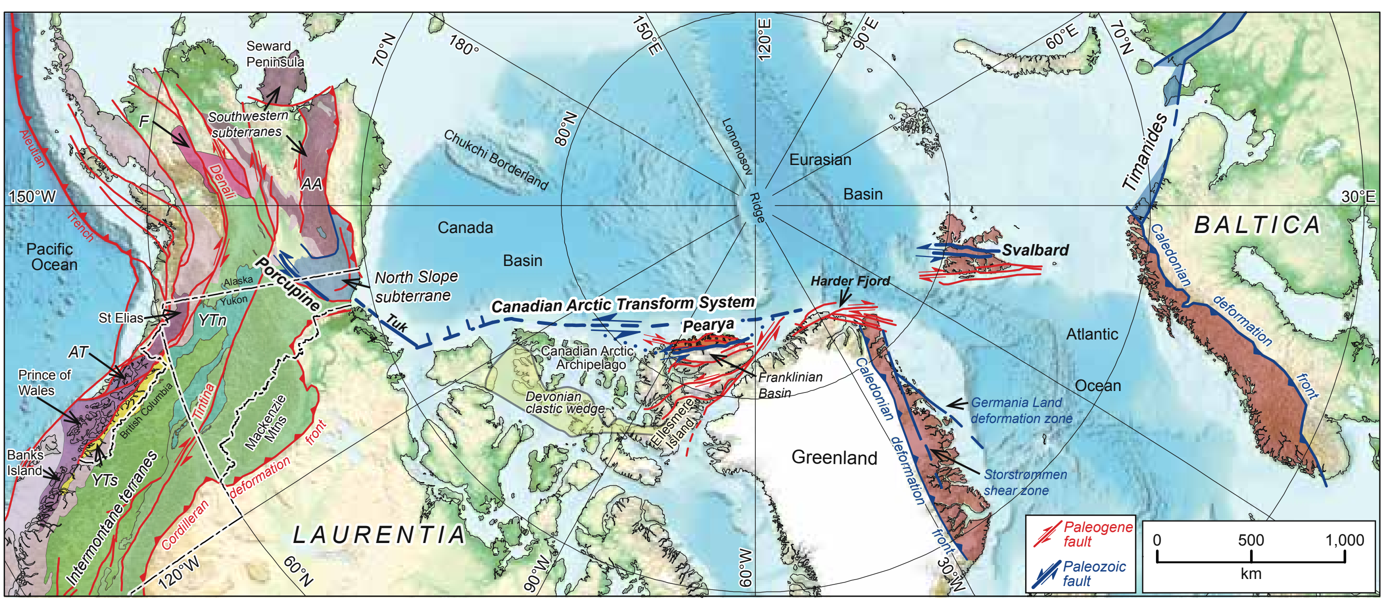


Figure 1. Generalized tectonic map of northern Laurentia showing the terrane distribution on the Arctic and Cordilleran margins of Laurentia and Paleozoic orogenic belts in the circum-Arctic region. AA—Arctic Alaska terrane; AT—Alexander terrane; F—Farewell terrane; YTn and YTs—northern and southern components of the Yukon-Tanana terrane.

as rifted blocks displaced and stranded from the margin (Malone et al., 2017; Strauss et al., 2019a, 2019b) or as continuous extensions of Laurentian crust (Hadlari et al., 2014; Lane et al., 2016). Others clearly have non-Laurentian origins that include connections to Neoproterozoic subduction along the Baltica margin (e.g., Alexander terrane and southwestern subterranes of Arctic Alaska; Miller et al., 2011; Beranek et al., 2013b) or intra-Iapetus arc magmatism (e.g., Doonerak arc of the Arctic Alaska terrane; Strauss et al., 2017). Here, we review the geology and currently available U/Pb and Hf detrital zircon data from portions of the northern Laurentian margin and the terranes thought to have migrated across this margin. Considerable variation in geochronologic and isotopic signatures from the Laurentian passive-margin sequences and various terranes helps to define permissible paleogeographic models for the tectonic evolution of the margin.

## PALEOZOIC EVOLUTION OF THE LAURENTIAN MARGIN IN GREENLAND

The Greenland and Scandinavian Caledonides (Fig. 1) expose the deeper crustal levels of a long-lived collisional orogen in which Laurentia (Greenland) was the overriding plate above the subducted margin of Baltica (Gee et al., 2008, and references therein). The Greenland Caledonides are a west-verging, fold-and-thrust belt composed of thin-skinned, low-angle thrusts to the west and steeper thick-skinned structures to the east (Higgins and Leslie, 2008). The structural and metamorphic characteristics of the orogen vary north and south of 76°N (Gilotti et al., 2008). To the south, the foreland is structurally overlain by a thrust sheet of Laurentian crystalline basement exhumed from lower crustal levels, a middle thrust sheet of midcrustal-level migmatitic gneisses, schists, and peraluminous granites, and an uppermost sheet of low-grade Neoproterozoic to Ordovician sedimentary rocks (Fig. 2). The thrust system was significantly modified by syn- to postorogenic extensional detachments that controlled the overall low-grade on high-grade architecture of the southern region (Gilotti and McClelland, 2008). Middle Devonian hinterland basins formed at higher structural levels within a syncollisional sinistral strike-slip system (Larsen et al., 2008, and references therein). Late Proterozoic clastic units of East Greenland have a detrital zircon U/Pb signature characterized by dominant Paleoproterozoic to Mesoproterozoic (1735–1080 Ma) and lesser Archean (2750 Ma) peaks (Fig. 3) that has been used to correlate stratigraphic units across the North Atlantic region (e.g., Olierook et al., 2020). The detrital signature of Devonian and Carboniferous units in East Greenland contains the same late Proterozoic signal, along with 435–410 Ma zircon derived from granites within the thrust sheets (Fig. 3; Kalsbeek et al., 2008a).

The thin-skinned thrust belt is discontinuously exposed north of 76°N from Dronning Louise Land to Kronprins Christian Land (Fig. 2). Deformation in Kronprins Christian Land resulted in west-directed emplacement of Mesoproterozoic sedimentary rocks (Kalsbeek et al., 1999) over Neoproterozoic to Ordovician shelf strata and Silurian synorogenic clastic rocks that are inferred to overlie Laurentian basement (Leslie and Higgins, 2008). Proterozoic clastic units in the foreland thrust sheets have major Paleoproterozoic U/Pb detrital zircon peaks (1950–1785 Ma) that are distinct from the detrital signature in East Greenland (Fig. 3) but similar to autochthonous units in North Greenland. They also reflect the dominant age of Paleoproterozoic crystalline basement in structurally higher thrust sheets to the east. Paleozoic rocks in the foreland fold-and-thrust belt in Kronprins Christian Land mark the westernmost extent of Caledonian deformation. The actual timing of thrusting in the foreland is poorly known, but the influx of Silurian synorogenic sediment onto the carbonate platform and its involvement in the thrust belt, with truncation of strata as young as Wenlockian, are cited as evidence for the onset of the collision between Baltica and Laurentia (Hurst et al., 1983; Rasmussen and Smith, 2001).

The thick-skinned thrust belt north of 76°N involves a heterogeneous suite of mafic and tonalitic to granodioritic orthogneiss derived from ca. 2000–1800 Ma calc-alkaline intrusive complexes that represent a juvenile arc and ca. 1750 Ma metagranitoids (Kalsbeek et al., 2008b; Gilotti and McClelland, 2011; Hallett et al., 2014). A large portion of the Paleoproterozoic gneiss experienced metamorphism at high-pressure (HP) and locally ultrahigh-pressure (UHP) conditions, forming the North-East Greenland eclogite province (Gilotti, 1993; Gilotti et al., 2008). Widespread HP metamorphism occurred from ca. 425 to 395 Ma (Gilotti et al., 2004; McClelland et al., 2016). The age of UHP metamorphism in the easternmost hinterland ranges from ca. 365 to 350 Ma (McClelland et al., 2006; Gilotti et al., 2014). The eclogite-bearing orthogneiss lies structurally above Mesoproterozoic metasedimentary rocks in the Nørreland window (Fig. 2); therefore, thrusting must have postdated the widespread eclogite-facies metamorphism at ca. 415–395 Ma and is significantly younger than the timing inferred from the Silurian synorogenic strata in Kronprins Christian Land (Gilotti et al., 2004). Eclogites have been documented as far north as Holm Land (McClelland et al., 2016), where the basement rocks are juxtaposed with Mesoproterozoic sedimentary rocks along a steep extensional fault.

The Greenland Caledonides are transected by an array of conjugate sinistral and dextral strike-slip faults. The sinistral Western fault zone south of 76°N is closely linked with Devonian basin development at structurally high levels of the East Greenland extensional province (Larsen and Bengaard, 1991). Strike-slip faults active at deeper structural levels north of 76°N include the sinistral transpressional Storstrømmen shear zone (Holdsworth and Strachan, 1991; Strachan et al., 1992; Hallett et al., 2014) and dextral Germania Land deformation zone (Hull and Gilotti, 1994; Sartini-Rideout et al., 2006). The available age constraints suggest that ductile displacement on these two faults was synchronous and active between ca. 370 and 340 Ma (Sartini-Rideout et al., 2006; Hallett et al., 2014). These Devonian–Mississippian conjugate strike-slip faults are interpreted through comparison to the modern Himalayan orogen as crustal-scale structures associated with intracratonic subduction resulting in

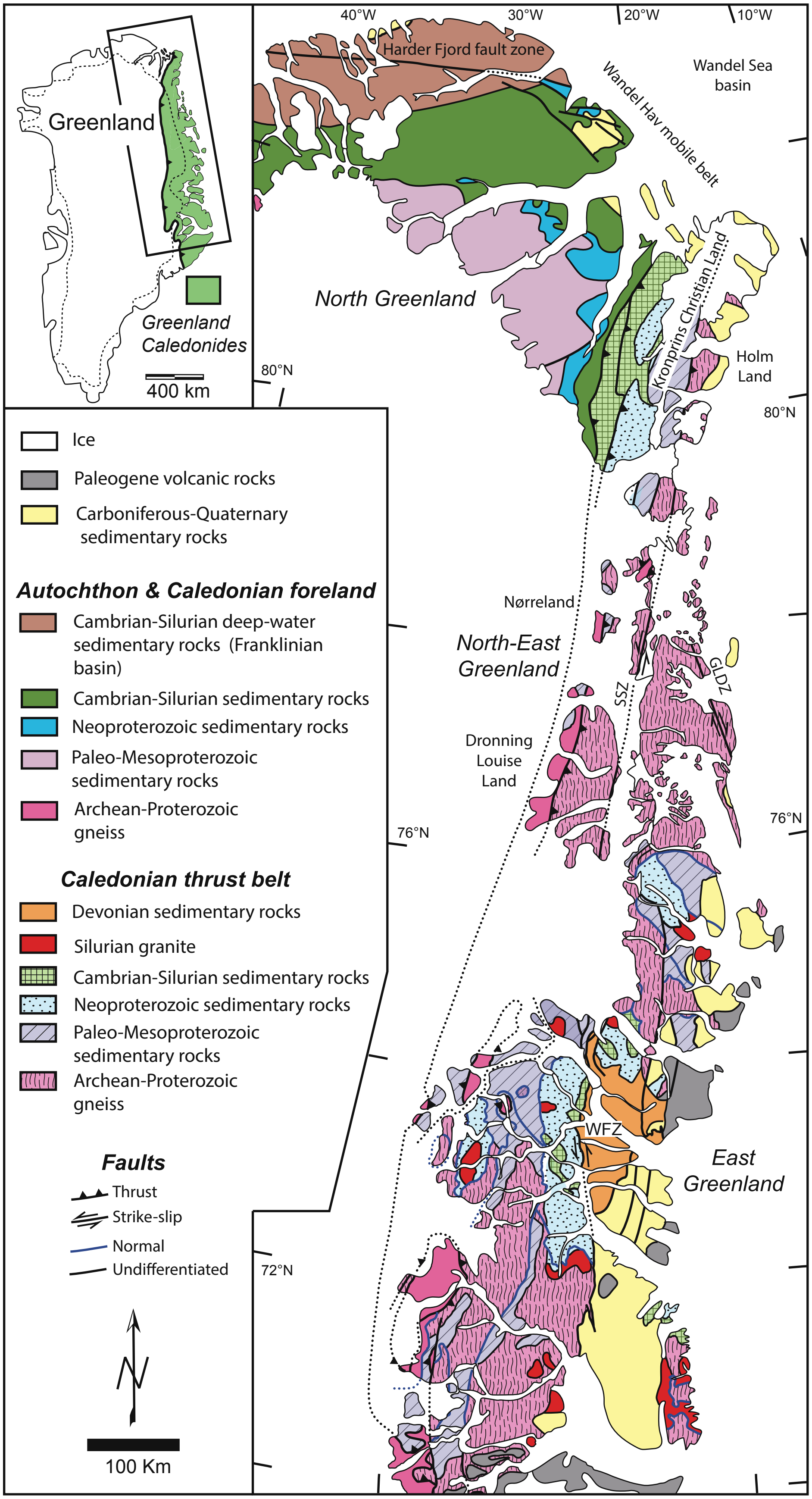


Figure 2. Simplified geologic map of East, North-East, and North Greenland, modified after Henriksen (2003), Gilotti and McClelland (2008), and Ineson and Peel (2011). WFZ—Western fault zone; SSZ—Storstrømmen shear zone; GLDZ—Germania Land deformation zone.

the formation and exhumation of the UHP terrane, as well as lateral escape of material northward (present coordinates) during the latest stage of the Caledonian collision between Laurentia and Baltica (Gilotti and McClelland, 2007, 2011).

Caledonian structures in North-East Greenland are overlain by Carboniferous strata of the Wandel Sea basin (Stemmerik and Worsley, 2005). Upper Viséan (ca. 340–330 Ma) nonmarine clastic units unconformably overlie HP crystalline rocks in Holm Land. Detrital zircon U/Pb age spectra from these strata record the progressive unroofing of the North-East Greenland Caledonides, with major peaks at ca. 1970, 1900, and 1750 Ma that reflect the signature of the basement units and Proterozoic to Cambrian clastic rocks in the foreland (Fig. 3; McClelland et al., 2016). Overlying Moscovian carbonates mark a transition to widespread shelf development in North Greenland, as well as throughout the Norwegian Barents Sea and Svalbard along the northern Pangean margin (Stemmerik, 2000; Stemmerik and Worsley, 2005).

Carboniferous strata north of Holm Land are overprinted by the Wandel Hav mobile belt—a series of northwest-striking late Carboniferous–Mesozoic structures that obscure the transition from the north-south–striking Caledonian structures to the east-west–striking Late Devonian–Carboniferous Ellesmerian structures of North Greenland (Stemmerik et al., 1998; von Gosen and Piepjohn, 2003). Structures of the Wandel Hav mobile belt mark the northern extent of autochthonous Laurentian basement and allochthonous Paleoproterozoic gneisses of the North-East Greenland eclogite province (Henriksen, 2003), suggesting that Carboniferous extensional structures were localized at the northern margin of the Greenland Caledonides (Døssing et al., 2010).

## PALEOZOIC TERRANES ON THE NORTHERN LAURENTIAN MARGIN

Sinistral strike-slip translation of allochthonous crustal blocks and arc fragments along the northern Laurentian margin initiated in the Ordovician–Silurian and culminated with the Devonian–Carboniferous Ellesmerian orogeny. These fragments include, from east to west, the terranes of Svalbard, the Pearya terrane on northern Ellesmere Island, and the Arctic Alaska terrane in Yukon and Alaska (Fig. 1).

### Svalbard

Pre-Devonian rocks of Svalbard have long been divided into three basement provinces, the Eastern, Northwestern, and Southwestern provinces (Fig. 4), based broadly on age and lithology (e.g., Harland, 1997; Gee and Teben'kov, 2004; Dallmann and Elvevold, 2015). Eastern Svalbard is further subdivided into the West Ny-Friesland and Nordaustlandet terranes (Gee et al., 1995). The West Ny-Friesland terrane is dominated by Archean to Mesoproterozoic granitic orthogneiss and metaclastic rocks with minor mafic intrusions (Hellman et al., 1997, 2001; Witt-Nilsson et al., 1998; Bazarnik et al., 2019). These crystalline basement rocks have an uncertain structural history with respect to the Nordaustlandet terrane, as well as the remainder of Svalbard (cf. Lyberis and Manby, 1999; Gee et al., 1994). Recent U/Pb dating suggests that the West Ny-Friesland terrane is distinct from the Nordaustlandet terrane and perhaps correlative with deformed foreland units in North-East and North Greenland (Bazarnik et al., 2019).

The Nordaustlandet terrane includes Mesoproterozoic–Tonian metaclastic and metavolcanic rocks intruded by Tonian orthogneiss, a Tonian–early Paleozoic siliciclastic and carbonate sequence inferred to depositionally overlie the older basement (Sandelin et al., 2001), and Silurian intrusions and migmatite complexes (Gee et al., 1995; Tebenkov et al., 2002; Johansson et al., 2004, 2005; McClelland et al., 2019). The Tonian granites and calc-alkaline volcanic rocks are cited as evidence for inclusion of the Nordaustlandet terrane in the Valhalla orogen, a convergent margin that developed along the periphery of Rodinia (Cawood et al., 2010). In contrast, Lorenz et al. (2012) included the Nordaustlandet terrane in the Grenville orogen based on unpublished detrital zircon data from metasedimentary rocks intruded by Tonian granites. Tillites in units above the Tonian succession have been used to correlate the Nordaustlandet terrane with East Greenland (Harland, 1997; Hoffman et al., 2012; Halverson et al., 2018). This correlation, along with the presence of similar early Paleozoic faunas (e.g., Fortey and Bruton, 1973; Fortey and Barnes, 1977; Lehnert et al., 2013), supports a Laurentian affinity for this portion of the Eastern province, although the primary relationships between the Nordaustlandet and East Greenland basement assemblages remain unclear (McClelland et al., 2019).

The Northwestern province includes Mesoproterozoic–Neoproterozoic metaclastic and marble units intruded by Tonian and Silurian granitoids (Dallmann et al., 2002; Gee and Teben'kov, 2004; Pettersson et al., 2009). The metaclastic rocks have major detrital zircon U/Pb peaks at ca. 1700–1600 Ma and a broad array of minor peaks between ca. 1800 and 1000 Ma that are interpreted to indicate a Laurentian origin (Fig. 4; Pettersson et al., 2009); however, the internal stratigraphy and affinities of these rocks are still poorly understood. Mafic rocks associated with Tonian orthogneiss in the Richarddalen complex record Ordovician HP metamorphism (Gromet and Gee, 1998; Labrousse et al., 2008; Elvevold et al., 2014).

The Southwestern province includes several terranes (Wala et al., 2021) consisting of Mesoproterozoic and Neoproterozoic meta-igneous and metasedimentary rocks that locally experienced ca. 640 Ma amphibolite-facies metamorphism and deformation (Majka et al., 2014), as well as Ordovician blueschist- to eclogite-facies metamorphism (Kośmińska et al., 2014; Barnes et al., 2020). Discontinuously exposed Cambrian–Silurian clastic and carbonate rocks presumably overlie the older units with depositional contacts, but many of the boundaries are structural and therefore ambiguous (e.g., Mazur et al., 2009; Wala et al., 2021). Detrital zircon signatures from the Southwestern province suggest affinities with either Laurentia or Baltica (e.g., Gasser and Andresen, 2013; Ziemniak et al., 2019; Olierook et al., 2020; Wala et al., 2021), indicating a composite origin for the basement province (Wala et al., 2021).

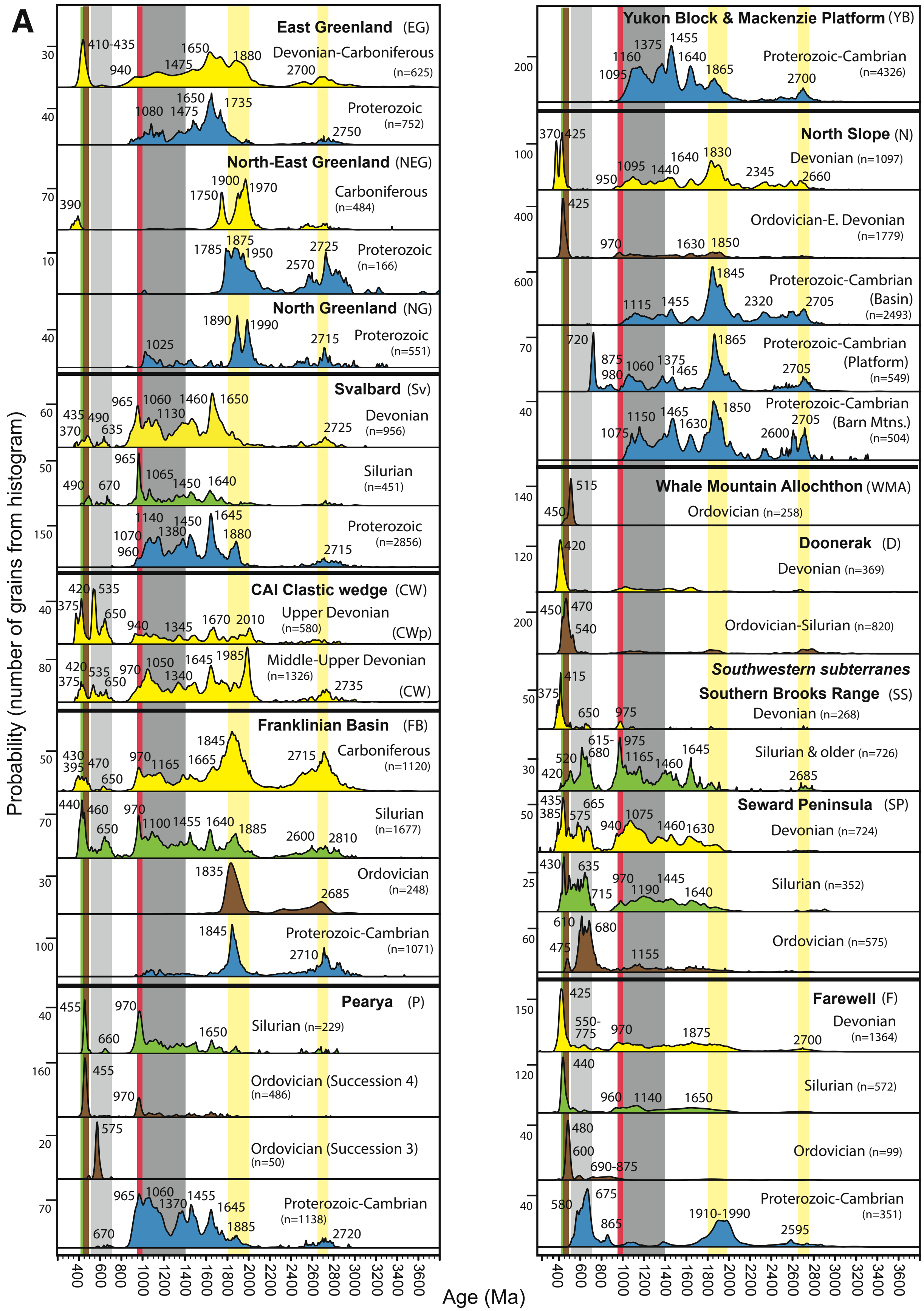


Figure 3. (*Continued on facing page.*)

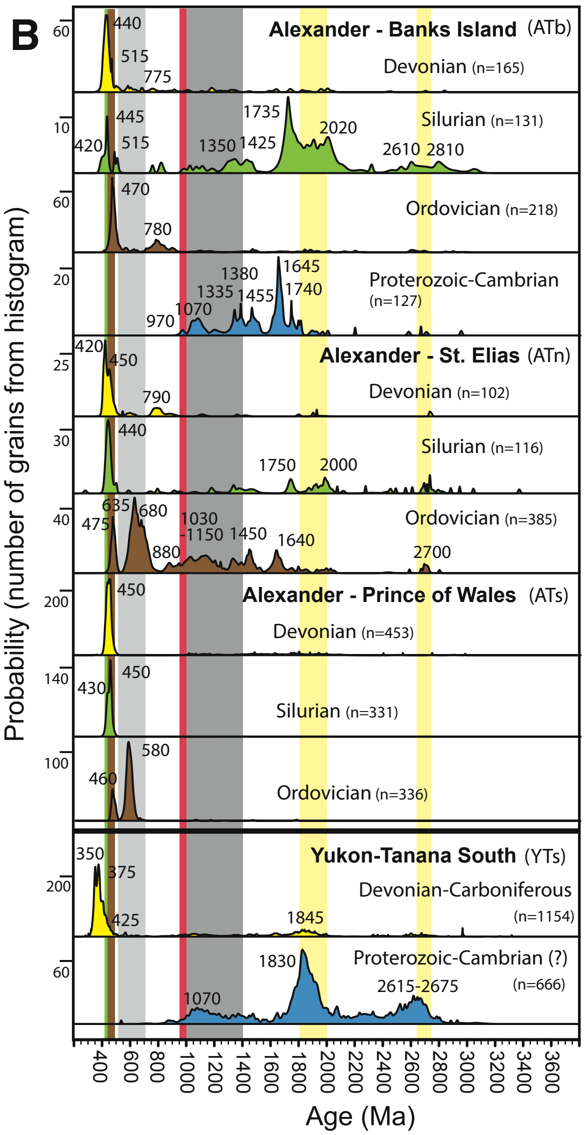


Figure 3 (*Continued*). Probability density plots (Ludwig, 2008) of U/Pb detrital zircon data from northern Laurentia and other selected areas, including East Greenland (Strachan et al., 1995; Watt et al., 2000; Knudsen et al., 2001; Leslie and Nutman, 2003; Dhuime et al., 2007; Slama et al., 2011; Olierook et al., 2020), North-East Greenland (Kalsbeek et al., 1999; Cawood et al., 2007; McClelland et al., 2016), North Greenland (Kirkland et al., 2009), Svalbard (Pettersson et al., 2009, 2010; Gasser and Andresen, 2013; Ziemniak et al., 2019; Beranek et al., 2020; Wala et al., 2021), Franklinian basin and Clements Markham belt (Beranek et al., 2013a, 2015; Anfinson et al., 2012b; Hadlari et al., 2014; Beauchamp et al., 2019; Dewing et al., 2019; Malone et al., 2019), the Devonian clastic wedge on the Canadian Arctic Archipelao (CAI; McNicoll et al., 1995; Anfinson et al., 2012a, 2012b), the Pearya terrane (Malone et al., 2014, 2019; Hadlari et al., 2014; Estrada et al., 2018b), the Yukon block and Mackenzie platform (Gibson et al., 2021, and references therein), the Arctic Alaska terrane including the North Slope subterrane (Macdonald et al., 2009; Strauss et al., 2013, 2019a, 2019b; Cox et al., 2015; McClelland et al., 2015; Johnson et al., 2016, 2019; Lane et al., 2016; Colpron et al., 2019), the Whale Mountain allochthon (Johnson et al., 2016, 2019; Strauss et al., 2019b), the Doonerak arc and related units (Strauss et al., 2013; Robinson et al., 2019), the southwestern subterranes including the southern Brooks Range (Strauss et al., 2017; Hoiland et al., 2018; Robinson et al., 2019) and Seward Peninsula (Amato et al., 2009; Till et al., 2014; Dumoulin et al., 2018b), the Farewell terrane (Bradley et al., 2014; Malkowski and Hampton, 2014; Dumoulin et al., 2018a, 2018b), the Alexander terrane (Beranek et al., 2013b, 2013c; Tochilin et al., 2014; White et al., 2016), and the Yukon-Tanana terrane in southeastern Alaska (Pecha et al., 2016). Colored bars highlight Silurian (444–419 Ma; green); Ordovician (485–444 Ma; brown); Ediacaran–Cryogenian (700–550 Ma; light gray); Tonian (1000–950 Ma; red); Mesoproterozoic (1400–1000 Ma; dark gray); and Paleoproterozoic and Archean (2000–1800 Ma and 2750–2650 Ma; yellow) detrital zircon populations.

The terranes of Svalbard record a complex history of Ordovician–Silurian and Silurian–Devonian deformation and metamorphism that have been labeled Caledonian and Ellesmerian, respectively, based on similarities in timing with the adjacent Caledonian and Ellesmerian orogens, sensu stricto. Ordovician HP metamorphism at numerous localities in the Northwestern and Southwestern provinces (e.g., Labrousse et al., 2008; Elvevold et al., 2014; Kośmińska et al., 2014; Barnes et al., 2020) is similar to that observed in some of the thrust sheets of Scandinavia (Brueckner and van Roermund, 2007) and thus is best interpreted to record protracted closure of the northern Iapetus Ocean leading up to the Caledonian collision of Baltica and Laurentia sensu stricto. Widespread Silurian deformation and metamorphism were accompanied by emplacement of undeformed ca. 440–410 Ma granites in the Eastern and Northwestern provinces (McClelland et al., 2019, and references therein) and strike-slip displacement on major shear zones at ca. 420–410 Ma (Gee and Page, 1994; Manecki et al., 1998; Mazur et al., 2009; Majka et al., 2015; Faehnrich et al., 2020). Strike-slip displacement resulted in late Silurian–Devonian juxtaposition of the Svalbard terranes, development of transtensional basins, and formation of orogen-parallel extensional complexes (Harland, 1997; Gee and Teben'kov, 2004; Braathen et al., 2018; Dallmann and Piepjohn, 2020), all of which are ascribed to the Caledonian orogen sensu stricto. Shortening of these Devonian clastic-dominated basins, locally referred to as Svalbardian deformation (vs. Ellesmerian; Dallmann and Piepjohn, 2020, and references therein), and crustal thickening at ca. 370–350 Ma (Kośmińska et al., 2020) likely represent a phase of Late Devonian–Mississippian sinistral transpression.

Late Silurian to Early Devonian synorogenic strata largely record detrital input from the surrounding basement units (Fig. 3;

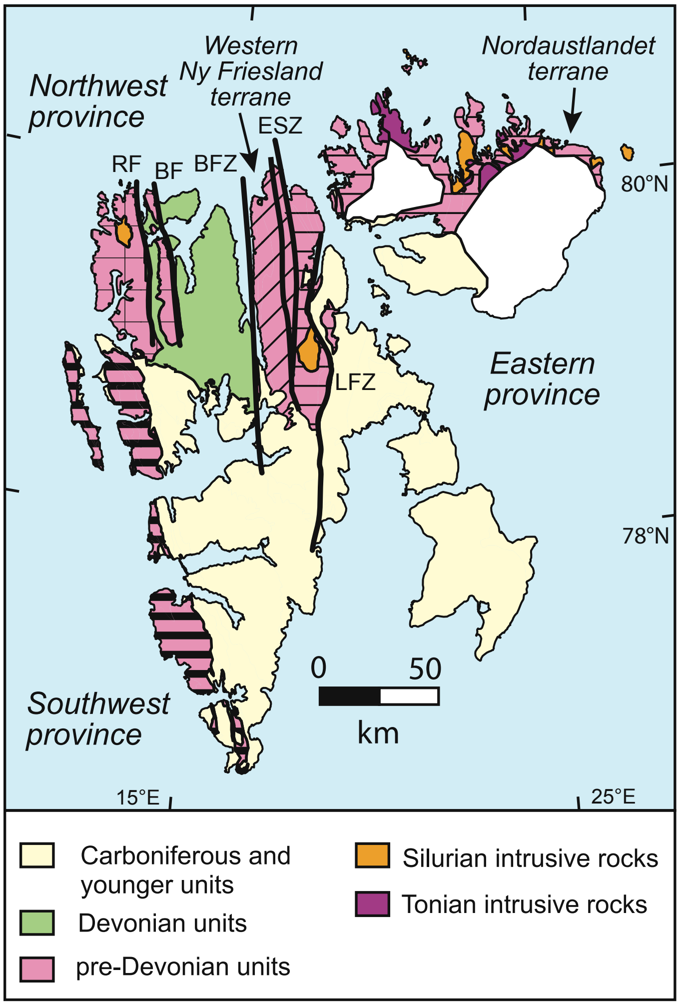


Figure 4. Simplified geologic map of Svalbard, Norway, showing the distribution of the major basement provinces (distinguished by pattern) and locations of major fault zones. Figure is modified from Dallmann and Elvevold (2015) and von Gosen et al. (2012). BF—Breibogen-Bockfjorden fault; BFZ—Billefjorden fault zone; ESZ—Eolussletta shear zone; LFZ—Lomfjorden fault zone; RF—Raudfjorden fault.

Beranek et al., 2020). For example, late Silurian strata are dominated by a ca. 965 Ma U/Pb age peak, reflecting sources from exhumed Tonian magmatic rocks, as well as lesser Mesoproterozoic peaks and small but significant peaks at ca. 670 and 490 Ma. This same detrital zircon signature persists into Devonian units, with the addition of input from Silurian granites. The ca. 965 Ma detrital zircon signature in clastic rocks of Svalbard is lacking in North-East and North Greenland (Fig. 3), suggesting that Svalbard terranes did not originate immediately adjacent to the Greenland margin. Based on the peri-Baltican or peri-Laurentian affinity of the basement units, Tonian magmatic history, and Ordovician–Silurian tectonism (e.g., McClelland et al., 2019; Wala et al., 2021), the Svalbard terranes are better interpreted as displaced fragments of the northernmost Caledonian orogen. Recognition of the Silurian–Devonian Canadian Arctic transform system along the northern margin of Laurentia (McClelland et al., 2021, and references therein) supports our preferred model of truncation, rather than a straightforward continuation, of early Paleozoic structures from the Caledonides to the northern Laurentian margin (e.g., Harland, 1997; Gee and Teben'kov, 2004).

## Pearya Terrane

The Arctic margin of Laurentia records a south to north transition from the Neoproterozoic–early Paleozoic Franklinian continental margin (Thorsteinsson and Tozer, 1970; Trettin et al., 1991; Dewing et al., 2008) to Ordovician and Silurian clastic and subduction-related mafic and ultramafic rocks (Clements Markham belt) and the composite Pearya terrane (Fig. 5; Trettin, 1998). The presence of a composite arc fragment with continental affinities (Pearya) outboard of a deep-water passive margin has long supported accretion and translation models for the Paleozoic evolution of the northern Laurentian margin (Trettin, 1987). The appearance of ca. 450 Ma mafic arc volcanic rocks inboard of the Pearya terrane in the Clements Markham belt (Trettin, 1998) suggests that the northern Laurentian margin was a convergent boundary in the early Paleozoic (Klaper, 1992; Bjørnerud and Bradley, 1992; Trettin, 1998).

Trettin (1987, 1991, 1998) divided the Pearya terrane into five fault- or unconformity-bounded successions: (1) a Mesoproterozoic–early Neoproterozoic basement complex including orthogneiss, schist, quartzite, and amphibolite; (2) Upper Proterozoic to Lower Ordovician metasedimentary and metavolcanic rocks; (3) Lower–Middle Ordovician(?) arc-related metavolcanic and metasedimentary rocks and ultramafic complexes; (4) Middle to Upper Ordovician sedimentary and calc-alkaline volcanic rocks; and (5) Upper Ordovician to Upper Silurian sedimentary and volcanic rocks (Fig. 5).

Arc-related rocks of Succession 3 were juxtaposed with Successions 1 and 2 in a poorly understood tectonic setting during the Early–Middle Ordovician M'Clintock orogeny (Trettin, 1987; Klaper, 1992; Trettin et al., 1992). The timing of the orogeny is bracketed by involvement of the ca. 490–470 Ma Thores Suite of succession 3 (Trettin et al., 1992; Estrada et al., 2018b; Majka et al., 2021), a late ca. 455 Ma pegmatite that crosscuts sinistral shear zone fabrics in Tonian orthogneiss (McClelland et al., 2012), and migmatites associated with A-type granites (Estrada et al., 2018b). Primary ties between Succession 3 and older units of Pearya suggest this juxtaposition represents intra-arc deformation rather than collision of unrelated fragments (Majka et al., 2021). Middle Ordovician clastic, volcanic, and carbonate rocks of Succession 4 unconformably overlie units deformed in the M'Clintock event. Volcaniclastic rocks from this overlap assemblage are dominated by ca. 464 Ma detrital zircons with $\varepsilon Hf_t$ values of +1.1 to −6.2 (Fig. 6; Malone et al., 2019), where $\varepsilon Hf_t$ is the Hf isotopic ratio relative to bulk earth at the time of zircon crystallization. Above this, Succession 5 includes Upper Ordovician clastic rocks with a detrital zircon U/Pb signature dominated by a single peak at ca. 453 Ma, which

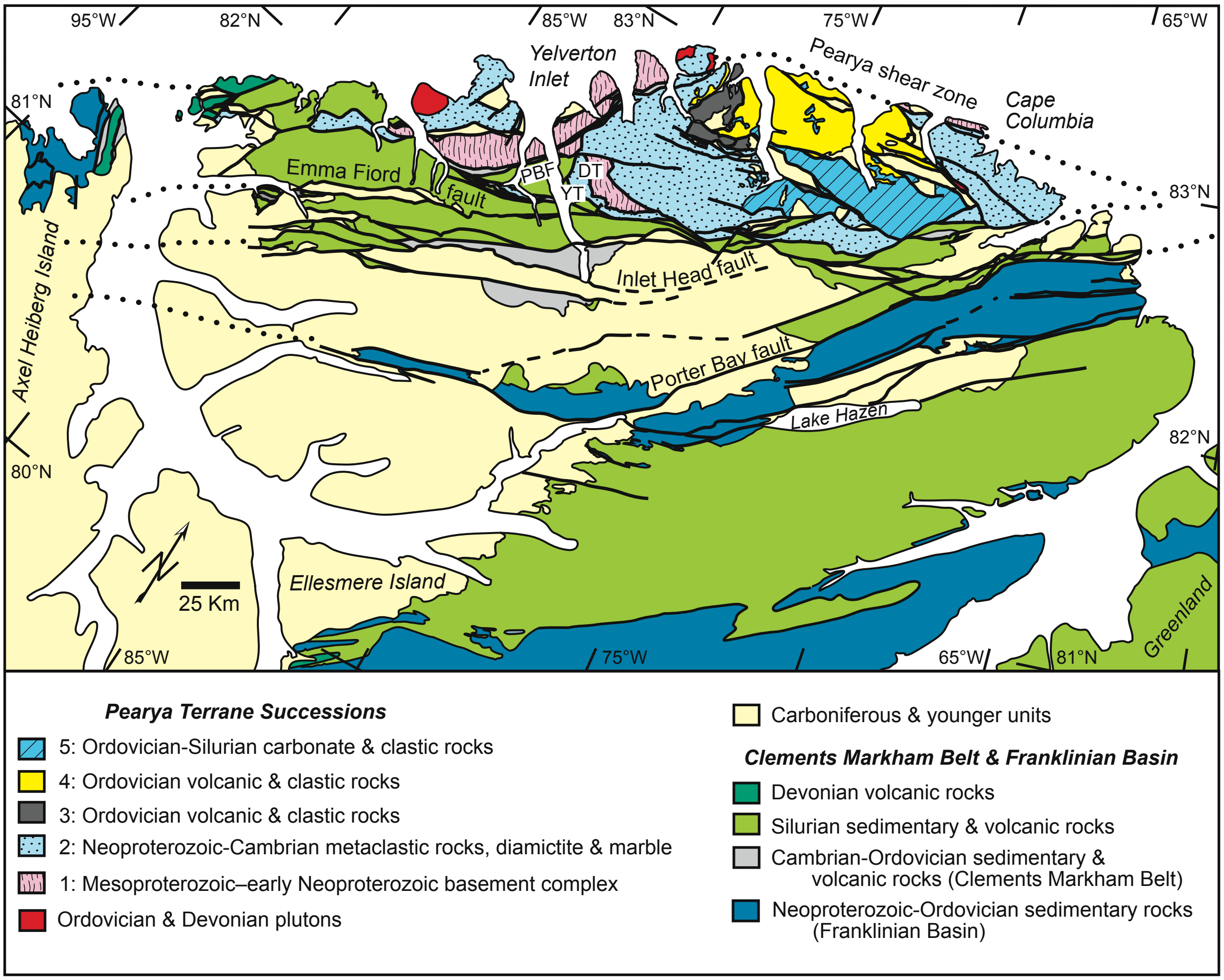


Figure 5. Simplified geologic map of northern Ellesmere Island, Canada, showing the distribution of units in the Pearya terrane, Clements Markham belt, and Franklinian basin. Map is modified after Trettin (1998). DT—Deuchars thrust fault; PBF—Petersen Bay fault; YT—Yelverton thrust fault.

indicates derivation from a juvenile ($\varepsilon Hf_t$ = +3.6 to +10.4) arc, as well as a broad spectrum of smaller peaks from ca. 1830 to 505 Ma (Malone et al., 2019). Younger units in Succession 5 contain peaks as young as ca. 450 Ma, in addition to abundant older peaks, and this pattern is consistent with recycling from other Pearya units (Hadlari et al., 2014; Malone et al., 2019). Silurian siliciclastic strata forming the upper part of Succession 5 have been correlated with the Danish River Formation in the Clements Markham belt and Franklinian basin (Trettin, 1998), and they are inferred to mark a broad overlap assemblage of flysch derived from the Caledonian orogen (Surlyk and Hurst, 1984; Higgins et al., 1991; Trettin, 1987, 1991, 1998; Trettin et al., 1991; Dewing et al., 2008).

Detrital zircon signatures from Neoproterozoic–Silurian strata in northern Ellesmere Island define clear differences between the Franklinian margin and the Pearya terrane (Fig. 3), but uncertainty in structural position and stratigraphic context, particularly within Paleozoic strata, allows for different interpretations (cf. Hadlari et al., 2014; Malone et al., 2014; Beranek et al., 2015; Dewing et al., 2019). Succession 2 of the Pearya terrane is strongly linked to the orthogneiss-dominated Succession 1 with a well-defined ca. 970 Ma peak (Malone et al., 2014) that, in combination with several major peaks between ca. 1885 and 1060 Ma, resembles the detrital signature of potentially age-equivalent Mesoproterozoic and Neoproterozoic rocks in Svalbard, North Greenland, and East Greenland (Fig. 3). The ca. 970 Ma peak persists in siliciclastic rocks of Successions 4 and 5, with the addition of major peaks between ca. 465 and 445 Ma that record derivation from local Ordovician magmatic rocks (Hadlari et al., 2014; Malone et al., 2019). Hf isotopic data from the Pearya terrane suggest that Tonian magmatism was generally evolved, whereas Ordovician magmatic sources ranged from juvenile to evolved (Fig. 6; Malone et al., 2014, 2019). In contrast, Neoproterozoic–Ordovician strata of the Franklinian margin are characterized by ca. 2700 and 1840 Ma peaks with minor ca. 1400–1000 Ma contributions (Anfinson et al., 2012a; Hadlari

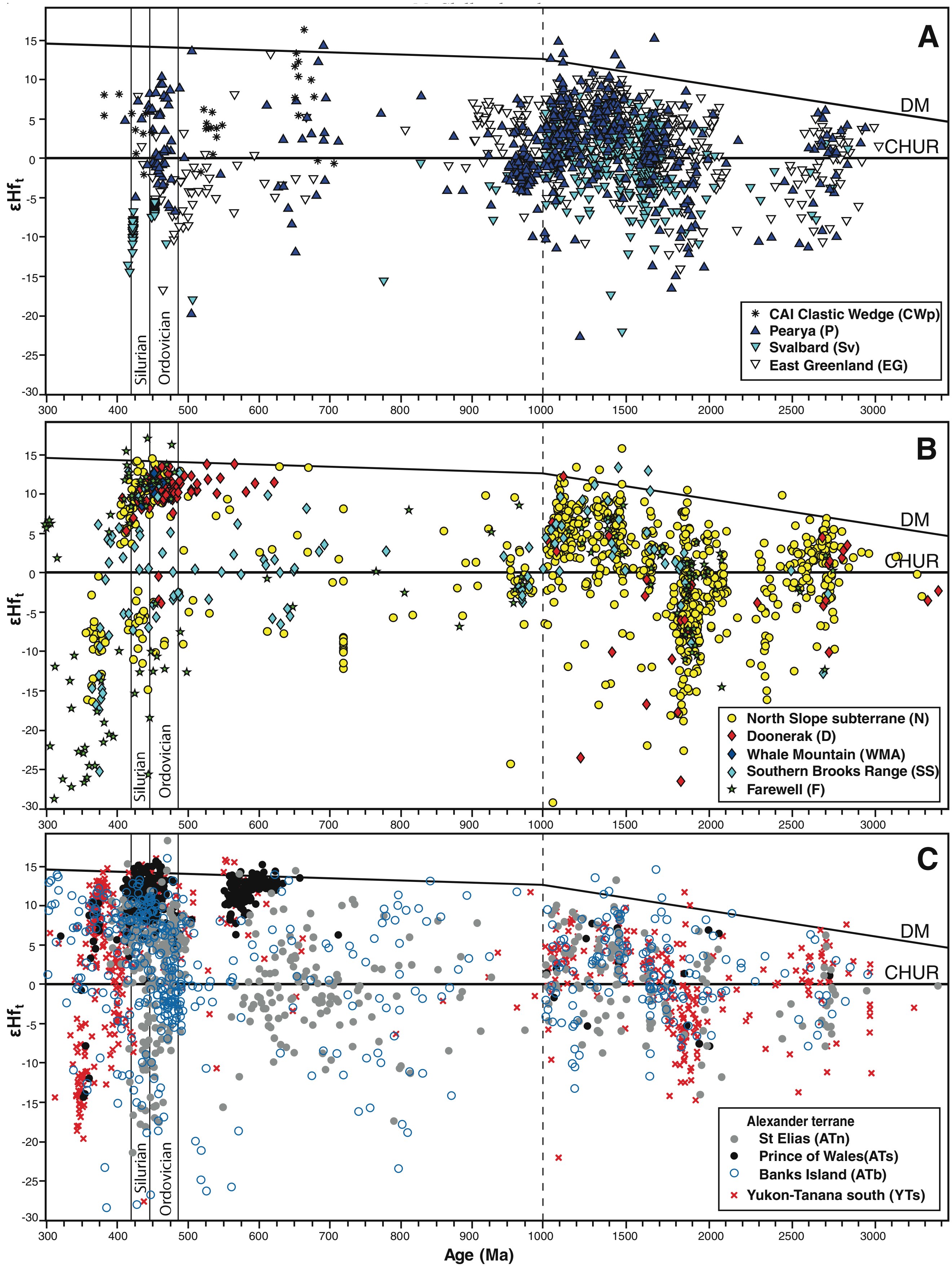
A
B
C
DM
CHUR
εHf$_t$
Silurian
Ordovician
CAI Clastic Wedge (CWp)
Pearya (P)
Svalbard (Sv)
East Greenland (EG)
North Slope subterrane (N)
Doonerak (D)
Whale Mountain (WMA)
Southern Brooks Range (SS)
Farewell (F)
Alexander terrane
St Elias (ATn)
Prince of Wales(ATs)
Banks Island (ATb)
Yukon-Tanana south (YTs)
Age (Ma)

Figure 6.

et al., 2012, 2014; Beranek et al., 2013c; Dewing et al., 2019). Silurian strata of Succession 5 strongly resemble the Ordovician Pearya signature, whereas Danish River units inboard of the Pearya terrane (plotted with the Franklinian basin; Fig. 3) record more consistent input from the Franklinian margin with minor contribution of detritus from the Ordovician–Silurian arc sources.

Three end-member models for the Pearya terrane have been put forth: (1) displacement of a composite arc fragment along the Franklinian margin on a continent-scale transform boundary (Trettin, 1998; McClelland et al., 2021); (2) accretion of an allochthonous composite arc fragment to the Franklinian margin by arc-continent collision following subduction of an intervening ocean basin (Klaper, 1992; Bjørnerud and Bradley, 1992; Trettin, 1998; Dumoulin et al., 2000); and (3) origin as a pericratonic fragment of the rifted Franklinian margin with little translation (Hadlari et al., 2014; Dewing et al., 2019). The steep structural boundary separating the Pearya terrane and the Franklinian margin with Paleozoic sinistral displacement inferred from the Yelverton and Deuchars thrust faults (e.g., Piepjohn et al., 2013, 2015), the exotic Tonian magmatism in the Pearya units (Malone et al., 2017), and the striking differences in detrital zircon signatures prior to the Silurian refute the pericratonic promontory model (Hadlari et al., 2014). The shift toward a more juvenile signature in the deep-water mudstones of the Franklinian basin at ca. 450 Ma may represent the far-field effects of synorogenic sedimentation in the Caledonides (Patchett et al., 1999) or a cryptic collision outboard of Pearya (Dewing et al., 2019). Alternatively, the change in isotopic signature may signal the arrival of the Pearya terrane on the northern Laurentian margin through oblique subduction of an ocean basin and subsequent translation along the margin. The appearance of Pearya-like detrital zircon components in early–middle Silurian turbidites on the Franklinian margin (Fig. 3) indicates that Pearya was proximal to the margin by that time.

Although details of the Ordovician–Silurian accretionary and translational history are still being worked out, the Pearya terrane was clearly involved in subsequent Devonian–Carboniferous deformation attributed to the Ellesmerian orogeny. Ellesmerian deformation on the Canadian Arctic Archipelago is reflected by a south-vergent fold-and-thrust belt, accompanied by the growth of an immense southwestward-propagating clastic wedge and the intrusion of minor ca. 375–365 Ma mafic and felsic plutonic rocks (Fig. 1; Thorsteinsson and Tozer, 1970; Embry, 1988; Trettin, 1998; Patchett et al., 1999; Anfinson et al., 2012a, 2012b, 2013). Synorogenic sedimentation in the clastic wedge is recorded by Middle–Late Devonian strata that yield prominent detrital zircon U/Pb age peaks at ca. 650, 535, 420, and 375 Ma, with additional peaks between ca. 2010 and 940 Ma and at ca. 2735 Ma (Fig. 3). Units as old as Middle Devonian (Eifelian) are interpreted to record the arrival of sediment from outboard terranes, but the major influx of juvenile material with non-Laurentian detrital zircon signatures is observed in the Upper Devonian (Famennian) Parry Islands Formation (Fig. 3; Anfinson et al., 2012a, 2012b). Mississippian strata (e.g., Borup Fiord and Emma Fiord Formations) show a return to locally derived Laurentian-dominated detrital zircon signatures (Fig. 3; Malone et al., 2019; Beauchamp et al., 2019) and record the initiation of regional extension that marks the transition from Ellesmerian contraction to the development of a passive margin across the Canadian Arctic margin (Trettin et al., 1991; Beauchamp et al., 2019).

Figure 6. Age-εHf$_t$ plots of available data from samples included in Figure 3: (A) East Greenland (Olierook et al., 2020), Svalbard (Beranek et al., 2020; Wala et al., 2021), Devonian clastic wedge on the Canadian Arctic Archipelago (CAI; CWp—Parry Islands Formation; Anfinson et al., 2012b), and the Pearya terrane (Malone et al., 2014, 2019); (B) the Farewell terrane (Malkowski and Hampton, 2014) and Arctic Alaska terrane, including the North Slope subterrane (Strauss et al., 2017, 2019a, 2019b; Colpron et al., 2019), Whale Mountain allochthon (Strauss et al., 2019b), the Doonerak arc (Strauss et al., 2013), and the southern Brooks Range (Hoiland et al., 2018; Strauss et al., 2017); and (C) the Alexander terrane (Beranek et al., 2013b, 2013c; Tochilin et al., 2014; White et al., 2016) and Yukon-Tanana terrane in southeastern Alaska (Pecha et al., 2016). The plots were generated using the Hf plotter routine of Sundell et al. (2019). Curves for depleted mantle (DM) array and chondritic uniform reservoir (CHUR) were adapted from Vervoort and Blichert-Toft (1999) and Bouvier et al. (2008), respectively.

## Arctic Alaska Terrane

The Arctic Alaska terrane of the greater Arctic Alaska–Chukotka microplate (Hubbard et al., 1987) records Late Jurassic–Cretaceous arc-continent collision that led to the Brookian orogeny, resulting in a southern metamorphic belt and a northward-propagating fold-and-thrust belt and foreland basin system (Moore et al., 1994, and references therein). Brookian deformation was responsible for the current distribution of pre-Mesozoic lithotectonic units, which include, from north to south, (1) Neoproterozoic–Devonian rocks of the North Slope subterrane, (2) Devonian–Carboniferous and younger strata of the Endicott Mountains allochthon and Neoproterozoic–Mesozoic metasedimentary and meta-igneous rocks of the Hammond, Coldfoot, and Slate Creek subterranes (Central, Schist, and Graywacke-Phyllite belts), collectively referred to as the southwestern subterranes, and (3) Mississippian–Jurassic oceanic rocks and ophiolitic slivers of the Angayucham terrane (Fig. 7; Moore et al., 1994, 1997). This Mesozoic deformation overprinted a complex mid-Paleozoic architecture of sutured Neoproterozoic–Paleozoic crustal fragments (Moore et al., 1997; Dumoulin et al., 2002, 2014; Strauss et al., 2013, 2017; Johnson et al., 2016).

The North Slope and southwestern subterranes define two pre-Mississippian basement types based on contrasts in stratigraphy, faunal affinities, and sediment provenance, separated by a prominent tectonic boundary marked by an early Paleozoic island-arc succession exposed in the Doonerak window (Fig. 7; Strauss et al., 2013, 2017; Hoiland et al., 2018; Robinson et al., 2019). The southwestern subterranes include units with

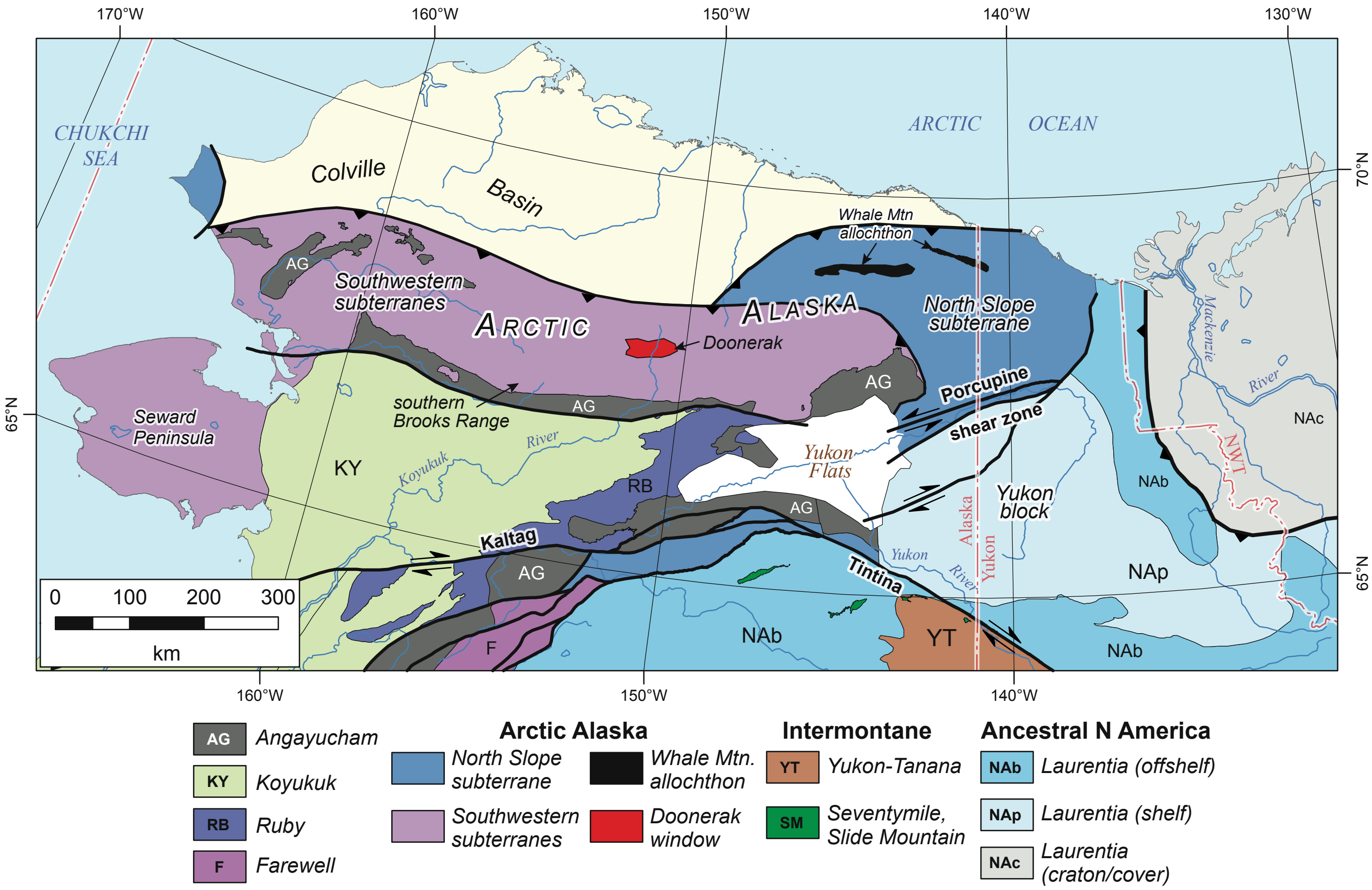


Figure 7. Simplified geologic map of northern Alaska and Yukon showing components of the Arctic Alaska terrane, modified after Colpron and Nelson (2011). NWT—Northwest Territories.

peri-Baltican detrital zircon affinity and possible peri-Siberian faunal affinity in the southern Brooks Range, Seward Peninsula, and Chukotka Peninsula of Russia (Amato et al., 2009, 2014; Miller et al., 2006, 2011, 2018; Dumoulin et al., 2014; Till et al., 2014; Hoiland et al., 2018; Robinson et al., 2019). In contrast, the North Slope subterrane has strong ties to the Franklinian basin of northern Laurentia (Strauss et al., 2013, 2019a, 2019b; Johnson et al., 2016, 2019; Colpron et al., 2019; Nelson et al., 2019; Gibson et al., 2021). Deformed rocks of the North Slope subterrane are juxtaposed with the northwest Laurentian margin along the Porcupine shear zone (Strauss et al., 2019b; Ward et al., 2019; Colpron et al., 2019; von Gosen et al., 2019; Faehnrich et al., 2021; McClelland et al., 2021). Dredge samples from the Chukchi Borderland suggest that some components of the Arctic Alaska–Chukotka microplate share affinity with the Pearya terrane and Franklinian margin (O'Brien and Miller, 2014; Brumley et al., 2015; O'Brien et al., 2016).

The North Slope subterrane is divided into the Northeast Brooks Range platformal and basinal successions, both of which are interpreted as displaced continental fragments of the Arctic margin of Laurentia (Strauss et al., 2019a, 2019b). The platformal succession consists of a basal Tonian clastic-carbonate succession that is overlain by ca. 720 Ma volcanic rocks associated with the Franklin large igneous province and a younger Cryogenian–Ordovician carbonate platform succession (Strauss et al., 2019a). Detrital zircon U/Pb data from the Tonian Mount Weller Group yield prominent peaks at ca. 2730–2450, 1980–1780, and 1250–1030 Ma with smaller age populations ranging ca. 2080–2000, 1490–1380, and 980–790 Ma (Strauss et al., 2013, 2019a). Neoproterozoic–Ordovician strata of the platformal succession are tilted and unconformably overlain by Lower Devonian (Emsian) shallow-water carbonate strata, which are in turn truncated by a prominent sub-Mississippian unconformity beneath coarse-grained clastic rocks of the Carboniferous Endicott Group (e.g., Blodgett et al., 1988; Strauss et al., 2019a). Sandstone in paleokarst cavities beneath the Middle Devonian unconformity yields detrital zircon signatures similar to the underlying Tonian succession, in addition to a U/Pb peak between ca. 475 and 405 Ma with $\varepsilon Hf_t = +10$ to $-5$ (Strauss et al., 2019a).

The Northeast Brooks Range basinal succession consists of deep-water clastic-dominated Cryogenian–Lower Devonian(?)

sedimentary and volcanic rocks (Strauss et al., 2019b). Neoproterozoic–Cambrian clastic strata of the Firth River Group and Neruokpuk Formation record detrital zircon U/Pb age populations of ca. 2950–2300 and 1980–1780 Ma with scattered Mesoproterozoic age populations ranging ca. 1630–1020 Ma (Strauss et al., 2013, 2019b; McClelland et al., 2015; Johnson et al., 2016; Lane et al., 2016; Colpron et al., 2019). These units are unconformably overlain by Middle Ordovician–Lower Devonian(?) synorogenic clastic strata of the Clarence River Group, which recorded the influx of ca. 990–670 and 490–420 Ma detritus derived from an arc system outboard of the Laurentian margin (Johnson et al., 2016; Colpron et al., 2019; Nelson et al., 2019; Strauss et al., 2019b). Cryogenian–early Paleozoic zircon populations in the Clarence River Group yielded $\varepsilon Hf_t$ values ranging from +15 to −10, while Tonian zircons defined a separate cluster of $\varepsilon Hf_t$ values ranging from +10 to −3 (Fig. 6; Colpron et al., 2019; Strauss et al., 2019b). The basinal succession is in local structural contact with Lower Cambrian–Upper Ordovician mafic volcanic rocks, carbonate, chert, phyllite, and rare coarser-grained clastic rocks of the Whale Mountain allochthon (Johnson et al., 2019). Volcaniclastic horizons and lithic arenite of the Whale Mountain allochthon record unimodal ca. 512, 505, and 452 Ma U/Pb detrital zircon peaks with predominantly juvenile $\varepsilon Hf_t$ values (Johnson et al., 2016, 2019; Strauss et al., 2019b). The regional field relationships in the Whale Mountain allochthon, its internal variation in volcanic geochemistry, and the exotic nature of its peri-Laurentian trilobite faunas led Johnson et al. (2019) to hypothesize that these imbricated oceanic rocks recorded Late Ordovician–Early Devonian(?) basin closure and associated imbrication with the Northeast Brooks Range succession in an oblique subduction zone, analogous to the Clements Markham belt between the Franklinian margin and Pearya terrane.

A regional pre–Middle Devonian deformational event in the North Slope subterrane, likely associated with the emplacement of the Whale Mountain allochthon, is locally reflected by intense imbrication and low-grade metamorphism of pre-Mississippian sedimentary and volcanic rocks of the Northeast Brooks Range basinal succession (Anderson et al., 1994; Moore et al., 1994; Lane, 2007; Johnson et al., 2016; Strauss et al., 2019b) and the development of the pre-Emsian angular unconformity in the platformal succession (Strauss et al., 2019a). This pre–Middle Devonian tectonic event, the Romanzof orogeny of Lane (2007), was followed by the intrusion of Late Devonian (ca. 375–368 Ma) granites in the North Slope subterrane of both Alaska and Yukon (e.g., Ward et al., 2019; Lane and Mortensen, 2019). Lane (2007) concluded that Romanzof shortening was associated with the accretion of an unknown continental fragment to northwestern Laurentia. Others have suggested that this event occurred solely in the North Slope subterrane in a position adjacent to the Canadian Arctic Archipelago, and the fragment was subsequently translated to its current location (Oldow et al., 1987; Strauss et al., 2013, 2019b; Johnson et al., 2016; Ward et al., 2019; Gibson et al., 2021; McClelland et al., 2021).

The southernmost exposure of the North Slope subterrane is marked by the Doonerak window (Moore et al., 1994, and references therein), which hosts an early Paleozoic island-arc succession referred to as the Apoon assemblage (Julian and Oldow, 1998). The Apoon assemblage reflects a long-lived Upper Cambrian (Furongian)–Upper Silurian or Lower Devonian(?) juvenile arc composed of Cambrian(?)–Middle Ordovician mafic volcanic and plutonic rocks and fine-grained clastic and tuffaceous rocks with minor carbonate (Mull et al., 1987; Julian and Oldow, 1998; Strauss et al., 2017). Detrital zircon U/Pb data from volcaniclastic and tuffaceous strata yield unimodal ca. 493, 443, and 440 Ma age populations with juvenile $\varepsilon Hf_t$ values of +5 to +13, as well as polymodal spectra including prominent peaks ca. 2830–2650, 1945–1750, 1500–1380, 1250–960, 540–510, and 490–420 Ma (Strauss et al., 2017; Robinson et al., 2019). The Apoon assemblage is tilted and unconformably overlain by coarse-grained strata of the Upper Devonian–Mississippian Endicott Group.

Pre-Mississippian metasedimentary and metavolcanic rocks of the southwestern subterranes of Arctic Alaska to the south and west of the Doonerak window form the metamorphic hinterland of the Brooks Range (Moore et al., 1997; Till et al., 2008). Although little consensus exists over the primary architecture of these highly deformed rocks, the most characteristic stratigraphic unit is a largely dismembered Upper Proterozoic(?)–Middle Devonian metacarbonate succession that appears to be the remnants of a long-lived carbonate platform (Dumoulin and Harris, 1994; Moore et al., 1997; Oldow et al., 1998; Dumoulin et al., 2002, 2014). This metacarbonate succession is in structural and presumed local depositional contact with older Meso-proterozoic–Neoproterozoic meta-igneous and metasedimentary rocks, some of which of yielded Neoproterozoic U-Pb zircon ages of ca. 968, 865, 742, 670–656, and 574 Ma (Amato et al., 2014; Hoiland et al., 2018, and references therein). Many of the surrounding metaclastic rocks were mapped as the Upper Devonian Beaucoup Formation (e.g., Dillon, 1989); however, subsequent work has subdivided these metasedimentary and metavolcanic rocks into several Proterozoic–Devonian structural or stratigraphic assemblages based on their regional structural positions and detrital zircon U/Pb signatures (e.g., Oldow et al., 1998; Moore et al., 1997; Hoiland et al., 2018; Robinson et al., 2019). For example, Hoiland et al. (2018) subdivided southwestern subterrane rocks into four different signatures: (1) Tonian or younger metaclastic rocks with detrital zircon U/Pb ages from ca. 1910 to 950 Ma and small Archean populations; (2) Ediacaran or younger metasedimentary rocks with a range of detrital zircon U/Pb ages from ca. 1910 to 950 Ma and smaller Archean and ca. 720–550 Ma populations; (3) Ordovician–Devonian(?) or younger metaclastic rocks with a spread of ages from 2090 to 950 Ma and an abundance of Neoproterozoic and Cambrian to Early Devonian(?) zircon; and (4) Middle to Late Devonian or younger metasedimentary rocks characterized by an abundance of Devonian and Ordovician–Silurian zircon, with additional peaks at ca. 2650, 1850, and 1020 Ma. These metasedimentary rocks are intruded by Middle–Late Devonian metaplutonic rocks (e.g., Dillon et al., 1980) and overlain by clastic rocks of the Endicott Group (Moore et al., 1994), suggesting that the Arctic Alaska terrane was assembled prior to or during the Carboniferous (e.g., Strauss et al., 2013).

The Endicott Mountains allochthon is dominated by imbricated Upper Devonian–Mississippian siliciclastic and carbonate rocks of the Endicott and Lisburne Groups that are interpreted to unconformably overlie the pre-Mississippian southwestern subterranes (Brosgé et al., 1962; Tailleur et al., 1967; Mull, 1982). These strata are inferred to be lateral equivalents of the much thinner Mississippian Kekiktuk Conglomerate and Kayak Shale of the North Slope subterrane (Brosgé et al., 1962; Armstrong et al., 1976; LePain et al., 1994), suggesting that they represent an overlap assemblage deposited during or after pre-Mississippian amalgamation and deformation in the Arctic Alaska terrane (Strauss et al., 2013). Early workers suggested that the Endicott Group was deposited in a foredeep basin adjacent to or along strike from the Ellesmerian orogen (Nilsen, 1981). Most subsequent studies have proposed deposition in an extensional setting based on correlations with Middle Devonian rift(?)-related strata in the northeastern Brooks Range (Anderson et al., 1994; Anderson and Meisling, 2021) and interpreted Middle Devonian(?)–Mississippian extensional grabens in the subsurface of the Colville Basin of Arctic Alaska (Bird and Molenaar, 1987; Kirschner and Rycerski, 1988; Anderson et al., 1994; Kelley, 1999; Dumoulin, 2001; Anderson and Meisling, 2021). The only published detrital zircon U/Pb data from the Endicott Mountains allochthon are from a low-*n* sample of the Kanayut Formation, which yielded ca. 2070–1800, 1520–1020, and 370–360 Ma age populations (Aleinikoff et al., 1995).

## TERRANES OF ARCTIC AFFINITY IN THE CORDILLERA

The early to middle Paleozoic translation of crustal blocks and arc fragments along northern Laurentia introduced terranes of Arctic affinity into northern Panthalassa—terranes that were subsequently incorporated into the Cordilleran collage in the Mesozoic (Fig. 1). The Farewell, Alexander, and Yukon-Tanana South terranes, in particular, have geologic elements and detrital zircon signatures with strong Arctic affinity. Some of their key features are summarized below.

### Farewell Terrane

The Farewell terrane in central Alaska (Fig. 1) is subdivided into a Proterozoic igneous and metamorphic basement overlain by a Neoproterozoic(?)–Devonian carbonate platform in the Nixon Fork subterrane, deep-water Cambrian(?)–Devonian clastic rocks of the Dillinger subterrane, and Devonian–Cretaceous clastic units of the Mystic subterrane (Decker et al., 1994; Bundtzen et al., 1997; Bradley et al., 2003). Proterozoic–Cambrian clastic units in the Farewell terrane are dominated by ca. 675–580 Ma detrital zircon U/Pb signatures and include Tonian magmatic and detrital components at ca. 970 and 850 Ma, as well as ca. 2060 Ma detrital components similar those of the Kilbuck and Arctic Alaska terranes (Bradley et al., 2014; Dumoulin et al., 2018a). Ordovician–Devonian clastic strata are dominated by unimodal peaks at ca. 480, 440, and 425 Ma (Fig. 3). Early Paleozoic faunas characteristic of Laurentia, Siberia, and Baltica link the Farewell terrane with coeval rocks in the Arctic Alaska–Chukotka microplate and Alexander terrane (Blodgett et al., 2002; Dumoulin et al., 2002, 2014; Soja, 2008). The Farewell terrane appears to have recorded a similar depositional or tectonic history to the Arctic Alaska and Alexander terranes in the Ordovician and Silurian but was likely independent by the Devonian (Dumoulin et al., 2018a). Deformation and metamorphism associated with the Permian Browns Fork orogeny (Bradley et al., 2003) may signify juxtaposition of the Farewell and Alexander terranes (Malkowski and Hampton, 2014; Beranek et al., 2014) and possibly the Yukon-Tanana terrane (Dumoulin et al., 2018b).

### Alexander Terrane

The Alexander terrane contains two distinct elements (Fig. 1). In southeastern Alaska, it consists mainly of a juvenile Neoproterozoic–Silurian magmatic arc (White et al., 2016). Relatively narrow U/Pb zircon peaks at ca. 580 and 460–450 Ma with juvenile $\varepsilon Hf_t$ signatures characterize Ordovician and Silurian strata (Figs. 3 and 6). Middle to Upper Devonian clastic rocks deposited during and after the Early Devonian Klakas orogeny (Gehrels and Saleeby, 1987) maintain the same signature and mark the transition to a stable Carboniferous carbonate platform. In contrast, the northern Alexander terrane exposed in the Saint Elias Mountains and the Banks Island assemblage in British Columbia and Yukon represent an arc system with continental underpinnings (Beranek et al., 2013a, 2013b; Tochilin et al., 2014). Older Banks Island strata define a broad range of Proterozoic U/Pb peaks from ca. 1740 to 1070 Ma that are replaced by dominant ca. 780 and 470 Ma peaks in Ordovician strata but then return to mixed U/Pb signals in overlying Silurian units (Fig. 3). Ordovician rocks of the Saint Elias region are dominated by Ordovician (ca. 470 Ma) and Neoproterozoic (ca. 880–635 Ma) U/Pb ages with a broad array of smaller Mesoproterozoic peaks. Both the Saint Elias and Banks Island units have a range of evolved to juvenile $\varepsilon Hf_t$ signatures (Beranek et al., 2013a, 2013b; Tochilin et al., 2014). The southern Alexander terrane clearly evolved in an intra-oceanic setting (e.g., White et al., 2016), whereas the northern Alexander terrane may have developed in proximity to the margin of Baltica (Beranek et al., 2013a, 2013b). Although faunal data (Soja, 1994, 2008) and lithologic comparisons (Soja and Krutikov, 2008; Soja and White, 2016) suggest that the southern Alexander terrane was located near the Caledonides, the juvenile $\varepsilon Hf_t$ isotopic signatures and low abundance of Proterozoic detrital grains in Devonian units associated with the Klakas collisional event are inconsistent with this interpretation. The Klakas collision may instead have recorded amalgamation of the northern and southern parts of the Alexander terrane north of the Laurentian margin, the location of which is based on paleomagnetic data from Devonian strata (Bazard et al., 1995; Butler et al., 1997).

### Yukon-Tanana South Terrane

Metaclastic and meta-igneous rocks in the Coast Mountains of British Columbia east of the Alexander terrane include: (1) a pre-Devonian passive-margin succession (Tracy Arm assemblage); (2) a Devonian arc complex (Endicott Arm assemblage); and (3) and a Carboniferous sedimentary succession (Port Houghton assemblage). These rocks have been correlated with the Yukon-Tanana terrane of Yukon and east-central Alaska (Fig. 1; Gehrels et al., 1990, 1991). Older quartz-rich metaclastic units have a major Paleoproterozoic U/Pb zircon peak at ca. 1830 Ma, with lesser Archean and Mesoproterozoic peaks (Fig. 3; Pecha et al., 2016). The overlying Devonian–Carboniferous units are dominated by Ordovician to Carboniferous U/Pb zircon peaks between 450 and 350 Ma (Pecha et al., 2016). Although the Proterozoic detrital components and Devonian–Carboniferous magmatic history are similar to the northern Yukon-Tanana terrane in Yukon (Colpron et al., 2006; Nelson et al., 2013), the Ordovician–Silurian components are unique and suggest that the southern exposures should be treated separately as Yukon-Tanana South (Pecha et al., 2016). The southern terrane either reflects eastward migration of Silurian magmatism onto the Cordilleran margin (e.g., Saleeby, 2000) or emplacement of a Silurian arc onto the Cordilleran margin by Devonian time (Pecha et al., 2016).

## PROVENANCE SIGNATURE OF NORTHERN LAURENTIAN VERSUS CORDILLERAN TERRANES

Variation in detrital zircon U/Pb isotopic signatures helps to define and track terrane displacement relative to the northern Laurentian (Franklinian) passive margin. Useful signals include: (1) direct juxtaposition of terranes with different Proterozoic signatures; (2) appearance of Tonian (ca. 970 Ma) and/or Cryogenian–early Cambrian (710–520 Ma) detrital components; and (3) variation in input from Ordovician, Silurian, and Devonian arc magmatism common to many of the displaced terranes. Numerous studies have concluded that Neoproterozoic–Cambrian (ca. 710–520 Ma) and Ordovician–Silurian (ca. 450–420 Ma) detrital zircon ages in Arctic terranes indicate derivation from the Timanian and Caledonian orogens, respectively (e.g., Miller et al., 2018, and references therein). In contrast, many of these terranes more likely evolved in distinct intra-oceanic convergent and transform margin settings that were extensions of the Timanian and/or the Caledonian collisions. Neoproterozoic–Cambrian and Ordovician–Silurian arc-related signals that are internal to Arctic terranes are considered plausible alternative sources. We suggest detrital components from displaced terranes should be described in age terms (e.g., Ediacaran, Silurian) rather than tied to specific orogens (e.g., Timanian, Caledonian), unless definitive links can be demonstrated. Below, we review contrasts and commonalities amongst key detrital zircon age signatures from the terranes discussed above.

### Mesoproterozoic and Older

Proterozoic to Cambrian units of Svalbard, Pearya, North Slope subterrane, Yukon-Tanana South, and the Banks Island assemblage of the Alexander terrane show clear evidence of Mesoproterozoic and older detritus consistent with derivation from Laurentia (Fig. 3). Several attempts have been made to define unique age distributions within this Laurentian signature based on the relative abundance of Mesoproterozoic (ca. 1450–1000 Ma) ages versus Paleoproterozoic (ca. 2100–1650 Ma) and Neoarchean (ca. 2800–2600 Ma) ages (e.g., Hadlari et al., 2012; Lane and Gehrels, 2014). Proterozoic–Cambrian strata of northern Laurentia demonstrate this variation (Fig. 8A). For example, Ediacaran–Cambrian strata in North-East Greenland, North Greenland, and the Franklinian basin are dominated by ca. 2080–1710 Ma and ca. 2750 Ma peaks with minor Mesoproterozoic input (Fig. 3). Similar-age strata in the Yukon block and Mackenzie platform of northwestern Laurentia have Paleoproterozoic and Neoarchean peaks but are instead dominated by Mesoproterozoic ages (Fig. 3; Gibson et al., 2021). In addition, Cambrian and older strata in thrust sheets of East Greenland share the Mesoproterozoic-dominated signature (e.g., Olierook et al., 2020, and references therein), which is absent in North-East Greenland.

The evaluation of terrane translation and offset of crustal fragments based on this broad variation in cratonic signature has been problematic. As an example, proportional variation between Mesoproterozoic and Paleoproterozoic zircon populations within the North Slope subterrane is observed as a function of depositional age in coherent sections rather than geographic location along the Laurentian margin (e.g., Strauss et al., 2019a). As a result, displacement is permissible but not required for the North Slope subterrane based solely on comparison of detrital zircon signatures in Laurentian strata using relatively small data sets (cf. McClelland et al., 2015; Lane et al., 2016). However, larger-*n* data sets (>100 grains/sample and >15 samples) support large-scale translation of the North Slope subterrane (Gibson et al., 2021), consistent with paleontological and geochemical observations that suggest a northeastern Laurentian origin (e.g., Strauss et al., 2013; Johnson et al., 2019; Nelson et al., 2019).

The broad variation in Archean to Mesoproterozoic detrital zircon U/Pb ages in Neoproterozoic and Cambrian strata of northern Laurentia may be useful to highlight direct juxtaposition of displaced fragments (e.g., Gibson et al., 2021), but it is generally not diagnostic due to widespread distribution of sources and recycling across multiple continents prior to the breakup of Rodinia. Specific or unique detrital components are typically required for the evaluation of terrane displacement. For example, the Pearya terrane has a clear Laurentian signature similar to the Yukon block and Mackenzie platform, but it also contains a distinct Tonian component not observed in the adjacent Laurentian margin (Fig. 8A).

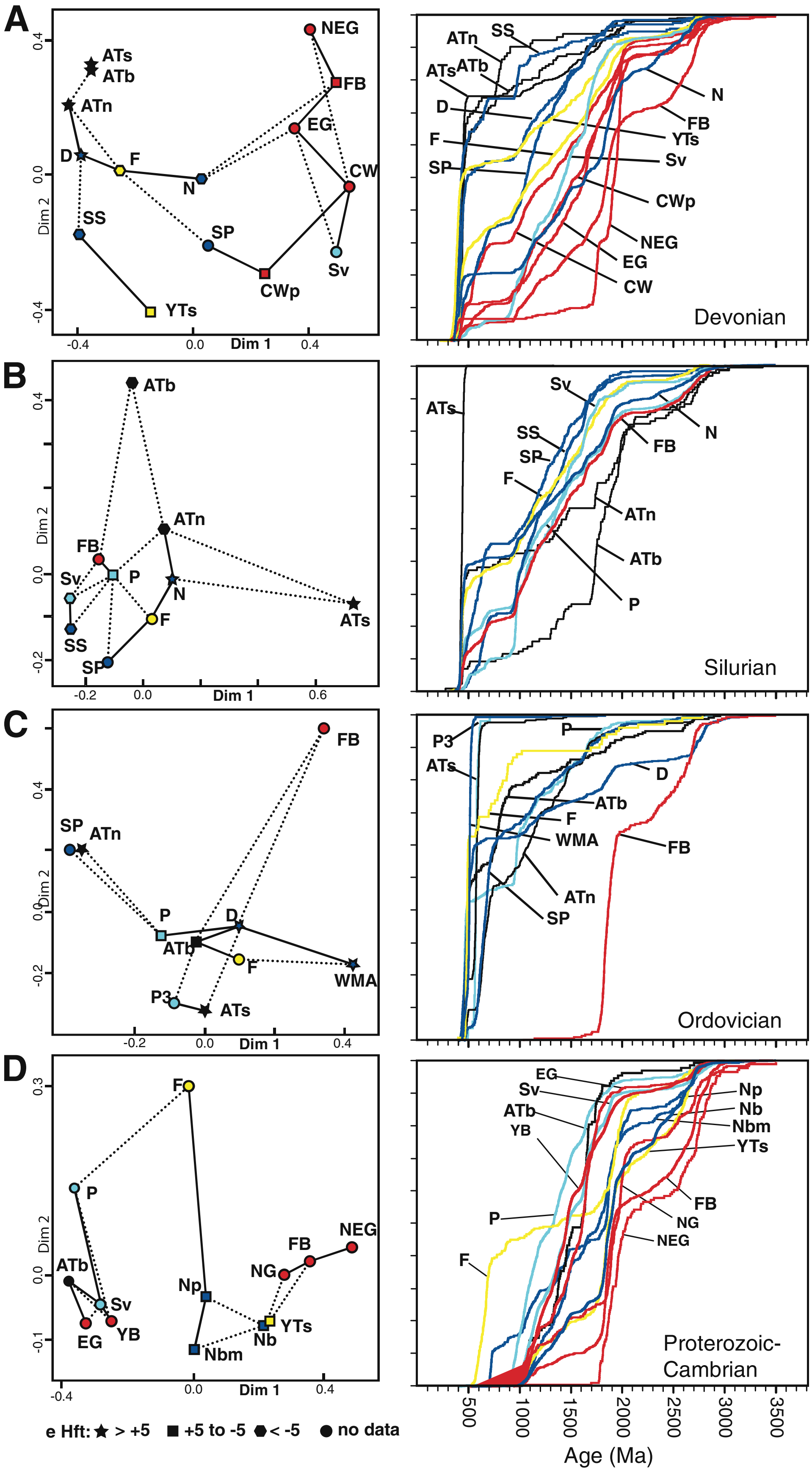


Figure 8. Two-dimensional multidimensional scaling (MDS) plots and cumulative probability plots of U/Pb detrital zircon data in Figure 3 grouped by age: (A) Devonian–Carboniferous, (B) Silurian, (C) Ordovician, and (D) Proterozoic–Cambrian. The MDS plots use a Kolmogorov-Smirnov comparison generated with the DZmds routine of Saylor et al. (2018). The cumulative probability plots were made using the DZmix routine based on Sundell and Saylor (2017). The $\varepsilon Hf_t$ designations are based on average isotopic values for each specific age group using data plotted in Figure 6. Arctic Alaska terrane: N—North Slope subterrane (Nb—basinal succession; Np—platformal succession; Nbm—Barn Mountains); SP—Seward Peninsula; SS—southwestern subterranes; D—Doonerak arc; WMA—Whale Mountain allochthon. Alexander terrane: ATn—northern, St. Elias; ATs—southern, Prince of Wales Island; ATb—Banks Island assemblage. CW—Canadian Arctic Islands clastic wedge (CWp—Parry Islands Formation); EG—East Greenland; F—Farewell terrane; FB—Franklinian basin; NEG—North-East Greenland; NG—North Greenland; P—Pearya terrane (P3—Succession 3); Sv—Svalbard; YB—Yukon block; YTs—Yukon-Tanana terrane in southeastern Alaska.

## Neoproterozoic (Tonian to Ediacaran)

The characteristic ca. 970 Ma Tonian signature of the continental arc built on the external margin of Rodinia—the Valhalla orogen of Cawood et al. (2010)—is a common igneous and detrital component of the Pearya terrane, as well as various Svalbard terranes, southwestern subterranes of Arctic Alaska, and the Farewell terrane (Fig. 3). Other terranes with a minor ca. 970 Ma detrital signature include the platformal succession of the North Slope subterrane (Fig. 3). The $\varepsilon Hf_t$ values of this age group range from −0.5 to +0.5, suggesting moderate crustal input. This early Tonian signature is notably only a very minor component or entirely lacking in the Alexander terrane and pre-Devonian successions along the Laurentian margin, making it a useful discriminator. The dominant ca. 970 Ma igneous and detrital signature in Pearya and Svalbard indicates these terranes originated closer to the external margin of Rodinia, whereas the North Slope subterrane evolved in a more internal position during Rodinia breakup and rifting of the northern Laurentian margin (Malone et al., 2014, 2017; Strauss et al., 2019a, 2019b; Wala et al., 2021). Similar-age Tonian magmatism extends to the thrust sheets of the Norwegian Caledonides with ties to Baltica (Kirkland et al., 2006) and to the Central Taimyr accretionary belt of Siberia (Vernikovsky et al., 2011). Distinctive ca. 880–830 Ma igneous and detrital peaks occur in the Farewell, Arctic Alaska, and Kilbuck terranes, which, when combined with the characteristic ca. 970 and 2080 Ma components, provide a convincing tie with western Siberia (e.g., Yenisey orogen; Vernikovsky et al., 2007), consistent with the general similarities in Mesoproterozoic and older basement ages in the Siberian and northern Laurentian cratons (Priyatkina et al., 2020). Thus, extension of a Tonian arc on the external margin of Rodinia from northeast Laurentia (Valhalla) to the Taimyr and Yenisey orogens (Priyatkina et al., 2018) can explain variations among Laurentian-derived terranes (Pearya terrane) with dominant ca. 970 Ma signatures to peri-Siberian terranes with magmatic signatures continuing throughout the Neoproterozoic (e.g., Farewell terrane).

Evidence for Neoproterozoic–early Paleozoic magmatism or deformation coeval with the ca. 700–550 Ma Timanide orogen (sensu lato) of Baltica (e.g., Gee and Pease, 2004; Kuznetsov et al., 2007) appears in the southwestern subterranes of Arctic Alaska and the Pearya, Svalbard, Farewell, and Alexander terranes (Fig. 3). The 700–550 Ma detrital signature is small in Pearya terrane units associated with the Tonian magmatic signature, but it becomes more abundant in volcaniclastic units associated with Ordovician mafic-ultramafic arc rocks (Succession 3 of Trettin, 1998). Detrital ages from Successions 3–5 in Pearya are also consistent with derivation from ca. 650–570 Ma igneous rocks adjacent to the Harder Fjord fault in North Greenland (Rosa et al., 2016; Estrada et al., 2018a). Neoproterozoic–early Paleozoic igneous and detrital zircon ages of ca. 710–520 Ma occur in the southwestern subterranes of the Arctic Alaska terrane and the Southwestern province of Svalbard (e.g., Gumsley et al., 2020) and are the dominant detrital component in the Farewell terrane (Fig. 2; Dumoulin et al., 2018a, 2018b). Terranes of the Southwestern province of Svalbard also record a prominent ca. 640 Ma deformation event (Torellian unconformity) that is consistent with connections to the Timanide accretionary orogen (e.g., Majka et al., 2014, 2015; Wala et al., 2021).

The broad Neoproterozoic U/Pb signature is noticeably absent from the North Slope subterrane, although grains attributed to the ca. 720 Ma Franklin large igneous province are present in the platform assemblage (Strauss et al., 2019a), and rare Neoproterozoic grains occur in the synorogenic Ordovician–Devonian(?) Clarence River Group (Strauss et al., 2019b). The Alexander terrane records two distinct Neoproterozoic detrital zircon signatures: Ordovician units in the Saint Elias region define a broad ca. 700–550 Ma peak, whereas similar units in the southern Alexander terrane on Prince of Wales Island are dominated by a narrow peak at ca. 580 Ma, reflecting a source from local arc basement units with igneous ages of ca. 595–530 Ma (Beranek et al., 2013a; White et al., 2016). Another prominent characteristic of the southern Alexander terrane is the strongly juvenile signal ($\varepsilon Hf_t > 5$) that dominates the igneous and detrital signature throughout its pre-Devonian history. These data suggest that terranes with evidence for Neoproterozoic–early Paleozoic magmatism or detritus may include crustal fragments derived from the Timanide orogen adjacent to Baltica, intra-oceanic arcs formed between Laurentia, Siberia, and Baltica following Rodinia breakup, or through the widespread delivery of this detritus in subsequent collisional events.

## Ordovician–Silurian

Widespread Ordovician to Silurian arc activity occurred across many Cordilleran and Arctic terranes, based on published igneous and detrital zircon U/Pb data sets. The age of individual peaks commonly varies by terrane, and the available Hf isotopes indicate juvenile to evolved magmatic settings (Fig. 6). Dominant Ordovician U/Pb peaks are common in the Pearya, Alexander, and Farewell terranes, as well as the North Slope/Doonerak arc and southwestern subterranes of Arctic Alaska (e.g., Strauss et al., 2017, 2019b; Dumoulin et al., 2018b; Hoiland et al., 2018; Malone et al., 2019). Silurian magmatism or abundant detritus derived from Silurian magmatic rocks continued in most of these regions and appears in portions of the southern Yukon-Tanana terrane in southeastern Alaska (Yukon-Tanana South; Pecha et al., 2016). Silurian magmatism is absent from the Pearya terrane, but detritus of this age is preserved inboard within the Clements Markham belt in Silurian–Devonian clastic rocks interpreted as an overlap assemblage (i.e., Danish River Formation; Trettin, 1998; Malone et al., 2019).

The $\varepsilon Hf_t$ signature for Ordovician and Silurian zircon in most terranes ranges from +5 to −15, with the important exceptions of the Apoon assemblage in the Doonerak arc, the Whale Mountain allochthon of the North Slope subterrane, and the Prince of Wales area of the southern Alexander terrane, which all have $\varepsilon Hf_t$ signatures ranging from +5 to +15 throughout the

Ordovician and Silurian. Silurian zircon grains from the Clarence River Group of the North Slope subterrane define a clear bimodal $\varepsilon Hf_t$ signature with average $\varepsilon Hf_t$ values at +10 and −5 (Fig. 6). The northern units (St. Elias) and Banks Island assemblage of the Alexander terrane define a pronounced decrease to more evolved Silurian $\varepsilon Hf_t$ values. The southwestern subterranes of Arctic Alaska define a consistent evolved signature in both the Ordovician and Silurian (Strauss et al., 2017; Hoiland et al., 2018; Robinson et al., 2019). In contrast, the Pearya terrane and Clements Markham belt see a shift toward more juvenile grains in the Silurian (Malone et al., 2019) that indicates input from a different arc source.

### Devonian–Carboniferous

Devonian–Carboniferous detrital zircon U/Pb data sets record major changes in provenance throughout most Arctic and Cordilleran terranes (Fig. 3). Carboniferous units overlying the Clements Markham belt show a renewed input of Precambrian detritus accompanied by dominant Tonian–Ediacaran and smaller Middle–Late Devonian peaks (Malone et al., 2019; Beauchamp et al., 2019). Limited $\varepsilon Hf_t$ analyses from these strata define a shift to more juvenile Devonian grains (Malone et al., 2019). Similarly, Upper Devonian strata (e.g., Parry Islands Formation) at the top of the Canadian Arctic Islands clastic wedge are dominated by Neoproterozoic–Devonian grains with juvenile $\varepsilon Hf_t$ signatures interpreted to represent a northern source region (Anfinson et al., 2012b). Carboniferous strata of the North Slope subterrane also record an increased Precambrian signature with important Tonian and Ordovician–Devonian peaks (Gottlieb et al., 2014; Strauss et al., 2017). The $\varepsilon Hf_t$ values for Ordovician–Early Devonian grains from these strata are markedly juvenile, but they also show a sharp decrease to negative $\varepsilon Hf_t$ values in Late Devonian grains (Strauss et al., 2017), largely reflecting input from the Upper Devonian Old Crow plutonic suite and equivalent rocks in Alaska (Ward et al., 2019). Devonian and younger units in the southwestern subterranes of Arctic Alaska and the Farewell terrane show a similar decrease to evolved values in Late Devonian grains (Dumoulin et al., 2018b; Hoiland et al., 2018). Interestingly, the Banks Island assemblage and northern units of the Alexander terrane show a transition from strongly evolved signatures in Ordovician and Silurian grains in older units to dominantly juvenile values across Ordovician to Devonian grains in Devonian units, a signature that is more consistent with the southern Alexander terrane (Beranek et al., 2013b, 2013c; Tochilin et al., 2014; White et al., 2016).

## PALEOZOIC TERRANE ACCRETION AND TRANSLATION ON THE CANADIAN ARCTIC TRANSFORM SYSTEM

Models for Paleozoic translation along the northern margin of Laurentia have long been invoked to explain connections between Svalbard and Pearya (e.g., Trettin, 1987) and terrane translation associated with Arctic Alaska (e.g., Sweeney, 1982). The Northwest Passage model for Paleozoic terrane transfer from the Arctic domain to the Cordilleran margin (Colpron and Nelson, 2009) also requires a transcurrent boundary along the Paleozoic Arctic margin of Laurentia. Building on structural studies of the Pearya terrane (von Gosen et al., 2012; McClelland et al., 2012; Piepjohn et al., 2013, 2015) and North Slope subterrane (von Gosen et al., 2019; Faehnrich et al., 2021), McClelland et al. (2021) proposed that Paleozoic terrane translation was achieved by the Canadian Arctic transform system.

The easternmost segments of the Canadian Arctic transform system are Silurian and Devonian strike-slip faults that juxtapose the various terranes of Svalbard (Mazur et al., 2009; Kośmińska et al., 2014; Majka et al., 2015; Faehnrich et al., 2020; Wala et al., 2021). These structures presumably extend to North Greenland (e.g., Harder Fjord fault zone; Piepjohn and von Gosen, 2001), although their Silurian–Devonian displacement history is obscured by Mesozoic–Cenozoic reactivation. We infer that the Harder Fjord fault system truncates coeval faults projecting from the Caledonian orogen, facilitating transfer of crustal fragments involved in the Laurentia-Baltica collision to the northern Laurentian margin. Many of these terranes were subsequently transferred to the Cordilleran realm. The timing of early displacement on the Harder Fjord fault zone in North Greenland is not well known, but it is inferred to have been an active part of the Canadian Arctic transform system because it juxtaposes Proterozoic–early Paleozoic metasedimentary and Ediacaran arc rocks (Rosa et al., 2016; Estrada et al., 2018a) with autochthonous rocks of the Franklinian margin.

Composite shear zones associated with the Pearya terrane record complex histories of reactivation (Piepjohn et al., 2013). Intraterrane shear zones locally record Ordovician sinistral deformation (McClelland et al., 2012), but many of the fault zones on Ellesmere Island also record multiple phases of younger reactivation (e.g., Piepjohn et al., 2016; Vamvaka et al., 2019). The development of a Silurian–Devonian overlap assemblage across Ellesmere Island is consistent with the proximity of the Pearya terrane to the Franklinian margin by that time, but the internal correlations and timing of this overlap are still controversial. Additional components of sinistral displacement, margin-normal contraction, and metamorphism are assigned to the Late Devonian–Carboniferous Ellesmerian orogeny (Piepjohn et al., 2015; Kośmińska et al., 2022).

The western expression of the Canadian Arctic transform system is the Porcupine fault system, which separates the North Slope subterrane from Laurentia. The structure records older sinistral and younger dextral brittle deformation (von Gosen et al., 2019). Older elements of displacement on the Porcupine shear zone that lies within the broader Porcupine fault system include pre–Late Devonian displacement of the North Slope subterrane (Colpron et al., 2019) with continued translation during emplacement of Late Devonian granites (Ward et al., 2019) and development of Late Devonian strike-slip basins (Faehnrich et al., 2021). Correlation of structures responsible for Paleozoic strike-slip translation of the Svalbard terranes, the Pearya terrane, and the North Slope subterrane defining a continuous transform system is based on broad similarities in timing and kinematics within each region (McClelland et al., 2021).

## PALEOZOIC EVOLUTION OF THE NORTHERN LAURENTIAN MARGIN

Understanding the evolution of the northern Laurentian margin ultimately requires reliable paleogeographic information from each terrane or crustal fragment (e.g., Torsvik and Cocks, 2013), as well as the major cratons (e.g., Cocks and Torsvik, 2011). This is particularly true for new rigid plate models that use fully closed and time-dependent plate boundaries (e.g., Shephard et al., 2013). The considerable variation in the placement of terranes in existing paleogeographic models of the circum-Arctic is likely due to large uncertainties or a lack of appropriate data and the assumption that the northern margin of Laurentia remained passive until the Ellesmerian orogeny (cf. Lawver et al., 2002, 2011; Cocks and Torsvik, 2011; Miller et al., 2011; Beranek et al., 2013b, 2013c). Here, we attempt to place the U/Pb-Hf detrital zircon data and structural observations summarized above into a revised paleogeographic sequence that fits the sparse faunal and paleomagnetic observations. This update of the Northwest Passage model (Colpron and Nelson, 2009, 2011) better accounts for the origin and emplacement of crustal fragments on the northern Laurentian margin by Devonian time and replaces the arbitrary term "Crockerland" (Embry, 1993) with specific terranes represented in the geologic record. There is still considerable uncertainty in current understanding of the placement and interrelationships between the various terranes and cratons, but the overarching tectonic processes envisioned for northern Laurentia are the collapse of an arc system against the Laurentian margin after the Baltica-Laurentia collision (Caledonian) followed by the transition to a transpressional strike-slip system (Ellesmerian) and subsequent incipient subduction along the western margin of North America (Cordilleran).

The observed variations in dominant U/Pb age peaks and $\varepsilon Hf_t$ signatures (Figs. 6 and 8) define subtle but significant differences in Paleozoic arc magmatism recorded in Arctic and Cordilleran terranes. The early Paleozoic arc-related terranes were fragments derived from the northern continuation of an arc system that accommodated closure of the Iapetus Ocean and the terminal Silurian collision of Baltica and Laurentia (Fig. 9A; Strauss et al., 2017). These poorly preserved arc complexes are best viewed as age-equivalent to subduction-related rocks now preserved in the thrust sheets of the Scandinavian Caledonides rather than derived from the Caledonides sensu stricto. For example, arc complexes that extended beyond the Caledonides are characterized by a mixture of juvenile intra-oceanic arc fragments (e.g., southern Alexander terrane, Doonerak arc) and composite arcs built on continental or thinned continental substrates derived from the rifted margins of Laurentia, Baltica, and Siberia (e.g., Pearya, northern Alexander, and Farewell terranes, respectively). They evolved in different tectonic settings than the Caledonian orogen sensu stricto, and, thus, they have fundamentally different U/Pb and $\varepsilon Hf_t$ signatures. The paleogeographic origin of these arc fragments along the northern extension of the Iapetus Ocean remains uncertain (Beranek et al., 2015; White et al., 2016; Strauss et al., 2017), but we envision a complex array of subduction boundaries accommodating closure of the Iapetus Ocean, rather than a simple convergent margin, to explain the observed variation (Fig. 9A). Ordovician tectonism in Pearya and Svalbard, such as the M'Clintock orogeny and Ordovician HP events in Svalbard, reflects intra-arc collision, basin closure, and perhaps the initial collapse of a fringing arc system on the northern Laurentian margin.

Translation along the Arctic margin of Laurentia initiated as Ordovician and Silurian subduction migrated westward in concert with the continued westward motion of Siberia (Fig. 9B). Silurian magmatism associated with collision-related crustal thickening extended from North-East Greenland only as far as the Nordaustlandet terrane (Eastern province) and Northwest province of Svalbard. On Pearya, the Ordovician arc had shut off before translation, and Silurian magmatism is recorded only in detrital zircon of the synorogenic sedimentary rocks that overlap both the Pearya terrane and Franklinian basin. Silurian synorogenic strata located inboard of the Pearya terrane are commonly assumed to be derived from the Caledonian orogen (e.g., Anfinson et al., 2012a); however, the U/Pb-Hf isotopic signature of these units is distinct from the highly evolved Caledonian sources, making local northerly derivation more likely (Fig. 6). Possible sources of Silurian arc magmatism outboard of the Pearya terrane include the Arctic Alaska, Alexander, and Farewell terranes. Westward migration of this hypothesized Silurian subduction system likely continued outboard of the Pearya terrane as it was translated along the Arctic margin (Fig. 9B).

In contrast to most models that infer orthogonal collision between Laurentia and outboard terranes, we hypothesize that a distinct phase of transpressional displacement on the Canadian Arctic transform system resulted in the Devonian–Carboniferous Ellesmerian orogeny (Fig. 9C). Final contraction in the northern Caledonides was marked by UHP metamorphism at ca. 360 Ma in North-East Greenland. This was accompanied by margin-parallel escape from the orogen along sinistral and dextral strike-slip zones. This intra-Caledonian strike-slip system was truncated by the Canadian Arctic transform system and effectively transferred Caledonian rocks of Svalbard to the Arctic margin (Fig. 9C). The onset of transpression on the Canadian Arctic transform system roughly coincided with a change to northward motion of Laurentia in the Middle–Late Devonian that continued through the Carboniferous (e.g., Cocks and Torsvik, 2011; Torsvik et al., 2012) and may have been associated with the onset of Acadian, Neo-Acadian, and Alleghenian deformation along the Appalachian margin.

Pearya and fragments of the Arctic Alaska terrane were located on the continental margin of Laurentia at this time, thereby providing key source regions for the Ellesmerian clastic wedge, whereas the Alexander terrane was likely located farther

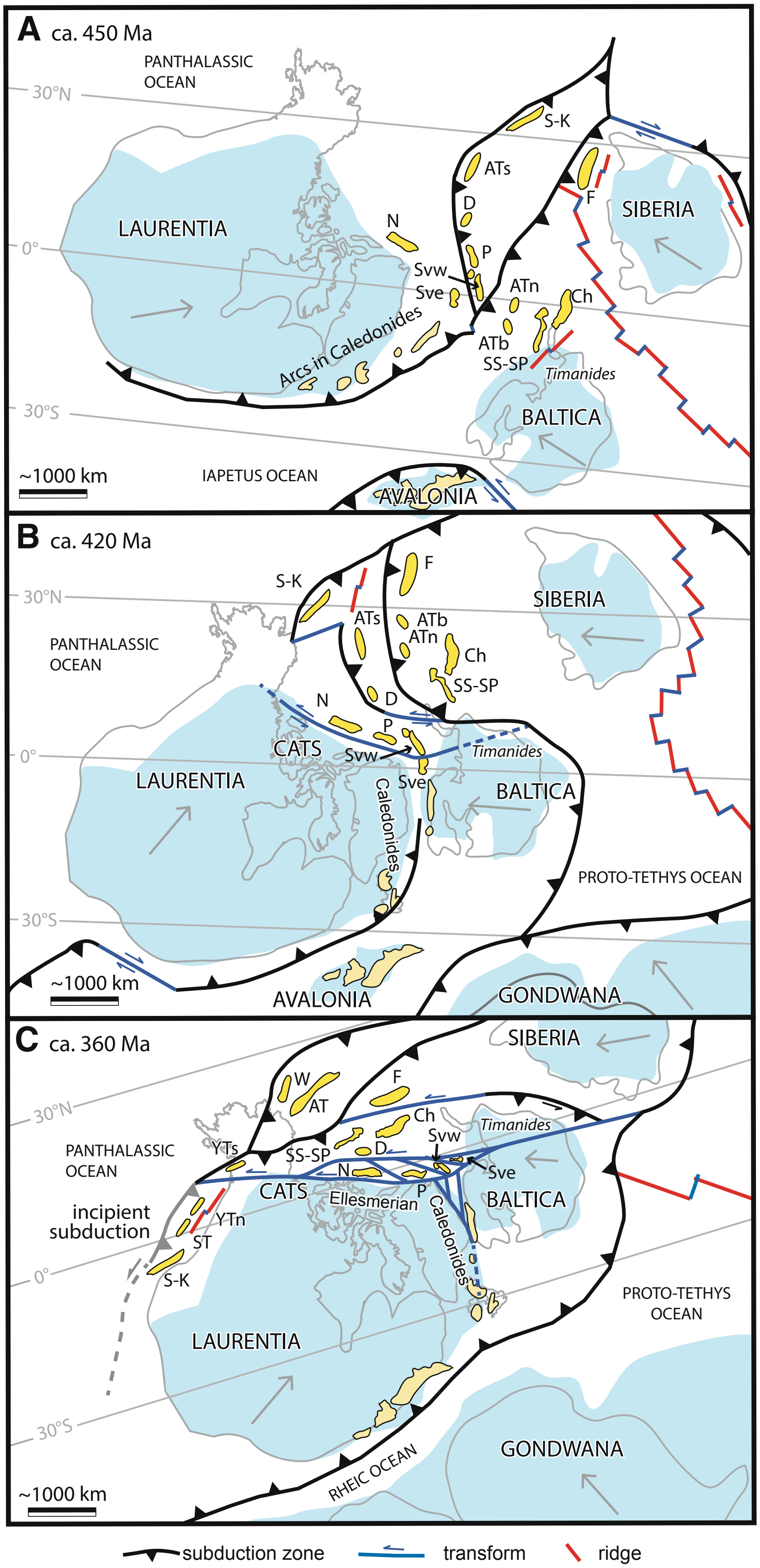


Figure 9. Schematic paleogeographic reconstructions of the circum-Arctic region in the: (A) Ordovician, (B) Silurian, and (C) Devonian, modified after Strauss et al. (2017), Torsvik and Cocks (2017), and Ward et al. (2019). Arctic Alaska: N—North Slope subterrane, SS-SP—southern Brooks Range and Seward Peninsula, and Ch—Chukotka of the southwestern subterranes; D—Doonerak. AT—Alexander terrane (ATn—northern, St. Elias; ATs—southern, Prince of Wales Island; ATb—Banks Island assemblage); F—Farewell terrane; P—Pearya terrane; S-K—Sierra-Klamath terranes; ST—Stikinia; Sve and Svw—eastern and northwestern-southwestern basement provinces of Svalbard, respectively; W—Wrangellia; YTn and YTs—Yukon-Tanana terrane in Yukon and southeastern Alaska, respectively. CATS—Canadian Arctic transform system.

outboard (Fig. 9C). Arctic Alaska and Pearya shed Neoproterozoic detritus and characteristic Ordovician–Silurian zircon with juvenile isotopic signatures (Patchett et al., 1999; Beranek et al., 2010; Anfinson et al., 2012b) southward into a Devonian clastic wedge that now covers the northern Canadian Arctic Archipelago and western Laurentia. Amalgamation of the Arctic Alaska terrane was facilitated by a transpressional collision with displacement on the Porcupine shear zone and other subterrane-bounding structures (e.g., Strauss et al., 2019b; von Gosen et al., 2019; Faehnrich et al., 2021; McClelland et al., 2021), resulting in juxtaposition of blocks with different origins and structural histories and recorded by a sharp decrease to more negative Devonian $\varepsilon Hf_t$ zircon values (Fig. 6). Middle–Late Devonian arc magmatism that developed on the different subterranes of Arctic Alaska provided source regions for Devonian zircon in the Ellesmerian clastic wedge; however, additional Hf isotopic data are needed to test this link. The Arctic Alaska arc activity was linked to coeval Uralian arc magmatism on the Baltican margin (e.g., Brown et al., 2006; Miller et al., 2018) by the Canadian Arctic transform system (Fig. 9C). Amalgamation of the Alexander terrane in the Early Devonian, recorded by convergence of both the U/Pb and Hf signatures (Figs. 6 and 8), is consistent with its involvement in this protracted Ellesmerian transpressional regime.

The Late Devonian marked a transition to subduction along the western margin of Laurentia. This is expressed as granitic magmatism in the Arctic Alaska and Yukon-Tanana terranes, as well as in other Cordilleran terranes such as Quesnellia, Kootenay, and the Sierra-Klamaths (Rubin et al., 1990). In addition, back-arc magmatism of this age has been recently described from autochthonous units in northwestern Laurentia (Cobbett et al., 2021). Subduction initiation along the Panthalassa margin has been related to the northward shift of Laurentia in the Late Devonian–Mississippian and the southward propagation of a sinistral transform fault system along the western Laurentian margin (e.g., Colpron and Nelson, 2009; Beranek et al., 2016). The Canadian Arctic transform system effectively accommodated migration of Silurian–Devonian arcs active outboard of the northern Laurentian margin into the Panthalassa realm. The Late Devonian–Carboniferous Cordilleran transform system probably truncated the Canadian Arctic transform system and translated some of the Arctic terranes southward (e.g., Alexander) as mid- to late Paleozoic arc and back-arc systems were developed along western Laurentia.

## CONCLUDING REMARKS

The geologic relationships and U/Pb-Hf geochronologic data summarized here support a revised Northwest Passage model in which crustal fragments and arc terranes migrated across, and then were emplaced along, the northern margin of Laurentia. Ordovician–Silurian arcs that had formed between Laurentia, Baltica, and Siberia obliquely collapsed against northern Laurentia as the Caledonian collision between Baltica and Laurentia evolved. Silurian–Devonian translation resulted in juxtaposition of the Pearya and Arctic Alaska terranes along the northern Laurentian margin, whereas other terranes continued westward to become involved in the Mesozoic Cordilleran orogen. Considerable uncertainty in our understanding of the tectonic evolution of the northern Laurentian margin remains. Field-based studies to determine the location, kinematics, and timing of structures that accommodated the proposed translation are still in their infancy due to the remoteness of the region, the extensive cover by younger strata, and the significant overprinting by younger tectonic activity. Combining field campaigns with geophysical surveys across the continent-ocean boundary would help to link land- and ocean-based results, leading to more comprehensive models and possible tests of the Paleozoic strike-slip model. Many outstanding problems remain. For example, the location of Silurian arc magmatism, widely represented in the detrital record, is largely unknown and remains a fundamental uncertainty in tectonic reconstructions. A wide variety of techniques beyond detrital zircon studies (e.g., paleomagnetic, faunal, and geochemical data) is required to better track terrane movement through the circum-Arctic region; there is still much work to be done.

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