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Detrital zircon U-Pb-Hf isotope signatures of Old Red Sandstone strata constrain the Silurian to Devonian paleogeography, tectonics, and crustal evolution of the Svalbard Caledonides

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ABSTRACT

Detrital zircon provenance studies of Mesoproterozoic basement and overlying Old Red Sandstone strata in northwestern Svalbard, Arctic Norway, were conducted to test competing models for Caledonian paleogeography and tectonics and constrain the magnitude of orogen-parallel, Silurian to Devonian strike-slip faulting following the Laurentia-Baltica collision. Mesoproterozoic basement strata, cut by earliest Tonian orthogneiss units, mostly yielded 1640–1050 Ma detrital zircon populations that are consistent with pre-Caledonian locations near northeast Greenland. Basal Old Red Sandstone deposits that filled pull-apart basins showed basement-derived signatures but also contained 530–450 Ma and 670–570 Ma populations with slightly subchondritic ($\varepsilon_{Hf[t]} = -4$ to -2) Hf isotope compositions. These results are consistent with late Silurian–Early Devonian proximity to the northeast Greenland Caledonides and Pearya, which indicates limited (<200 km) strike-slip displacement of Svalbard's Caledonian allochthons after the Laurentia-Baltica collision. Previously interpreted connections between the Svalbard Old Red Sandstone and British Caledonides are incompatible with these detrital zircon results. Lochkovian Old Red Sandstone strata were deposited after a second episode of strike-slip faulting and show recycled basement signatures. The lack of 530–450 Ma and 670–570 Ma populations suggests that the second deformation episode reorganized local drainages. Pragian–Givetian strata have provenance from local Old Red Sandstone sources that were uplifted during a third and final episode of strike-slip deformation. The results indicate that northern Caledonian (Svalbard, Pearya) crustal evolution was characterized by the reworking of Mesoproterozoic–Paleoproterozoic sources and mostly <600 m.y. crustal residence times, whereas the southern Caledonides (UK, Ireland) show evidence for the reworking of older basement and mostly >600 m.y. crustal residence times.

INTRODUCTION

The continent-continent collision between Baltica (ancestral northern European craton) and Laurentia (ancestral North American craton) resulted in the formation of the supercontinent Laurussia and growth of the Caledonian mountain belt (Fig. 1; e.g., Gee, 1975; McKerrow et al., 2000; Roberts, 2003; Cocks and Torsvik, 2011). The timing of initial collision and subsequent strike-slip faulting and extensional collapse are in part constrained by Old Red Sandstone units along the length of the orogen (Steel et al., 1985; McClay et al., 1986; Friend et al., 2000; Larsen et al., 2008). Detrital mineral provenance studies of Old Red Sandstone strata in the UK and Ireland have proven useful for constraining the evolution of the southern Caledonides (e.g., Stuart et al., 2001; Sherlock et al., 2002; Ennis et al., 2015; Fairey et al., 2018; McKellar et al., 2019). Time-equivalent units in the northern Caledonides have received comparatively less attention, and, as a result, there are many open questions about the provenance, tectonic significance, and paleogeography of Old Red Sandstone strata outside of the British Isles. The purpose of this study was to test models for northern Caledonian geology through new, targeted provenance studies of Old Red Sandstone rock units that are exposed in northwestern Spitsbergen, Svalbard archipelago, Arctic Norway.

The Svalbard Caledonides consist of three basement provinces—Northeastern, Northwestern, and Southwestern—separated by Old Red Sandstone basins and orogen-parallel, late- to postcollisional faults (Fig. 2A). The latter are thought to have assembled Svalbard's basement complexes near northeast Greenland toward the end of the Caledonian orogeny. The amount of lateral displacement along these faults is controversial and varies from a few tens to thousands of kilometers (Harland, 1985, 1997; Gee and Page, 1994; Lyberis and Manby, 1999). Limited displacement models are supported by structural and lithological correlations between the west-directed thrust sheets of the Northeastern and Northwestern provinces and the higher allochthons of the northeast Greenland Caledonides (e.g., Gee and Teben'kov, 2004; Higgins et al., 2008; Gee, 2015). In these models, pre-Caledonian rocks of the Northeastern and Northwestern provinces represent the northern continuation of the northeast Greenland shelf; overlying Old Red Sandstone successions are similarly interpreted to have formed near northeast Greenland. In contrast, competing models that advocate long-distance displacement are based on lithological correlations between rock units in the Northwestern province and southern Caledonides (e.g., Pettersson et al., 2009a, 2009b, 2010). These long-distance displacement models require Old Red Sandstone strata to have sources from the Grenville Province of eastern Canada and peri-Gondwanan Avalon terrane (Avalonia) and related Iapetan elements in the British Isles. Limited to long-distance displacements have also been proposed for the Southwestern province, which has uncertain Proterozoic and younger connections with the Greenland Caledonides, and some similarities with the Pearya

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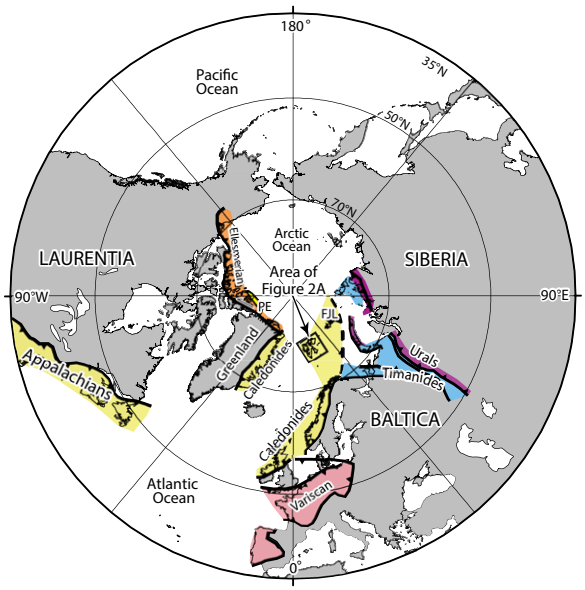

Figure 1. Circum-Arctic cratons and orogens modified from base map of Colpron and Nelson (2009). Abbreviations: FJL—Franz Josef Land, PE—Pearya.

terrane of Arctic Canada (PE in Fig. 1), and the northern, Timanian margin of Baltica (e.g., Gasser and Andresen, 2013).

In northwestern Svalbard, the postcollisional Raudfjorden and Breibogen-Bockfjorden faults (Figs. 2A and 2B) controlled the location of Old Red Sandstone successions during the Silurian and Devonian (all stratigraphic and numerical ages follow the time scale of Cohen et al., 2013). Although the physical stratigraphy of these rock units has been established (Friend et al., 1997; McCann, 2000), the influence of strike-slip faulting on sediment provenance and drainage patterns remains untested. The late Silurian(?) Siktefjellet Group (Gee and Moody-Stuart, 1966) is the oldest Old Red Sandstone succession of Svalbard (Figs. 3A and 3B) and was involved in an episode of pre–Early Devonian strike-slip faulting and regional uplift known locally as the Haakonian deformation (Gee, 1972). Unconformably overlying strata of the Lochkovian Red Bay Group were subsequently deposited in north-trending grabens that extend for ~100 km from Raudfjorden in the north to Blomstrandhalvøya in the south (Figs. 2B, 3A, and 3B). A successive episode of late Lochkovian strike-slip faulting and folding, known locally as the Monacobreen deformation, resulted in the inversion of Red Bay Group basins (McCann, 2000). Middle to Upper Devonian strata of the Andrée

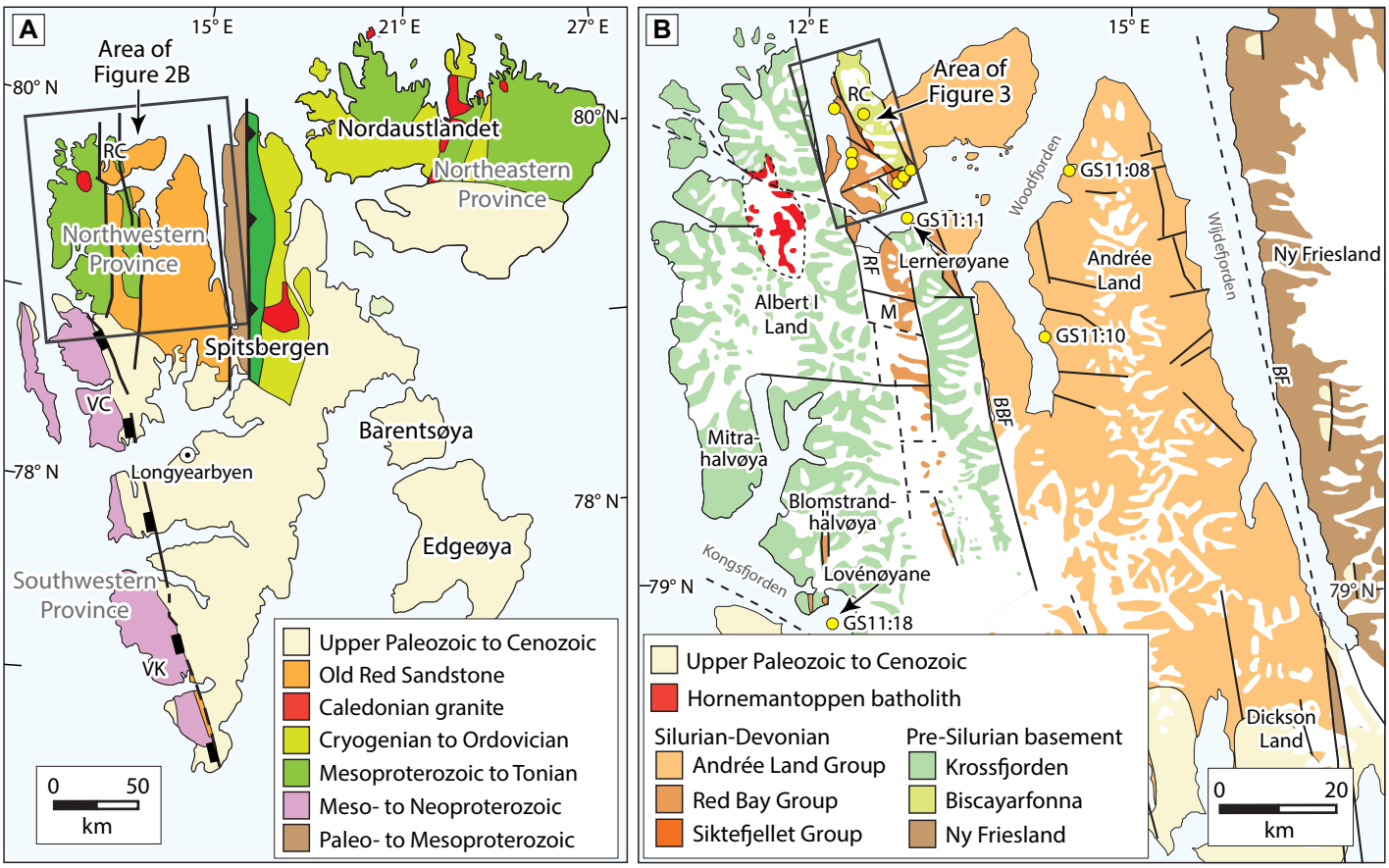

Figure 2. (A) Tectonostratigraphic map of the Svalbard Caledonides modified from Gee (2015). (B) General geology of northwestern Svalbard modified from McCann (2000). Yellow circles indicate the locations of detrital zircon samples. BF—Billefjorden fault, BBF—Breibogen-Bockfjorden fault, M—Monacobreen area, RC—Richarddalen complex, RF—Raudfjorden fault, VC—Vestgötabreen complex, VK—Vimsodden-Kosibapasset shear zone.

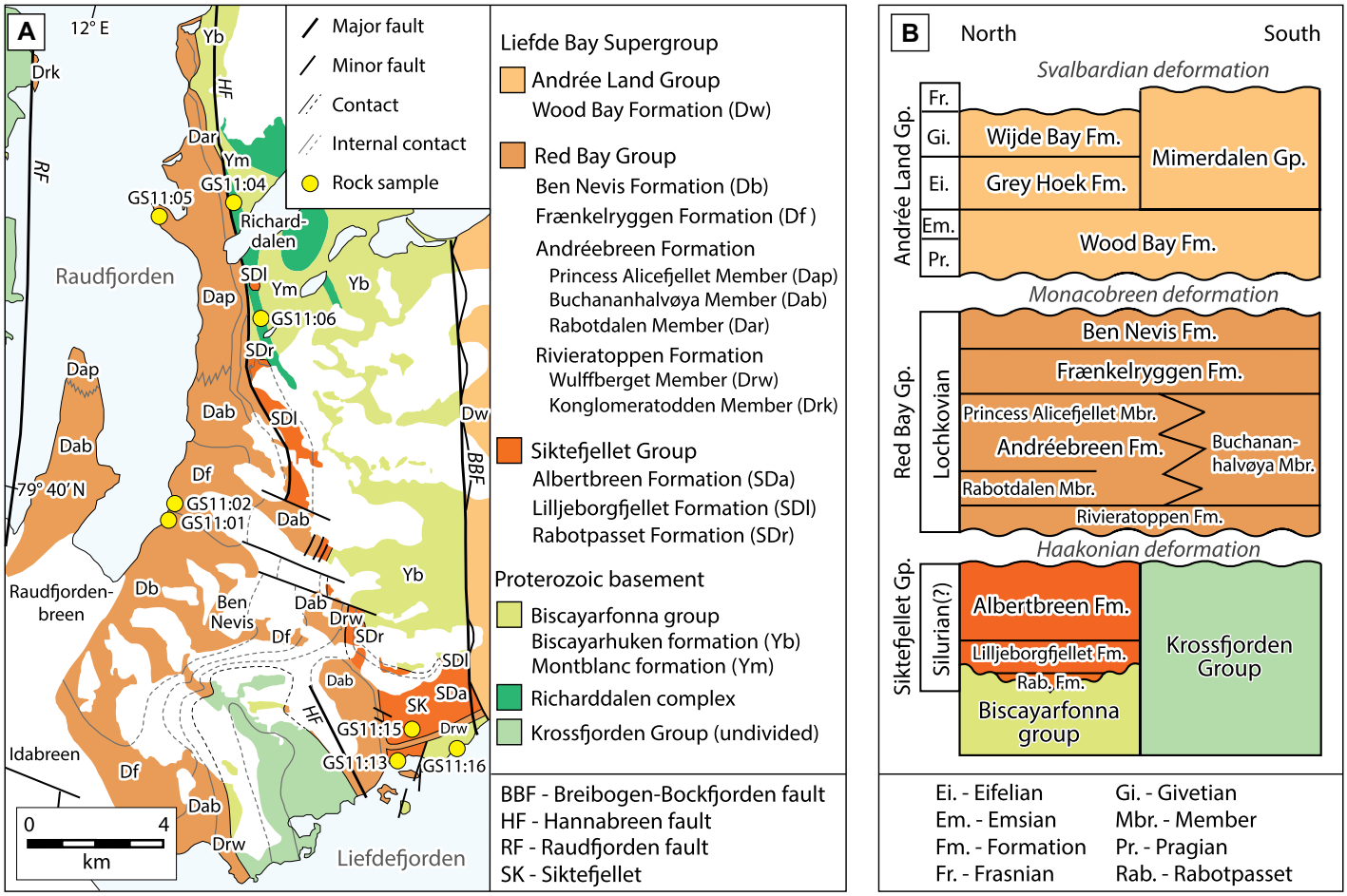

Figure 3. (A) General geology of the Raudfjorden area modified from Friend et al. (1997). Yellow circles indicate the locations of detrital zircon samples. Solid (observed) and dashed (inferred) internal contacts indicate age-equivalent facies of the Andréebreen Formation. (B) Schematic stratigraphy (following the International Union of Geological Sciences time scale of Cohen et al., 2013) of the Siktefjellet, Red Bay, and Andrée Land groups in northwestern Svalbard compiled from Friend et al. (1997) and McCann (2000).

Land Group filled the ~50-km-wide Andréeland-Dicksonland graben, the largest Old Red Sandstone depocenter in Svalbard (Figs. 2B and 3B; Friend and Moody-Stuart, 1972), the basement of which is nowhere exposed.

In this study, we used detrital zircon U-Pb-Hf laser ablation techniques to constrain the provenance of Mesoproterozoic metasediments and overlying Old Red Sandstones of the Siktefjellet, Red Bay, and Andrée Land Groups in northwestern Svalbard. The samples were collected to improve our understanding of the bedrock geology and to develop new working hypotheses that concern: (1) the metasedimentary basement correlations between Svalbard's provinces and equivalent Laurentian-Baltican successions in the North Atlantic region, including the Pearya terrane; (2) the influence of late- to postcollisional strike-slip faulting episodes on sediment provenance and drainage patterns; and (3) the Silurian to Devonian paleogeography of Svalbard and its ties with the northern and/or southern parts of the Caledonian orogen. The results provide a detrital zircon reference frame for northwest Svalbard's crustal evolution, which is distinguishable from parts of the southern Caledonides and may be useful for future paleogeographic reconstructions.

PRE-DEVONIAN TECTONIC AND PALEOGEOGRAPHIC FRAMEWORK: SVALBARD'S BASEMENT PROVINCES

Northeastern Province

The Northeastern province (Fig. 2A) comprises a composite block that has been subdivided into the Nordaustland and West Ny Friesland terranes (e.g., Harland, 1997; Gee and Teben'kov, 2004); these have more recently been referred to as allochthons (Gee, 2015), based on comparability with the long-transported thrust sheets in northeast Greenland (Higgins and Leslie, 2000). Comparisons with the Laurentian margin of northeast Greenland are based mainly on their pre-Caledonian stratigraphic assemblages (e.g., Harland, 1985, 1997); Proterozoic and Caledonian tectonothermal histories (summarized in Gee and Teben'kov, 2004) are also remarkably similar. The Nordaustland allochthon includes a lower complex of deformed, metamorphosed, and partly migmatized late Mesoproterozoic to earliest Neoproterozoic metasedimentary rocks (Brennevinsfjorden Group) that are intruded by 970–950 Ma granites (e.g., Johansson et al., 2004, 2005; McClelland et al., 2019) and unconformably overlain (Ohta, 1982) by ca. 950 Ma intermediate to felsic volcanic rocks. This early Tonian complex is itself unconformably overlain (Gee and Teben'kov, 1996; Sandelin et al., 2001) by Cryogenian siliciclastic and carbonate formations (including tillites; Halverson et al., 2004) comprising the Murchisonfjorden Supergroup,

which passes up into Cambrian to Early Ordovician continental-margin strata of the Hinlopenstretet Supergroup. These little-metamorphosed, several-kilometer-thick, Cryogenian (perhaps also late Tonian) to Ordovician assemblages of the Nordaustland allochthon compare closely with the Eleonore Bay Supergroup and early Paleozoic carbonate bank units of northeastern Greenland. Likewise, the underlying early Tonian complex in Nordaustlandet is similar to the Hager Bjerg allochthon in northeast Greenland. Subsequent Caledonian orogeny in both regions involved Late Ordovician–Silurian (450–430 Ma) migmatization and Silurian (430–420 Ma) granite intrusion in the lower structural levels of the allochthons (Johansson et al., 2005; Higgins et al., 2008).

The West Ny Friesland allochthon, consisting of a stack of amphibolite-facies thrust sheets (Witt-Nilsson et al., 1998), is juxtaposed with the Nordaustland allochthon on its east side by a west-vergent thrust and bounded on its west side by the Billefjorden fault and the Andréeland-Dicksonland graben (Figs. 2A and 2B). The West Ny Friesland thrust sheets are dominated by Paleoproterozoic (ca. 1750 Ma) granitic gneiss (Johansson et al., 1995; Hellman et al., 2001), locally with evidence of Neoarchean (ca. 2700 Ma) orthogneiss. Together with unconformably overlying Mesoproterozoic strata, these rocks are intruded by ca. 1300 Ma mafic intrusions (Hellman and Witt-Nilsson, 1999). Subordinate tectonic intercalations of younger metasedimentary formations, including carbonates lacking the mafic intrusions, have yielded detrital zircon populations as young as 1190 Ma (Gee and Hellman, 1996). The West Ny Friesland allochthon has not yielded evidence of the Tonian tectonism that characterizes the early history of the Nordaustland allochthon. The amphibolite-facies metamorphism of the Caledonian thrust sheets may have started in the Middle to Late Ordovician (Gee and Page, 1994) and continued into the early Silurian. There is evidence for late Silurian–Devonian ductile deformation (Lyberis and Manby, 1999) adjacent to the Billefjorden fault zone and regional uplift within the Andréeland-Dicksonland graben that reaches westward to the Breibogen-Bockfjorden fault (Fig. 2B; Gee and Page, 1994). The West Ny Friesland allochthon has many features in common with the Niggli Spids thrust sheets and correlatives in the northeast Greenland Caledonides in the footwall of the Hager Bjerg allochthon.

Northwestern Province

The Northwestern province extends from the Breibogen-Bockfjorden fault, defining the western margin of the Andréeland-Dicksonland graben, to the Greenland Sea coast in the west. This province is divided by the north-trending Raudfjorden graben, separating the Caledonian complexes into two domains. East of the graben, in the northern parts, the Biscayarfonna-Holtedahlfonna horst contains Mesoproterozoic to earliest Neoproterozoic amphibolite-facies metasedimentary rocks of the Biscayarfonna group (Biscayarhuken and Montblanc formations). These units locally overlie the Richarddalen complex, which consists of metasedimentary and meta-igneous rocks with eclogites (Gee, 1966; Harland, 1997; Ohta et al., 2003; Labrousse et al., 2008). This enigmatic higher-pressure complex includes granitic augen gneiss and corona metagabbro units yielding ca. 960 Ma zircon U-Pb ages and geochemical signatures that indicate reworking of preexisting crust (Peucat et al., 1989; Gromet and Gee, 1998). Mafic and felsic intrusions cut this Tonian basement; they were emplaced at 670–620 Ma and likely reflect magmatism during late Cryogenian rifting prior to the opening of the northern Iapetus Ocean (e.g., Gromet and Gee, 1998). The timing of high-pressure metamorphism of the Richarddalen complex remains uncertain, but subsequent amphibolite-facies metamorphism (Gromet and Gee, 1998) occurred during the Middle Ordovician (ca. 455 Ma) to mid-Silurian (ca. 430 Ma). Near Richarddalen (Fig. 3A), the complex is thrust over Biscayarfonna group rocks; farther south, it directly underlies the basal Old Red Sandstone conglomerate units.

West of the Raudfjorden graben, basement in Albert I Land contains Mesoproterozoic metasedimentary rocks of the Krossfjorden Group, Tonian (ca. 996–970 Ma) orthogneiss, and Silurian-Devonian (ca. 430–419 Ma) migmatite and felsic intrusions (e.g., Hornemantoppen batholith; Fig. 2B; e.g., Myhre et al., 2008; Pettersson et al., 2009a). Krossfjorden Group strata mostly contain late Paleoproterozoic to Mesoproterozoic detrital zircon grains, including modal peaks between 1760 and 1620 Ma, which Pettersson et al. (2009b) interpreted to indicate provenance from the Grenville Province of eastern Laurentia. The overall stratigraphy and tectonothermal evolution of Northwestern province basement, with the exception of the Richarddalen complex, are similar to the Tonian complex on Nordaustlandet. The comparability of Northwestern and Northeastern province basement units with thrust sheets in northeastern Greenland supports precollisional links with the northeastern Laurentian margin (Gee et al., 2008; Gee, 2015).

Southwestern Province

Basement rocks of the Southwestern province crop out along the coastline of southwestern Spitsbergen, where Old Red Sandstones are locally represented (Fig. 2A). This part of the Caledonian orogen is a basement component within the Cenozoic fold-and-thrust belt of western Svalbard; its eastern, pre-Cenozoic boundary remains to be precisely defined. The province is composed of several pre-Devonian domains that were influenced by early Caledonian deformation and high-pressure metamorphism and subsequent Silurian deformation and Old Red Sandstone deposition. The prominent late Neoproterozoic (ca. 640 Ma) Torrelian unconformity (Birkenmajer, 1981) interrupts these pre-Devonian successions in the southern parts of the Southwestern province and is comparable with the age of early Timanian orogenesis along the northern margin of Baltica (Gee and Teben'kov, 2004). For example, Mazur et al. (2009) proposed that the Vimsodden-Kosibapasset shear zone in Wedel Jarlsberg Land (VK in Fig. 2A) is a major terrane boundary that juxtaposes Laurentian and Timanian crustal blocks. Southwest of the Vimsodden-Kosibapasset shear zone, late Mesoproterozoic meta-igneous units were imbricated with Neoproterozoic metasedimentary rocks during late Neoproterozoic (650–640 Ma) thrusting, amphibolite-facies metamorphism, and local pegmatitic magmatism (e.g., Majka et al., 2008, 2010, 2012). Northeast of the Vimsodden-Kosibapasset shear zone, recent data indicate that Mesoproterozoic rocks were intruded by Tonian (950 Ma) granite and similarly metamorphosed ca. 640 Ma (Majka et al., 2014). Mesoproterozoic quartzite beneath the Torrelian unconformity mostly contains 1800–1000 Ma detrital zircon grains, including modal peaks between 1750 and 1600 Ma, which are similar to the Krossfjorden Group and coeval rock units in northern (Sværholt succession) and central-northern (Heggmovatn supracrustals) Norway (Gasser and Andresen, 2013). These results not only indicate that much of the Southwestern province was affected by Torrelian deformation, thus calling into question the significance of the Vimsodden-Kosibapasset shear zone, but they also indicate that many parts of Svalbard share histories of Mesoproterozoic sedimentation and Tonian magmatism (Bjørnerud, 1990; Majka et al., 2014). North of the Vimsodden-Kosibapasset shear zone, the Vestgötabreen complex (VC in Fig. 2A) represents a high-pressure metamorphic succession that is in faulted contact with underlying Neoproterozoic rocks, including Marinoan(?) diamictite (Harland, 1997; Labrousse et al., 2008). Blueschist- to eclogite-facies metamorphism occurred during the Early to Middle Ordovician (Dallmeyer et al., 1990; Bernard-Griffiths et al., 1993) and corresponds with the timing of arc-continent collision events in Norway, Ireland, and Scotland (Grampian

orogeny), the Northern Appalachians (Taconic orogeny), and the Pearya terrane (PE in Fig. 1; M'Clintock orogeny). Ordovician to Silurian strata (Bullbreen Group) that unconformably overlie the Vestgötabreen complex have yielded 1700–920 Ma and 760–640 Ma detrital zircon grains of uncertain provenance within the Laurentia–greater Baltica convergent-margin system (Gasser and Andresen, 2013).

OLD RED SANDSTONE STRATIGRAPHY AND TECTONICS OF NORTHWESTERN SVALBARD

Siktefjellet Group

The Siktefjellet Group is the lowermost unit of the Liefde Bay Supergroup and consists of three formations in the Raudfjorden-Liefdefjorden area of northwestern Svalbard (Figs. 3A and 3B; Gee and Moody-Stuart, 1966; Friend et al., 1997). Monomictic to polymictic breccia units of the basal Rabotpasset Formation (0–25 m thick) occur in depositional, but often faulted contact with metamorphic basement in two small subbasins. Rabotpasset Formation strata are more indurated and fractured than overlying Siktefjellet Group rock units, which is evidence for local compression after deposition (Friend et al., 1997). The overlying Lilljeborgfjellet Formation (100–400 m thick) crops out as a linear unit of conglomerate east of the north-trending Hannabreen fault (HB in Fig. 3A) and contains clasts of local augen gneiss, quartzite, and marble, and boulders of unmetamorphosed 1740 Ma quartz-feldspar porphyry derived from the basement beneath the western part of the Andréeland-Dicksonland graben (Hellman et al., 1998). The overlying Albertbreen Formation (up to 1400 m thick) includes trough cross-bedded sandstone, ripple cross-laminated siltstone, and mudstone. Plant remains and spores indicate a late Silurian to earliest Devonian age for the Albertbreen Formation (e.g., Murašcov and Mokin, 1979; Harland, 1997). Siktefjellet Group facies are consistent with debris-flow (Rabotpasset and Lilljeborgfjellet Formations) and braided river (Albertbreen Formation) deposits that filled pull-apart basins in the Siktefjellet strike-slip zone, which Friend et al. (1997) informally named for the geographic area between the north-trending Raudfjorden and Breibogen-Bockfjorden faults (see RF and BBF in Fig. 2B).

Red Bay Group

Lochkovian strata sit unconformably on the Siktefjellet Group and also overlap metamorphic basement across northwestern Svalbard (Fig. 2B). The Lochkovian depositional surface was established after Haakonian deformation (Gee, 1972), which is named for pre-Lochkovian sinistral strike-slip movement on the Siktefjellet fault zone. The basal unconformity varies from being angular to having little angular discordance, suggesting that Haakonian deformation was localized (Friend et al., 1997).

Stratigraphic units of the Red Bay Group are assigned to five formations (Figs. 3A and 3B). The basal Rivieratoppen Formation (up to 300 m thick) is notably pervasive across the grabens of northwestern Svalbard (Harland, 1997). Conglomerate units that make up the Konglomeratodden and Wulffberget members of the Rivieratoppen Formation are composed of metamorphic basement clasts and apparently lack rock fragments from the underlying Siktefjellet Group (Friend et al., 1997). The Andréebreen Formation (up to 1300 m thick) consists of the lower Rabotdalen member and laterally equivalent facies of the Buchananhalvøya and Princess Alicefjellet members. The formation is dominated by pebble conglomerate and breccia, cross- to planar-bedded sandstone, and mudstone. Gravelly facies of the Andréebreen Formation are polymictic and include clasts of vein quartz, quartz–mica schist, quartzite, gneiss, psammite, and marble (e.g., Harland, 1997). The Frænkelryggen Formation (up to 750 m thick) contains vertebrate and invertebrate fossil horizons that provide Lochkovian depositional ages for the Red Bay Group (e.g., Friend, 1961). Frænkelryggen Formation strata include cross- to planar-bedded sandstone, calcareous pebble conglomerate, and mudstone. The Ben Nevis Formation (up to 900 m thick), the uppermost unit of the Red Bay Group, consists of cross-bedded micaceous sandstone, siltstone, and mudstone that yield a late Lochkovian fauna (e.g., Harland, 1997). Red Bay facies show a fining-upward trend, with fault-proximal, alluvial-fan strata (Rivieratoppen Formation) at the base that transition into sandy braided river to lacustrine (Andréebreen Formation) and mostly north-directed, stable fluvial to marginal-marine (Frænkelryggen and Ben Nevis Formations) deposits at the top (e.g., Friend et al., 1997).

Andrée Land Group

Late Lochkovian sinistral strike-slip deformation in the Monacobreen area (M in Fig. 2B) resulted in north-south extension and fault block rotation followed by east-west shortening (McCann, 2000). Red Bay Group basins were inverted during the latter folding and thrusting event, known as the Monacobreen deformation phase (McCann, 2000), and were likely sediment source areas for Pragian and younger strata of the Andrée Land Group that crop out east of the Breibogen-Bockfjorden fault. Where exposed, basal Andrée Land Group strata sit unconformably on both metamorphic basement and deformed Red Bay Group rocks (McCann, 2000).

The Andréeland-Dicksonland graben is bounded by the Breibogen-Bockfjorden fault on the west and the Billefjorden fault on the east (BBF and BF in Fig. 2B). The Andrée Land Group is exposed across the northern parts of this graben (e.g., Friend, 1961; Friend and Moody-Stuart, 1972) and consists of three stratigraphic units (Fig. 3B). The basal Wood Bay Formation (up to 3000 m thick) contains Pragian cross-bedded to massive micaceous sandstone, pebble conglomerate, and silty sandstone, and Emsian mudstone and calcareous siltstone (e.g., Harland, 1997). The Grey Hoek Formation (up to 1000 m thick) consists of Eifelian massive to cross-bedded sandstone, mud-flake conglomerate, calcareous mudstone with desiccation cracks, and silty limestone with carbonate nodules (e.g., Harland, 1997). The Wijde Bay Formation (up to 600 m thick), the uppermost unit of the northern Andrée Land Group, contains quartz sandstone, shale, and fossiliferous siltstone with late Eifelian to Givetian marine and nonmarine faunas (Harland, 1997). Andrée Land Group facies are consistent with the Pragian to Emsian establishment of north- to northeast-directed fluvial systems (Wood Bay Formation) followed by Eifelian to Givetian (Grey Hoek and Wijde Bay Formations) deposition with coastal marine influences (Friend and Moody-Stuart, 1972). The southern Andrée Land Group in Dickson Land yields Givetian to Famennian strata with similar fluvial to marginal-marine origins, but also a more complicated Late Devonian history that includes local uplift adjacent to the Billefjorden fault (Piepjohn and Dallmann, 2014).

Late Famennian (possibly early Tournaisian) west-vergent thrusting and folding in northwestern Svalbard, known as Svalbardian deformation (Fig. 3B; Vogt, 1938), marked the end of Old Red Sandstone deposition (e.g., Piepjohn et al., 2000). The Svalbardian thrust belt is exposed for ~20 km from the Billefjorden fault westward to Woodfjorden. Farther west on Mitrahalvøya and Blomstrandhalvøya (see locations in Fig. 2B), Proterozoic and younger rock units may also have been influenced by Svalbardian folding (Piepjohn, 2000). Svalbardian deformation is inferred to represent the eastern, along-strike continuation of the Ellesmerian fold-and-thrust belt of Arctic Canada and northeastern Greenland (Fig. 1; e.g., Piepjohn, 2000), which, in the type area, was active during the Middle Devonian to Early Mississippian (Thorsteinsson and Tozer, 1970; Lane, 2007).

TABLE 1. SUMMARY OF DETRITAL ZIRCON SAMPLES COLLECTED FROM NORTHWESTERN SVALBARD

Sample	Latitude (°N)	Longitude (°E)	Age	Rock unit
GS11:06	79°44′38.8″	12°21′50.9″	Late Mesoproterozoic	Richarddalen complex, Richarddalen group
GS11:16	79°38′05.8″	12°50′08.1″	Late Mesoproterozoic	Biscayarhuken formation, Biscayarfonna group
GS11:04	79°45′12.1″	12°16′04.0″	Cryogenian	Felsic dike in Richarddalen complex
GS11:13	79°37′41.3″	12°43′42.7″	Late Silurian(?)	Albertbreen Formation, Siktefjellet Group
GS11:15	79°38′08.3″	12°45′43.0″	Late Silurian(?)	Albertbreen Formation, Siktefjellet Group
GS11:11	79°33′56.4″	12°38′13.0″	Lochkovian	Wulffberget Member, Rivieratoppen Formation, Red Bay Group
GS11:05	79°44′38.8″	12°11′06.1″	Lochkovian	Princess Alicefjellet Member, Andréebreen Formation, Red Bay Group
GS11:02	79°40′32.5″	12°19′39.7″	Lochkovian	Frænkelryggen Formation, Red Bay Group
GS11:01	79°40′00.5″	12°19′35.2″	Lochkovian	Ben Nevis Formation, Red Bay Group
GS11:18	78°56′12.6″	12°17′10.0″	Lochkovian(?)	Red Bay Group (undivided)
GS11:10	79°23′30.9″	14°00′03.9″	Pragian to Emsian	Wood Bay Formation, Andrée Land Group
GS11:08	79°39′15.1″	14°12′26.4″	Eifelian	Grey Hoek Formation, Andrée Land Group

MATERIALS AND METHODS

Twelve rock samples were analyzed for detrital zircon U-Pb geochronology and Hf isotope geochemistry at Memorial University of Newfoundland, St. John's, Newfoundland, Canada, and Washington State University, Pullman, Washington (Table 1; see sample locations in Figs. 2B and 3A). Laboratory analyses were mostly conducted using the laser ablation split-stream approach outlined by Fisher et al. (2014), which allows for simultaneous collection of U-Pb and Hf isotopes using two independent inductively coupled plasma–mass spectrometers. The analytical methods and laser ablation techniques are outlined in the Appendix. Detrital zircon U-Pb-Hf isotope results are reported in the GSA Data Repository (Table DR1[1]). U-Pb dates are presented in probability density plots (Figs. 4–7) made with a Microsoft Excel macro developed at the Arizona LaserChron Center (https://sites.google.com/a/laserchron.org/laserchron/). The modes for each age population, which we informally refer to as age peaks (e.g., Dickinson and Gehrels, 2003), were calculated with the AgePick Microsoft Excel macro developed at the Arizona LaserChron Center.

RESULTS

Proterozoic Basement

Richarddalen complex quartzite (GS11:06) contained Mesoproterozoic (1492–1009 Ma; 75%) and Paleoproterozoic (1892–1604 Ma; 22%) detrital zircon grains with age peaks of 1050, 1129, 1373, 1441, and 1647 Ma (Fig. 4A). Biscayarhuken formation quartzite (GS11:16) yielded Mesoproterozoic (1587–1068 Ma; 30%) and Paleoproterozoic (2081–1606 Ma; 66%) detrital zircon grains with age peaks of 1108, 1143, 1515, and 1643 Ma (Fig. 4B). Minor Neoarchean (2600–2500 Ma) ages occurred in both samples. A felsic dike in Richarddalen complex marble (GS11:04) yielded four ages of 651 ± 7 Ma (96% concordant), 651 ± 11 Ma (91% concordant), 654 ± 7 Ma (96% concordant), and 701 ± 16 Ma (90% concordant). A weighted mean $^{206}Pb/^{238}U$ age of 652 ± 5 Ma (n = 3, mean square of weighted deviates [MSWD] = 0.29) is interpreted as the crystallization age of the dike using the 654–651 Ma grains.

Siktefjellet Group

Albertbreen Formation sandstone (GS11:13) collected near the Liefdefjorden coast mostly contained Cambrian to Ordovician (531–481 Ma; 8%), Mesoproterozoic (1559–1015 Ma; 39%), and Paleoproterozoic (2121–1600 Ma; 37%) detrital zircon grains with age peaks of 490, 1370, 1491, 1660, 1760, and 2013 Ma (Fig. 4C). Minor Ediacaran (623–570 Ma), Tonian (968–914 Ma), and Neoarchean to Mesoarchean (3021–2560 Ma) ages also occurred in this sample. Cambrian to Ordovician zircon grains that comprised the 490 Ma peak yielded subchondritic $\varepsilon_{Hf(t)}$ values of –10.3 to –2.4 ($\bar{X}$ = –4.7), whereas the majority of Tonian and older zircons (90%) had chondritic to superchondritic $\varepsilon_{Hf(t)}$ values of 0 to +8.9 ($\bar{X}$ = +4.6; Fig. 4E).

Albertbreen Formation sandstone (GS11:15) collected near Siktefjellet yielded Cambrian to Ordovician (526–455 Ma; 16%), Tonian (979–904 Ma; 10%), Mesoproterozoic (1583–1018 Ma; 36%), Paleoproterozoic

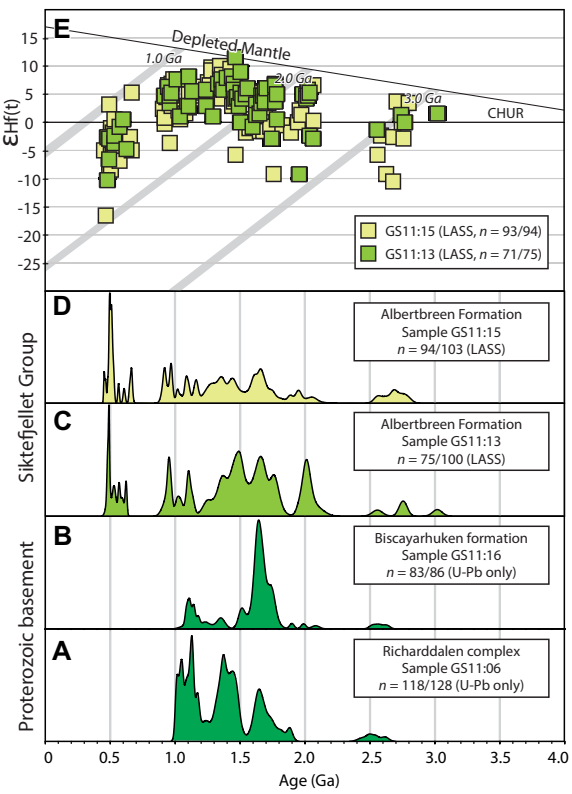

Figure 4. Detrital zircon results from Precambrian metasedimentary basement and Siktefjellet Group rock units. (A) Richarddalen complex quartzite (sample GS11:06). (B) Biscayarhuken formation quartzite (sample GS11:16). (C) Albertbreen Formation sandstone (sample GS11:13). (D) Albertbreen Formation sandstone (sample GS11:15). (E) $\varepsilon_{Hf(t)}$ vs. U-Pb age diagram for Albertbreen Formation detrital zircon samples. Precambrian metasedimentary basement samples were only analyzed with conventional U-Pb dating techniques (shown in figure as U-Pb only), whereas the Siktefjellet Group samples were analyzed by laser ablation split stream (LASS) techniques. The total number of analyses is presented with the results; for example, n = 118/128 indicates that a total of 128 analyses for sample GS11:06 yielded 118 ages that passed the discordance filter and were used for interpretation (see also Figs. 5–7). The Appendix contains supporting information about the laser ablation methods used. CHUR—chondritic uniform reservoir.

[1]GSA Data Repository item 2020101, LA-ICP-MS detrital zircon U-Pb age and Hf isotope results, is available at http://www.geosociety.org/datarepository/2020 or by request to editing@geosociety.org.

(2060–1603 Ma; 23%), and Neoarchean to Mesoarchean (2801–2558 Ma; 10%) detrital zircon grains with peaks of 498, 510, 920, 969, 1357, 1441, and 1660 Ma (Fig. 4D). A minor Cryogenian to Ediacaran (667–566 Ma) grouping also occurred in this sample. Paleozoic zircon grains yielded $\varepsilon_{Hf(t)}$ values of –16.7 to +3.3 (Fig. 4E), with most subpopulations having average $\varepsilon_{Hf(t)}$ values of –10.9 to –2.4. The minor Ediacaran population yielded $\varepsilon_{Hf(t)}$ values that ranged from –6.8 to +5.3 ($\bar{X}$ = –2.4). Most Tonian and older detrital zircon grains had chondritic to superchondritic $\varepsilon_{Hf(t)}$ values of 0 to +9.9 (71%; $\bar{X}$ = +4.2), but there were generally lower values for 979–904 Ma ($\bar{X}$ = +3.0) and 2801–2558 Ma ($\bar{X}$ = –2.9) zircon grains.

Red Bay Group

Wulffberget Member sandstone of the Rivieratoppen Formation (GS11:11) contained Cambrian to Ordovician (524–462 Ma; 16%), Mesoproterozoic (1584–1044 Ma; 50%), and Paleoproterozoic (1989–1606 Ma; 24%) detrital zircon grains with age peaks of 483, 1053, 1137, 1436, 1509, and 1661 Ma (Fig. 5A). Minor Cryogenian to Ediacaran (665–634 Ma) and Tonian (996–959 Ma) ages were also present. Middle Ordovician (467, 462 Ma) and late Cambrian to Early Ordovician (491–481 Ma) subpopulations yielded subchondritic $\varepsilon_{Hf(t)}$ values of –4.1 to –3.6 ($\bar{X}$ = –3.9) and –9.6 to –2.6 ($\bar{X}$ = –5.9), respectively (Fig. 5C). Tonian and older grains mostly had superchondritic $\varepsilon_{Hf(t)}$ values of +0.9 to +10.2 (90%; $\bar{X}$ = +3.1).

Princess Alicefjellet Member sandstone of the Andréebreen Formation (GS11:05) yielded Tonian (968–901 Ma; 18%), Mesoproterozoic (1544–1056 Ma; 36%), and Paleoproterozoic (2167–1618 Ma; 36%) detrital zircon grains with age peaks of 921, 1124, 1330, 1394, 1493, 1677, and 1754 Ma (Fig. 5B). A minor grouping of Neoarchean (2787–2611 Ma) zircon grains was also recognized. The main 2167–901 Ma population showed mostly positive $\varepsilon_{Hf(t)}$ values with Tonian, Mesoproterozoic, and Paleoproterozoic ages having averages of +5.4, +4.0, and +1.7, respectively (Fig. 5C).

Frænkelryggen Formation sandstone (GS11:02) contained Tonian (965–888 Ma; 12%), Mesoproterozoic (1587–1030 Ma; 41%), and Paleoproterozoic (1914–1605 Ma; 42%), detrital zircon grains with age peaks of 944, 1390, 1496, 1570, 1663, and 1764 Ma (Fig. 6A). The Mesoproterozoic to Paleoproterozoic populations had $\varepsilon_{Hf(t)}$ values that ranged from –2.5 to +8.4 ($\bar{X}$ = +3.4), with the dominant 1663 Ma peak yielding values of –0.4 to +8.4 ($\bar{X}$ = +3.3; Fig. 6D).

Ben Nevis Formation sandstone (GS11:01) yielded Cryogenian (659–640 Ma; 6%), Tonian (999–755 Ma; 32%), Mesoproterozoic (1581–1010 Ma; 41%), and Paleoproterozoic (1858–1619 Ma; 21%) detrital zircon grains with main age peaks of 965 and 996 Ma (Fig. 6B). Detrital zircon grains with ages of 1117, 1224, and 1513 Ma yielded $\varepsilon_{Hf(t)}$ values of +5.6, +1.8, and +5.6, respectively (Fig. 6D).

Lower Devonian sandstone (GS11:18) collected from Lovénøyane, an island south of Blomstrandhalvøya, contained Mesoproterozoic (1521–1005 Ma; 66%) and Paleoproterozoic (2494–1606 Ma; 26%) detrital zircon grains with age peaks of 1087, 1330, 1466, 1653, and 1708Ma (Fig. 6C). Minor Tonian (973–966 Ma) and Neoarchean (2790–2641 Ma) age groupings were also recognized. The Mesoproterozoic (–4.1 to +9.4) and Paleoproterozoic (–4.4 to +7.8) populations (Fig. 6D) yielded average $\varepsilon_{Hf(t)}$ values of +3.9 and +0.3, respectively. The minor Neoarchean age grouping showed superchondritic $\varepsilon_{Hf(t)}$ values ($\bar{X}$ = +2.3), whereas the Tonian zircons yielded $\varepsilon_{Hf(t)}$ values of –4.0 to –3.7.

Andrée Land Group

Wood Bay Formation sandstone (GS11:10) yielded Cambrian to Silurian (540–436 Ma; 25%), Tonian (976–806 Ma; 13%),

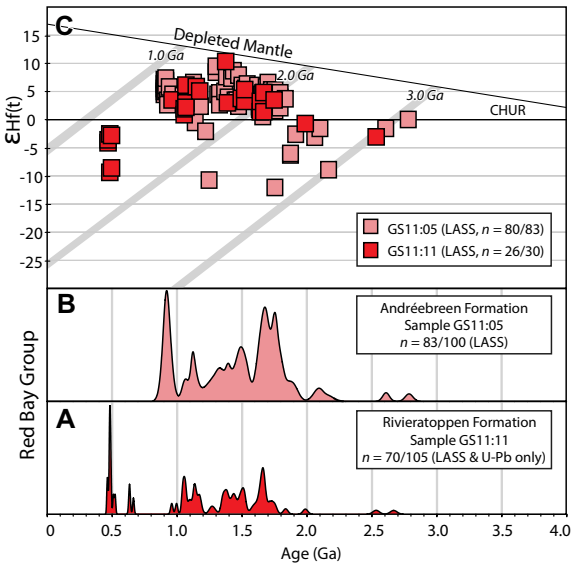

Figure 5. Detrital zircon results from lower Red Bay Group rock units. (A) Rivieratoppen Formation sandstone (sample GS11:11). (B) Andréebreen Formation sandstone (sample GS11:05). (C) $\varepsilon_{Hf(t)}$ vs. U-Pb age diagram for Rivieratoppen and Andréebreen Formation detrital zircon samples. The sample of Riveriatoppen Formation sandstone (Wulffberget Member) was analyzed by conventional U-Pb dating (shown in figure as U-Pb only) and laser ablation split stream (LASS) techniques. The Appendix contains supporting information about the laser ablation methods used. CHUR—chondritic uniform reservoir.

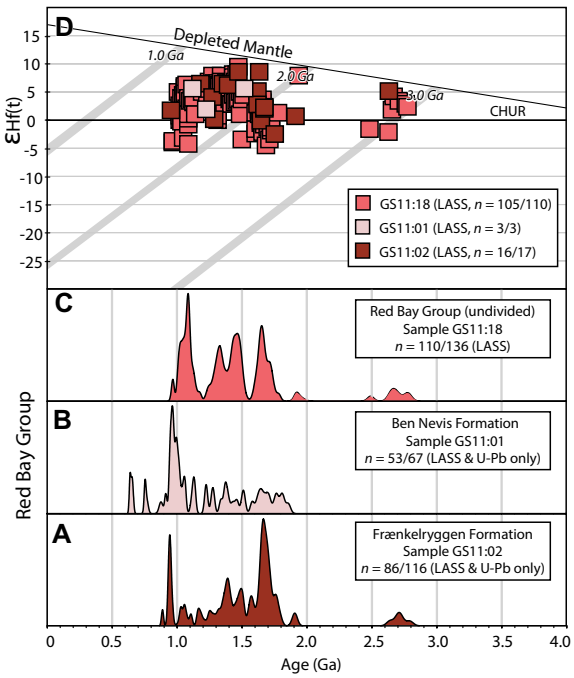

Figure 6. Detrital zircon results from upper Red Bay Group rock samples. (A) Frænkelryggen Formation sandstone (sample GS11:02). (B) Ben Nevis Formation sandstone (sample GS11:01). (C) Undivided Red Bay Group sandstone from Lovénøyane (sample GS11:18). (D) $\varepsilon_{Hf(t)}$ vs. U-Pb age diagram for Frænkelryggen Formation, Ben Nevis Formation, and undivided Red Bay Group detrital zircon samples. Frænkelryggen Formation and Ben Nevis Formation sandstone samples were analyzed by conventional U-Pb dating (shown in figure as U-Pb only) and laser ablation split stream (LASS) techniques. The Appendix contains supporting information about the laser ablation methods used. CHUR—chondritic uniform reservoir.

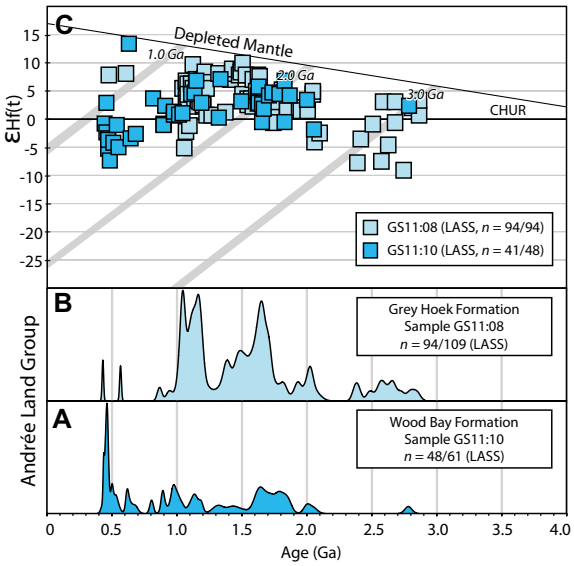

Figure 7. Detrital zircon results from Andrée Land Group rock samples. (A) Wood Bay Formation sandstone (sample GS11:10). (B) Grey Hoek Formation sandstone (sample GS11:08). (C) $\varepsilon_{Hf(t)}$ vs. U-Pb age diagram for Wood Bay and Grey Hoek Formation detrital zircon samples. Andrée Land Group rock samples were analyzed by laser ablation split stream (LASS) techniques. The Appendix contains supporting information about the laser ablation methods used. CHUR—chondritic uniform reservoir.

Mesoproterozoic (1490–1006 Ma; 19%), and Paleoproterozoic (2050–1624 Ma; 30%) detrital zircon grains with age peaks of 462, 1644, and 1789 Ma (Fig. 7A). Minor Ediacaran to Cryogenian (677–617 Ma) and Neoarchean (2782 Ma) age groupings were also recognized. Early Paleozoic zircon grains mostly had subchondritic $\varepsilon_{Hf(t)}$ values (90%; $\bar{X} = -3.7$; Fig. 7C); Silurian zircon grains with ages of 438 Ma and 436 Ma yielded $\varepsilon_{Hf(t)}$ values of –0.7 and +1.6, respectively. Tonian and older zircon grains ranged from –1.1 to +7.1 ($\bar{X} = +2.8$).

Grey Hoek Formation sandstone (GS11:08) mostly contained Mesoproterozoic (1596–1008 Ma; 54%), Paleoproterozoic (2486–1603 Ma; 33%), and Mesoarchean to Neoarchean (2847–2555 Ma; 9%) detrital zircon grains with age peaks of 1046, 1165, 1388, 1489, 1651, and 2026Ma (Fig. 7B). Minor Silurian (436 Ma), Ediacaran (566 Ma), and Tonian (943–867 Ma) single grains or subpopulations also occurred. Precambrian zircon grains mostly yielded $\varepsilon_{Hf(t)}$ values that ranged from –8.8 to +10.1 ($\bar{X} = +3.3$; Fig. 7C) with Mesoproterozoic, Paleoproterozoic, and Archean populations having average values of +5.0, +1.8, and –0.9, respectively. Silurian (431 Ma) and Ediacaran (566 Ma) single grains yielded $\varepsilon_{Hf(t)}$ values of +8.0 and +8.2, respectively.

DISCUSSION

Proterozoic Strata of NW Svalbard: Age, Provenance, and Correlations

Metasedimentary rocks that comprise the Caledonian basement domains of the North Atlantic region have been important for constraining the stratigraphy and paleogeography of East Laurentia and Baltica in a Rodinian framework (e.g., Cawood et al., 2007; Kirkland et al., 2007). Detrital zircon studies have greatly informed the depositional age, tectonic setting, and regional correlation of these metasedimentary strata, although there remain debates about the nature of early Neoproterozoic convergence (Cawood et al., 2010; Malone et al., 2014) and extension of the Grenville-Sveconorwegian orogen into the High Arctic (Lorenz et al., 2012). The assembly of Rodinia is generally marked by Mesoproterozoic to lower Neoproterozoic strata with populations of first-cycle detrital zircon grains that closely approximate the time of deposition, whereas supercontinent breakup is evidenced by Neoproterozoic to lower Paleozoic rift and passive margin strata with polycyclic detrital zircon grains that are much older than the time of sediment accumulation (Cawood and Nemchin, 2001; Cawood et al., 2007, 2012). New results support these hypotheses and indicate that metasedimentary basement rocks in northwestern Svalbard were deposited in proximity to a latest Mesoproterozoic to earliest Neoproterozoic orogen near northeastern Laurentia. For example, Richarddalen complex quartzite contains 1017–1009 Ma zircon grains that overlap at 2σ (see Dickinson and Gehrels, 2009) and yield a weighted mean age of 1012 ± 5 Ma ($n = 5$, MSWD = 0.3). Krossfjorden Group strata west of Raudfjorden also have latest Mesoproterozoic zircon grains that yield a maximum depositional age of 1021 ± 11 Ma ($n = 5$, MSWD = 1.2; Pettersson et al., 2009b). Metasedimentary rocks in northwestern Svalbard are intruded by early Tonian (996–960 Ma) augen gneiss (Peucat et al., 1989; Myhre et al., 2008; Pettersson et al., 2009a, 2009b), which is consistent with coincident sedimentation and magmatism. Metasedimentary rocks of the Southwestern province are also cut by Tonian (950–927 Ma) intrusions and have zircon grains that demonstrate a maximum depositional age of 1016 ± 13 Ma ($n = 3$, MSWD = 0.46; Gasser and Andresen, 2013).

Biscayarhuken formation and Richarddalen complex strata contain Mesoproterozoic to Paleoproterozoic detrital zircon grains with 1051, 1129, 1370, 1444, and 1644 Ma age peaks (Fig. 8A) that are consistent with provenance from the Grenville-Sveconorwegian orogen in its eastern Laurentia–northern Baltica type areas or a northern extension through the Caledonian hinterland in Svalbard and related High Arctic regions (Lorenz et al., 2012). The prominent 1644 Ma age peak could reflect original sources from the Trans-Labrador batholith and equivalents in eastern Laurentia, with younger age peaks demonstrating provenance from rocks that were generated during the Grenville (sensu stricto), Shawinigan, Elzevirian, and Pinwarian episodes of Grenville evolution (e.g., Rivers, 1997). The 1644 Ma age peak could also indicate original sources from the Trans-Scandinavian igneous belt and comparable successions of Baltica, with younger peaks showing sources from the Idefjorden, Kongsberg, Bamble, and Telemarkia terranes of the Sveconorwegian orogen (e.g., Bingen and Solli, 2009). Northwestern (Fig. 8B) and Southwestern (Fig. 8C) province strata are characterized by 1640 Ma age peaks and minor groupings ca. 1110–1190, 1380, 1440, and 1700 Ma, which strengthens the late Mesoproterozoic to early Neoproterozoic connections between the basement domains of Svalbard. Although the Southwestern province has a late Cryogenian (Torrelian) tectonothermal history that is absent in the Northwestern and Northeastern provinces, it appears that Svalbard's basement domains had similar sediment sources during the assembly of Rodinia. This observation suggests that Svalbard's basement units may continue across the boundaries of its Caledonian provinces (e.g., Ziemniak et al., 2019).

Metasedimentary successions of the Pearya terrane (Fig. 8D), Scandinavian Caledonides (Fig. 8E), Sveconorwegian province (Fig. 8F), and East Greenland Caledonides (Fig. 8G) share many Mesoproterozoic to Paleoproterozoic age peaks with Svalbard's basement units and in some locations are also associated with Tonian intrusive rocks (e.g., Kirkland et al., 2006, 2007). In the case of the Pearya terrane, metasedimentary and orthogneiss units are overlain by Neoproterozoic diamictite and other clastic units correlated with the Southwestern province (e.g., Trettin, 1987; Harland, 1997; Malone et al., 2014, 2017). The Pearya terrane has no evidence of Silurian deformation and metamorphism, which suggests that it was located to the north

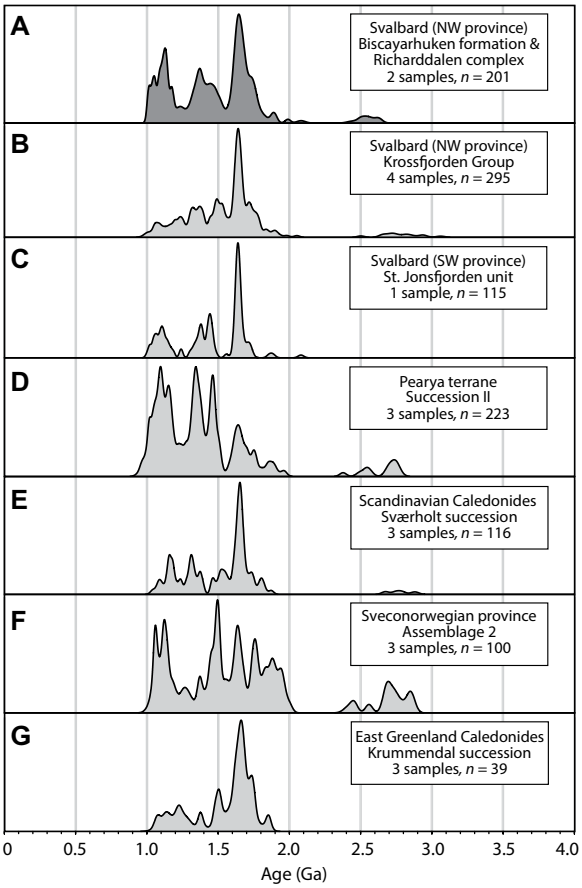

Figure 8. Detrital zircon U-Pb reference frames for Mesoproterozoic to Neoproterozoic strata in the North Atlantic region. (A) Biscayarhuken formation and Richarddalen complex, Northwestern province, Svalbard (this study). (B) Krossfjorden Group, Northwestern province, Svalbard (Pettersson et al., 2009b). (C) St. Jonsfjorden unit, Southwestern province, Svalbard (Gasser and Andresen, 2013). (D) Succession II, Pearya terrane, Ellesmere Island, Canada (Malone et al., 2014). (E) Sværholt succession, Scandinavian Caledonides (Kirkland et al., 2007). (F) Sveconorwegian province, Norway and Sweden (de Haas et al., 1999; Bingen et al., 2003). (G) Krummendal succession, East Greenland Caledonides (Leslie and Nutman, 2003).

of Greenland during the early Paleozoic and not involved in the Laurentia-Baltica collision. It follows that detrital zircon U-Pb(-Hf) provenance signatures of Svalbard basement and related circum–North Atlantic (Pearya, East Greenland, Scandinavia) successions are not necessarily indicative of their early Paleozoic locations within or outside the Caledonian mountain belt.

Late Cryogenian Magmatism in Northwestern Svalbard

The separation of eastern Laurentia from its western Baltica and Amazonian conjugate margins during the Neoproterozoic breakup of the supercontinent Rodinia resulted in 760–550 Ma rift-related magmatism and basin-forming events within basement domains later modified by Caledonian-Appalachian orogenesis (Cawood and Nemchin, 2001; Nystuen et al., 2008; Cawood et al., 2016). In northwestern Svalbard, mafic to felsic dikes that intrude Tonian and older basement rocks of the Richarddalen complex have yielded isotope-dilution $^{206}Pb/^{238}U$ ages and direct evaporation $^{207}Pb/^{206}Pb$ ages of 660–620 Ma (Peucat et al., 1989) and 667–647 Ma (Gromet and Gee, 1998), respectively. A newly dated felsic dike within the Richarddalen complex (this study) crystallized ca. 652 Ma and is consistent with late Cryogenian rift-related magmatism in the region. All these ages on Svalbard are ~50 m.y. older than the mafic magmatism (Baltoscandian dike swarms; Andréasson, 1994) that defines the timing of the opening of the Iapetus Ocean along the Scandinavian outer margin of Baltica (Gee, 2020). Late Cryogenian to early Ediacaran (677–633 Ma) detrital zircon grains in Old Red Sandstone rock units, which may have been sourced from dikes in underlying basement, yielded $\varepsilon_{Hf(t)}$ values that range from –5.1 to +5.3 ($\bar{X}$ = –1.6) and demonstrate crustal contributions to rift-related magmatism.

Provenance and Influence of Haakonian and Monacobreen Deformation on Silurian–Devonian Sedimentation Patterns

Siktefjellet Group

Intermontane molasse strata have recycled orogen provenance from uplifted basement rocks (e.g., Dickinson et al., 1983) and detrital zircon grains that are older than the age of sediment accumulation (e.g., Cawood et al., 2012). In northwestern Svalbard, lower Siktefjellet Group rocks were deposited in pull-apart basins and contain angular to rounded basement clasts (Friend et al., 1997). Lilljeborgfjellet Formation strata therefore yielded ca. 960 Ma and 1360 Ma detrital zircon grains that were sourced from local basement (Fig. 9A) and a conspicuous 1740 Ma age peak marking provenance from Paleoproterozoic rocks of similar age to those in the Northeastern province (Fig. 9B; Pettersson et al., 2010). This age was also obtained from boulders (Hellman et al., 1998) of enigmatic, unmetamorphosed quartz porphyry in Lilljeborgfjellet Formation conglomerate; these boulders increase in frequency eastward toward the Breibogen-Bockfjorden fault and were inferred to have been sourced from the basement beneath the western part of the Andréeland-Dicksonland graben.

The Siktefjellet strike-slip zone probably controlled local topography in the Raudfjorden region, but orogen-scale processes that affected northeastern Laurentia are interpreted to have influenced drainage at a regional scale. For example, Late Ordovician (ca. 455 Ma) to Silurian (ca. 430 Ma) crustal thickening and subsequent exhumation of basement rocks along major faults preceded Old Red Sandstone deposition in northwestern Svalbard (Gromet and Gee, 1998; Labrousse et al., 2008). Metamorphic rocks in the Billefjorden fault zone and Ny Friesland (Fig. 2B), east of Raudfjorden, show evidence of Late Ordovician to Early Devonian cooling (Gee and Page, 1994; Michalski et al., 2012), which is consistent with the exhumation of Northwestern and Northeastern province basement prior to and during Siktefjellet Group deposition.

Braided river deposits of the Albertbreen Formation contain post–960 Ma detrital zircon grains (Fig. 9C) that indicate extrabasinal derivation or previously unrecognized sources in northwestern Svalbard. Tonian (938–904 Ma) zircon grains form a 921 Ma age peak and are demonstrably younger than granitic gneisses of the Richarddalen complex and adjacent basement units (Peucat et al., 1989; Myhre et al., 2008; Pettersson et al., 2009a), but these ages broadly overlap with the timing of I- and S-type magmatism in southwestern Norway (938–932 Ma; Bolle et al., 2018), the Scandinavian Caledonides (ca. 925 Ma; Agyei-Dwarko et al., 2012), the Southwestern province (927 Ma; Gasser and Andresen, 2013), the Northeastern province (937–936 Ma; Johansson et al., 2005), and East Greenland (ca. 920 Ma; Leslie and Nutman, 2003). There remains debate as whether or not these rocks were the result of subduction-related (e.g., Malone et al., 2017) or collision-related (e.g., Johansson et al., 2005) processes; however, 938–904 Ma detrital zircon grains in the Albertbreen Formation yielded $\varepsilon_{Hf(t)}$ values that range from –0.4 to +6.4 ($\bar{X}$ = +3.5) and are consistent with the reworking of juvenile Mesoproterozoic

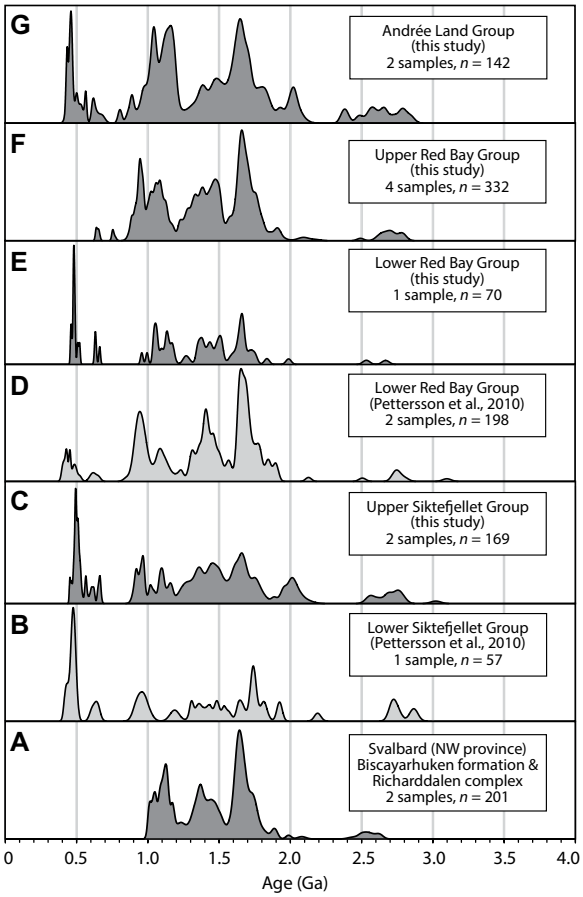

Figure 9. Detrital zircon U-Pb signatures of northwestern Svalbard rock units. (A) Biscayarhuken formation and Richarddalen complex (this study). (B) Lower Siktefjellet Group (Pettersson et al., 2010). (C) Upper Siktefjellet Group (this study). (D) Lower Red Bay Group (Pettersson et al., 2010). (E) Lower Red Bay Group (this study). (F) Upper Red Bay Group (this study). (G) Andrée Land Group (this study).

crust and/or the incorporation of existing crust during mantle-derived magmatism. The entire Old Red Sandstone data set yielded 38 Tonian (979–901 Ma) detrital zircon grains that similarly recorded $\varepsilon_{Hf(t)}$ values ranging from –4.0 to +7.6 ($\bar{X}$ = +3.6). Although the provenance of these Siktefjellet Group detrital zircon grains is ambiguous because of multiple source areas in the circum–North Atlantic region, the results can be explained by sediment contributions from the Northeastern and Southwestern provinces and, as a result, support late Silurian to Early Devonian connections between Svalbard's basement domains.

Cryogenian to early Ediacaran (668–594 Ma) detrital zircon grains in the upper Siktefjellet Group (Fig. 9C) could have provenance from ca. 650 Ma felsic rocks in the Raudfjorden area (Gromet and Gee, 1998; this study), ca. 650 Ma pegmatite in the Southwestern province (Majka et al., 2012), and/or Iapetan rift rocks in Norway, Canada, and elsewhere (e.g., Kamo et al., 1995; Bingen and Solli, 2009). Rosa et al. (2016) proposed that 628–570 Ma arc rocks along the Timanian margin of Baltica (Fig. 1) were emplaced against northern Greenland after the Laurentia-Baltica collision and therefore were available source areas for Old Red Sandstone basins if river systems cut across the Caledonian mountains similar to some modern Himalayan drainages. Late Neoproterozoic detrital zircon grains in the Albertbreen Formation yielded $\varepsilon_{Hf(t)}$ values of –6.8 to +5.3 ($\bar{X}$ = –2.4), indicating that varying proportions of Proterozoic or older crust were involved in the genesis of some Cryogenian to Ediacaran igneous source rocks.

Early Paleozoic detrital zircon grains in the Albertbreen Formation range in age from 531 Ma to 455 Ma. The majority of the grains (90%; 19 of 21 analyses) are subchondritic with Cambrian (531–485 Ma) and Early to Middle Ordovician (484–455 Ma) populations having average $\varepsilon_{Hf(t)}$ values of –3.7 and –8.3, respectively. Cambrian to Ordovician magmatism in the Appalachian-Caledonian mountain system is recorded by arc successions that developed during the closure of the Iapetus Ocean (e.g., Grenne et al., 1999; van Staal and Hatcher, 2010); continental arc magmatism along northeastern Laurentia is a feature of Ordovician–Silurian tectonic evolution (e.g., Rehnström, 2010; Augland et al., 2012). The Taconic belt of Atlantic Canada is perhaps the best understood Cambrian to Ordovician orogenic system along the Appalachian-Caledonian convergent margin and is used here as a proxy for interpreting early Paleozoic detrital zircon grains in the Old Red Sandstone. The composite Taconic belt records: (1) an east-facing 510–500 Ma arc built on oceanic lithosphere; (2) obduction of the arc onto a peri-Laurentian block by 493 Ma; (3) east-directed subduction beneath the block, generation of 490–476 Ma crustally contaminated arc rocks, closure of the Taconic seaway, and collision with the Laurentian margin by 476 Ma; and (4) development of an east-facing continental arc by 466 Ma (e.g., van Staal and Barr, 2012). The Grampian orogenic system in the British Isles preserves a similar sequence of events that occurred southeast and east of Greenland, with the former having a well-constrained orogenic phase from 475 to 460 Ma (Dewey and Mange, 1999). Likewise, the ophiolites and overlying Laurentian-affinity succession in the Løkken-Hølanda districts of the Scandinavian Caledonides (Grenne et al., 1999; Slagstad et al., 2014) compare well with the Appalachian proxy. The northern extent of this Taconic arc system probably continued from northern Scandinavia across the Barents Shelf between Svalbard and Franz Josef Land (FJL in Fig. 1; Knudsen et al., 2019) and also the Lomonosov Ridge (Knudsen et al., 2018); it may have been related to the Pearya terrane, where Early Ordovician (481 Ma) arc rocks and variably serpentinized ultramafic-mafic assemblages were juxtaposed with a passive margin succession during the M'Clintock orogeny. The timing of the M'Clintock orogeny is constrained by 475 Ma syntectonic and 462 Ma posttectonic intrusive rocks (Trettin, 1987), whereas 453 Ma late-tectonic intrusions within a shear zone record the sinistral translation of Pearya along northern Laurentia during the initial stages of Caledonian collision (McClelland et al., 2012). Ordovician strata that sit unconformably on the M'Clintock belt mostly yield detrital zircon grains from the M'Clintock arc complex (Hadlari et al., 2014; Malone et al., 2019); 478–456 Ma detrital zircon grains yielded an average $\varepsilon_{Hf(t)}$ value of –1.2 (Malone et al., 2019). Early Paleozoic (531–455 Ma) detrital zircon grains in the Andréebreen Formation are consistent with M'Clintock belt or equivalent provenance and yielded comparable, but slightly lower, average $\varepsilon_{Hf(t)}$ values of –4.8.

Red Bay Group

Regional deformation events have the potential to influence topography and reorganize drainage patterns in compressional, extensional, and strike-slip settings (e.g., Gawthorpe and Hurst, 1993; Friend et al., 1999). In northwestern Svalbard, Lochkovian strata of the Red Bay Group were deposited in the Siktefjellet strike-slip zone after Haakonian deformation (Friend et al., 1997) and exhibit two provenance signatures

that are linked to differences in stratigraphic age and depositional environment. Alluvial-fan and sandy braided river deposits of the lowermost Red Bay Group (Rivieratoppen Formation) characterize the first provenance signature and yield metasedimentary basement clasts (Friend et al., 1997) and early Paleozoic to Proterozoic detrital zircon ages and Hf isotope compositions that are similar to those of the underlying Siktefjellet Group (Figs. 9D and 9E). Pettersson et al. (2010) recognized Silurian to earliest Devonian ($n = 5$) detrital zircon grains in the Konglomeratodden Member, which indicates that some Caledonian-related igneous rocks in the Northwestern (e.g., 418 Ma Hornemantoppen batholith in Fig. 2B) and/or Northeastern provinces of Svalbard were exhumed or erupted to the surface by early Lochkovian time. The available evidence is consistent with proximally derived Rivieratoppen Formation strata having provenance from underlying rock units that were uplifted and eroded as a result of Haakonian deformation.

Fluvial to marginal-marine strata of the upper Red Bay Group (Andréebreen, Frænkelryggen, and Ben Nevis Formations and undivided Red Bay Group at Lovénøyane) are characterized by a second provenance signature that is dominated by metasedimentary basement clasts (Friend et al., 1997) and Mesoproterozoic to Tonian detrital zircon age populations (Fig. 9F). These mid- to late Lochkovian rock units generally lack the early Paleozoic and late Neoproterozoic detrital zircon grains that are typical of the underlying Siktefjellet Group and reworked equivalents in the Rivieratoppen Formation. Pettersson et al. (2010), however, observed some early Paleozoic detrital zircon grains in a sample of lower Andréebreen Formation sandstone ~10 km north of Ben Nevis (see location in Fig. 3A), which, at this location, might reflect the local recycling of Lilljeborgfjellet Formation strata into the overlying Rabotdalen Member (Fig. 9D). New results from the middle to upper Red Bay Group therefore demonstrate provenance from Northwestern province basement with minor contributions from the underlying Siktefjellet Group. If some source areas were extrabasinal (e.g., from Pearya or the Southwestern province), Haakonian deformation may have altered pre-Lochkovian topography and sediment dispersal patterns during the Early Devonian or been associated with sinistral strike-slip displacement of the Northwestern province away from source rocks with Paleozoic detrital zircon grains.

Andrée Land Group

Andrée Land Group strata of the Andréeland-Dicksonland graben were sourced from Red Bay Group basins inverted by late Lochkovian Monacobreen deformation (McCann, 2000). Wood Bay and Grey Hoek Formation samples yield Mesoproterozoic to early Paleoproterozoic (1044, 1162, 1388, 1484, 1650 Ma) age peaks that are consistent with Red Bay Group derivation (Fig. 9G), but the presence of 677–431 Ma zircon grains, including modes of 436 and 462 Ma (>5 grains each), requires additional sources. Pragian Wood Bay Formation fluvial strata, which in northern Andrée Land were fed by small meandering rivers with headwaters west of the Breibogen-Bockfjorden fault (see Fig. 2B; Harland, 1997), contain 86% ($n = 13$ of 15) of the early Paleozoic to Cryogenian zircon grains recognized in the Andrée Land Group sample suite. This observation suggests that Siktefjellet Group strata, Caledonian granites, and extrabasinal arc sources or their sedimentary derivatives were western provenance areas for the Wood Bay Formation. Eifelian Grey Hoek Formation strata, which were instead influenced by coastal marine processes, mostly yield Tonian to Archean detrital zircon grains and indicate provenance from basement rocks units, such as the Mesoproterozoic Biscayarhuken formation. Further studies on Monacobreen deformation and its significance to Pragian to Givetian sediment dispersal are warranted; specifically, the Wood Bay and Grey Hoek Formation samples contain chondritic to superchondritic Silurian and Ediacaran zircon grains that are unlike those in the Siktefjellet or Red Bay Groups and may indicate additional provenance areas, including allochthonous crustal fragments that may have been proximal to the northern Caledonides after the Laurentia-Baltica collision (e.g., Trettin, 1998; Rosa et al., 2016).

Paleogeographic Implications: Limited versus Long-Distance Displacement Models for Svalbard's Assembly

Caledonian deformation and metamorphism in Laurentia have been explained by oblique, transpression-related collision followed by orthogonal convergence (Soper et al., 1992) or east-west–directed, orthogonal collision followed by the north-south lateral extrusion of crustal fragments along deep crustal shear zones (e.g., Gee and Page, 1994; Lyberis and Manby, 1999; Gee, 2020). The evidence for orogen-parallel, lateral movements between Laurentia and Baltica is manifested in Svalbard by the north-trending fault zones separating the Northwestern, Northeastern, and Southwestern provinces (e.g., Harland, 1997; Dewey and Strachan, 2003). The amount of sinistral displacement involved in the assembly of Svalbard's provinces is contentious and ranges from a few tens of kilometers to over 1000 km (e.g., Harland, 1985; Gee and Teben'kov, 2004; Pettersson et al., 2010). Old Red Sandstone deposition was linked to the evolution of these fault zones, and therefore new detrital zircon results from the Biscayarhuken formation, Richarddalen complex, and Siktefjellet, Red Bay, and Andrée Land groups allow us to examine the published plate-tectonic and paleogeographic scenarios for Svalbard.

Late Mesoproterozoic to Late Neoproterozoic Evolution

Biscayarhuken formation and Richarddalen complex rocks are characterized by ca. 1050, 1130, 1450, and 1640 Ma detrital zircon age populations that indicate sources from the Grenville Province and correlations with basement units in Svalbard, East Greenland, Scandinavia, and Pearya (Fig. 8). These age populations are ubiquitous in the North Atlantic region and have therefore generated debate about the paleolocation of Svalbard's basement domains. Pettersson et al. (2009b, 2010) used detrital zircon U-Pb ages from the Krossfjorden Group and evidence for ca. 970–960 Ma magmatism to restore the Northwestern province near southern Greenland during the late Mesoproterozoic to late Neoproterozoic, in part because of the apparent lack of age-equivalent, earliest Tonian igneous rocks in east-central and northeast Greenland. Recent studies in Arctic Canada, however, have identified 972–964 Ma arc-related granitoid magmatism in Pearya, north of the Grenville Province (sensu stricto), and developed the hypothesis that it was originally proximal to the Northwestern and Northeastern provinces near northeastern Greenland (Malone et al., 2014, 2017). Pearya has established ties with the Southwestern province (Harland, 1997; Trettin, 1998; Gee and Teben'kov, 2004), and our preferred model calls for the Cryogenian and older rocks of the Nordaustlandet allochthon, including correlatives in the Northwestern province, to have been located to the east of northeasternmost Greenland prior to the opening of the Iapetus Ocean. Late Mesoproterozoic strata in the Southwestern province were intruded or associated with 950–927 Ma igneous rocks (Gasser and Andresen, 2013; Majka et al., 2014); ca. 950 Ma ages are more consistent with a northern position for the Southwestern province, but ca. 927 Ma ages, if correct (see reinterpretation by McClelland et al., 2019), suggest a location to the south of northeast Greenland, perhaps near the northern (Timanian) margin of Baltica prior to the opening of the Iapetus Ocean. The Timanian margin option may explain the evidence of ca. 640 Ma deformation, metamorphism, and magmatism in the Southwestern province (e.g., Majka et al., 2008, 2014). Future stratigraphic and isotopic dating studies are warranted to test these hypotheses.

Early to Mid-Paleozoic Evolution

Siktefjellet, Red Bay, and Andrée Land group strata yield Cambrian to Ordovician detrital zircon U-Pb populations that indicate provenance from sources outside of the Northwestern province. These detrital zircon grains have subchondritic Hf isotope compositions and suggest derivation from Cambrian to Ordovician arc successions that are comparable to those of Taconic, Grampian, and M'Clintock convergent margin systems. In combination with published late Mesoproterozoic to late Neoproterozoic paleogeographic scenarios, these early Paleozoic arc connections have played an important role in proposing lateral displacement models for Svalbard's basement provinces and overlying Old Red Sandstone strata. Much of the current debate centers on Cryogenian to Ediacaran and Cambrian to Ordovician detrital zircon populations in the lower Siktefjellet Group (Lilljeborgfjellet Formation) and their proposed connections between the Northwestern province and Iapetus suture zone in the southern Caledonides. In the Pettersson et al. (2010) model, metamorphism recorded by fault slivers in the Northwestern (Richarddalen complex) and Southwestern (Vestgötabreen complex) provinces occurred near southern Greenland and preserves Cambrian to Ordovician tectonothermal histories comparable to those of the Taconic-Grampian system and Avalonia. It follows that the oldest Old Red Sandstone units of northwestern Svalbard were deposited near southern Greenland and in the vicinity of the Scottish and Irish Caledonides. Pettersson et al. (2010) called for the Northwestern and Southwestern provinces to have subsequently undergone ~2000 km of sinistral translation from the southern Caledonides to their Carboniferous–Paleogene position near northeastern Greenland. The Northeastern province was interpreted by Pettersson et al. (2010) to have evolved in proximity to the East Greenland Caledonides prior to their ~1000 km lateral displacement to northeast Greenland.

The new results from the Siktefjellet Group (Albertbreen Formation) are not consistent with provenance from the Iapetus suture zone or southern Greenland areas, based on available detrital zircon U-Pb-Hf isotope data from the Avalonian and Grampian arc systems. Neoproterozoic (ca. 670–560 Ma) detrital zircon grains from Ediacaran arc-proximal basins in Newfoundland, which are used as a proxy for the Avalonian arc, mostly yield superchondritic Hf isotope values (279 of 300 analyses) with an average $\varepsilon_{Hf(t)}$ of +5.3 (Pollock et al., 2015), notably different from the average $\varepsilon_{Hf(t)}$ of –2.4 for 667–566 Ma ages in the Albertbreen Formation. These observations indicate that Cryogenian to Ediacaran detrital zircon grains in the Siktefjellet Group were derived from crustal assemblages more evolved than those recognized in Avalonia. Cambrian to Ordovician (ca. 530–450 Ma) detrital zircon grains from the South Mayo trough of western Ireland, which are used to characterize the Grampian arc in the southern Caledonides, yield subchondritic Hf isotope values (57 of 57 analyses) with an average $\varepsilon_{Hf(t)}$ of –13.2 (Yin et al., 2012), which is much lower than the average $\varepsilon_{Hf(t)}$ of –4.8 for 531–455 Ma ages in the Albertbreen Formation. These findings demonstrate that Cambrian to Ordovician detrital zircon grains in the Siktefjellet Group were derived from crustal assemblages less evolved than those recognized in the Grampian arc. Ordovician (478–456 Ma) detrital zircon grains in the Cape Discovery Formation of Pearya, which overlies rocks of the M'Clintock arc system, yield an average $\varepsilon_{Hf(t)}$ value of –1.2 (Malone et al., 2019) and provide a closer match for the Siktefjellet Group results. We favor an interpretation where the Siktefjellet Group, and overlying Lochkovian to Givetian strata of the Red Bay and Andrée Land groups, not only has paleogeographic ties with the northern Caledonides, but also with adjacent fragments like Pearya that escaped collisional deformation and show evidence of Late Ordovician to Devonian sinistral strike-slip assembly and extrusion along northeastern Laurentia. Underlying basement rocks of the Northwestern province are interpreted to represent the northern continuation of the northeast Greenland shelf and have lithological and structural correlations with the higher allochthons in the northeast Greenland Caledonides. We conclude that limited lateral displacement models (<200 km) best explain the Silurian to Devonian assembly of Svalbard. Future detrital zircon U-Pb-Hf studies in Greenland and Arctic Canada can investigate such stratigraphic connections with Svalbard and test this hypothesis. For example, east-derived Silurian flysch units in northern Ellesmere Island, Arctic Canada, contain ca. 420–480, 650, 970, 1450, and 1650 Ma detrital zircon grains (Beranek et al., 2015) and may have provenance ties with those now recognized in the Siktefjellet, Red Bay, and Andrée Land groups and Pearya.

Detrital Zircon U-Pb-Hf Record of Northeast Laurentian Crustal Evolution

The establishment of conventional laser ablation–based techniques (e.g., Gehrels, 2012) and laser ablation split stream methods (e.g., Fisher et al., 2014) has resulted in the generation of large detrital zircon U-Pb-Hf reference frames globally. Although detrital zircon O isotope compositions are typically used to characterize the stratigraphic record of crustal growth (e.g., Lancaster et al., 2011), complementary U-Pb-Hf data are capable of discriminating crustal evolution patterns in cratons, orogenic belts, and arc-proximal basins (e.g., Gerdes and Zeh, 2006; Liu et al., 2017). The new results allow us to identify such patterns for northeast Laurentian crustal evolution (Figs. 10A–10F); we conclude that future studies can use and develop these ideas to test hypotheses for the Old Red Sandstone and its correlatives in Laurentia and Baltica.

Detrital zircon grains in the Liefde Bay Supergroup record major age peaks of 490, 950, 1050, 1380, 1480, and 1660 Ma (Fig. 10A), which correspond to accretionary and crust-forming events along the eastern Laurentian and Baltican margins (e.g., Rivers, 1997; Bingen and Solli, 2009). Based on the Hf isotope compositions of these detrital zircon grains, juvenile early Mesoproterozoic to late Paleoproterozoic continental crust was continually reworked and sampled during tectonic events that culminated with the Grenville-Sveconorwegian orogen and assembly of Rodinia. A main conclusion of our analysis is that detrital zircon grains from Pearya strata show analogous U-Pb-Hf patterns (Figs. 10B and 10E; Malone et al., 2014), which further supports its previously discussed connections with Svalbard and the northeast Greenland sector of Laurentia. In contrast, Proterozoic to lower Paleozoic strata that are proxies for the North Atlantic craton and Scottish Caledonides yield ca. 1800 and 2800 Ma detrital zircon populations associated with the stabilization of the Nuna and Superia supercontinents, respectively (Fig. 10C; Lancaster et al., 2011). Synorogenic strata that were part of the Grampian arc system and Irish Caledonides are dominated by 530–450 Ma and 1200–1000 Ma detrital zircon populations associated with the closure of peri-Laurentian marginal basins and stabilization of the Rodinia supercontinent, respectively (Fig. 10D). The Hf isotope compositions of detrital zircon grains in the Scottish and Irish Caledonides are generally more subchondritic than those of Svalbard, Pearya, and the global zircon average (Fig. 10E), indicating proximity to evolved sources near southern Greenland during magma genesis and/or emplacement. The crustal residence times (difference between U-Pb crystallization and Hf model ages) of ca. 475, 1800, and 2800 Ma detrital zircon grains in the Scottish and Irish Caledonides mostly range from 600 to >1500 m.y. (Fig. 10F), which demonstrates that Mesoproterozoic and Archean materials were involved in the reworking of southern Caledonian crust. Detrital zircon grains of the Liefde Bay Supergroup, however, show contributions from more juvenile Mesoproterozoic to early Paleoproterozoic crust and have shorter (mostly <600 m.y.) crustal residence times (Figs. 10E and 10F). These distinctions between the northern and

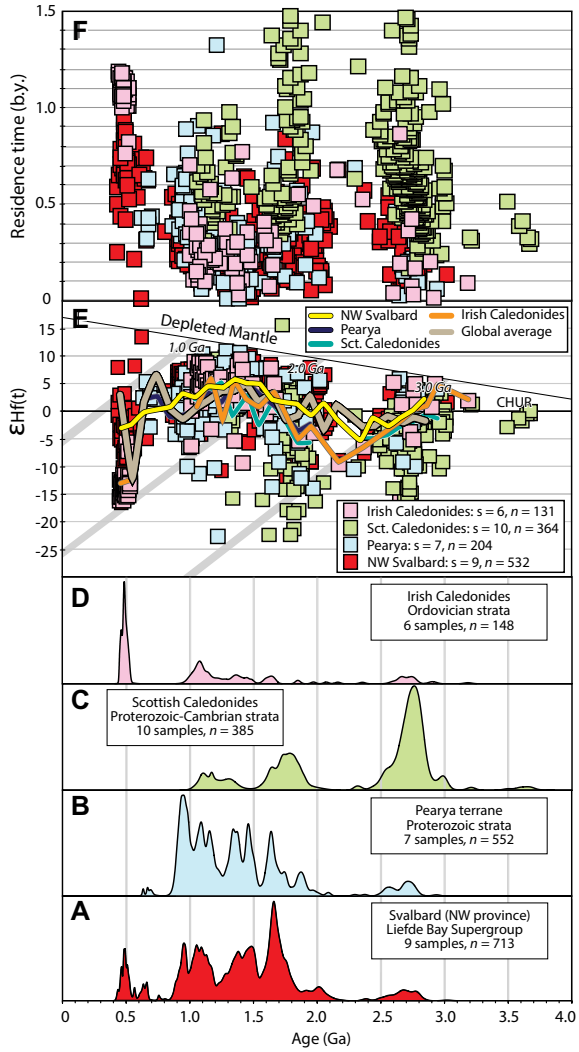

Figure 10. Detrital zircon U-Pb-Hf crustal evolution trends of northern and southern Caledonian rock units. (A) Liefde Bay Supergroup (Siktefjellet, Red Bay, and Andrée Land groups) strata, Svalbard (this study). (B) Proterozoic strata, Pearya terrane (Malone et al., 2014). (C) Proterozoic to Cambrian strata, Scottish Caledonides (Lancaster et al., 2011). (D) Ordovician strata, Irish Caledonides (Yin et al., 2012). (E) $\varepsilon_{Hf(t)}$ vs. U-Pb age diagram for Svalbard (this study), Pearya terrane, Scottish Caledonides, and Irish Caledonides. Running averages are shown for Svalbard (this study), Pearya, Scottish (Sct) Caledonides, and Irish Caledonides, and the globe (Belousova et al., 2010). (F) Residence time vs. U-Pb crystallization age diagram for Svalbard (this study), Pearya, Scottish Caledonides, and Irish Caledonides. CHUR—chondritic uniform reservoir.

southern Caledonides are considered useful for future sediment provenance, paleogeographic, and crustal evolution studies in the greater Caledonian–Northern Appalachian convergent-margin system.

CONCLUSIONS

Detrital zircon U-Pb-Hf isotope results of Old Red Sandstone strata in northwestern Svalbard provide new constraints on Silurian to Devonian deposition and its significance to northern Caledonian tectonics and paleogeography. Siktefjellet Group alluvial-fan to braided river strata were deposited in late Silurian(?) pull-apart basins following the initial Laurentia-Baltica collision and yield ca. 450–530, 595–670, 960, 1000–1650, and 2700 Ma detrital zircon age populations. Proterozoic to Archean grains have provenance from underlying late Mesoproterozoic and Tonian basement units in Svalbard, whereas the Cambrian to Ordovician age populations indicate derivation from sources that are comparable to those of M'Clintock convergent-margin system in Pearya. The new results support deposition of the Siktefjellet Group, and overlying Lochkovian to Givetian Old Red Sandstone succession of northwestern Svalbard, in proximity to the northeast Greenland Caledonides during the Silurian to Devonian periods. Tectonic models that involve limited sinistral strike-slip displacement (<200 km) of the Caledonian allochthons of the Northeastern and Northwestern provinces during late-orogenic assembly are consistent with these findings. Lochkovian strata of the lower Red Bay Group have detrital zircon U-Pb-Hf signatures that indicate provenance from the Siktefjellet Group and basement rocks that were uplifted as a result of Haakonian deformation. Upper Red Bay Group strata, however, are characterized by early Paleoproterozoic to Tonian detrital zircon age populations and demonstrate local basement provenance. A regional drainage reorganization caused by Haakonian tectonism can explain provenance changes observed in the Red Bay Group. Andrée Land Group strata, which were deposited in the Andréeland-Dicksonland graben after Monacobreen strike-slip deformation, represent the youngest Old Red Sandstone strata in northwestern Svalbard and have western provenance from metamorphic basement and Silurian to Devonian cover assemblages. The U-Pb-Hf crustal evolution patterns for the Svalbard Caledonides are distinct from those of the southern Caledonides and should prove useful for future studies that use Old Red Sandstone strata to test paleogeographic models after the assembly of the supercontinent Laurussia.

APPENDIX

Zircon U-Pb Geochronology and Hf Isotope Geochemistry Methods

Zircon crystals were separated from rock samples, handpicked onto double-sided tape, and mounted in epoxy. After polishing to expose the interior of the crystals, cathodoluminescence imaging of the mounts using a JEOL JSM 7100F scanning electron microscope was completed at the Memorial University of Newfoundland. The images were used to locate homogeneous regions of the zircons and to avoid complex internal structures, cracks, and zones of potential Pb loss.

Four samples (GS11:01, GS11:02, GS11:11, GS11:18) were analyzed at Washington State University using a New Wave 213 nm Nd:YAG laser coupled to a single-collector inductively coupled plasma–mass spectrometer (ICP-MS; ThermoFinnigan Element2) for U-Pb isotopes and multicollector ICP-MS (ThermoFinnigan Neptune) for Hf isotopes. The laser ablation parameters included a repetition rate of 10 Hz, fluence of 7 J/cm^2, and spot size of 40 µm. U-Pb methods at Washington State University followed the protocols of Chang et al. (2006); unknowns were calibrated to the Plešovice zircon standard (Sláma et al., 2008) for ^{206}Pb/^{238}U ages and FC-1 zircon standard (Paces and Miller, 1993) for ^{207}Pb/^{206}Pb ages. Reference materials 91500 (Wiedenbeck et al., 1995) and GJ-1 (Jackson et al., 2004) were interspersed throughout the runs and treated as unknowns. Hf isotope methods followed the protocols of Fisher et al. (2011); analyses were calibrated to the Plešovice zircon standard, and the 91500 and FC-1 standards were treated as unknowns. Hf isotope data were reduced using the Iolite software program (Fisher et al., 2014). Traditional, one-spectrometer U-Pb methods were used when the 40 µm spot size was not possible for small zircons in samples GS11:01, GS11:02, GS11:11, and GS11:18. Five samples (GS11:05, GS11:08, GS11:10, GS11:13, GS11:15) were analyzed at the Memorial University of Newfoundland using a GeoLas 193 nm excimer laser coupled to a single-collector ICP-MS (ThermoFinnigan Element XR) for U-Pb isotopes and a multicollector ICP-MS (ThermoFinnigan Neptune) for Hf isotopes. Proterozoic samples GS11:04, GS11:06, and GS11:16 were only analyzed for zircon U-Pb geochronology. The laser ablation parameters and mass spectrometer protocols closely followed those used at Washington State University. U-Pb and Hf isotope analyses were calibrated to the 91500 and Plešovice zircon standards, respectively, and all data were reduced offline with the Iolite software program (Paton et al., 2010). Age calculations were made using the VizualAge reduction routine of Petrus and Kamber (2012).

Analyses with excessive discordance (>10% discordance or >5% reverse discordance) or high error (>10% uncertainty) in $^{206}Pb/^{238}U$ or $^{207}Pb/^{206}Pb$ ages were filtered out and not included in Figures 4–7. The $^{207}Pb/^{206}Pb$ ages were selected for analyses older than 1200 Ma, whereas the $^{206}Pb/^{238}U$ ages were selected for analyses younger than 1200 Ma. Initial $^{176}Hf/^{177}Hf$ ratios are reported as $\varepsilon_{Hf(t)}$ and represent the isotopic composition at the time of crystallization relative to the chondritic uniform reservoir (CHUR). Our calculations used the ^{176}Lu decay constant of Söderlund et al. (2004) and CHUR values of Bouvier et al. (2008). The depleted mantle Hf evolution array was calculated from values reported by Vervoort and Blichert-Toft (1999). Crustal evolution lines shown in Figures 4–7 use $^{176}Lu/^{177}Hf = 0.015$ (Goodge and Vervoort, 2006).

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