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Provenance Analysis of the Andrée Land Basin and Implications for the Paleogeography of Svalbard in the Devonian

Owen A. Anfinson[1], **Margo L. Odlum**[2], **Karsten Piepjohn**[3], **Eirini M. Poulaki**[4], **Grace E. Shephard**[5], **Daniel F. Stockli**[4], **Devin Levang**[1,6], **Maria A. Jensen**[7], and **Elena A. Pavlovskaia**[8]

[1]Department of Geology, Sonoma State University, Rohnert Park, CA, USA, [2]Department of Geosciences, University of Nevada Las Vegas, Las Vegas, NV, USA, [3]Federal Institute for Geosciences and Natural Resources, Hannover, Germany, [4]Department of Geological Sciences, University of Texas at Austin, Austin, TX, USA, [5]Centre for Earth Evolution and Dynamics (CEED), Department of Geosciences, University of Oslo, Oslo, Norway, [6]Department of Geoscience, University of Wisconsin-Milwaukee, Milwaukee, WI, USA, [7]The University Centre in Svalbard, Longyearbyen, Norway, [8]Institute of Earth Sciences, St. Petersburg State University, St. Petersburg, Russia

Key Points:

- Provenance analysis of the Andrée Land Basin identifies N-NE paleodrainage in the Early Devonian and W-SW in the Middle-Late Devonian
- Svalbard's three basement provinces were likely juxtaposed into a relative position similar to the present day by the end of the Devonian
- Detrital zircon U-Pb age comparisons of circum Arctic Devonian strata further constrain Svalbard's paleogeographic position in the Devonian

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

O. A. Anfinson,
anfinson@sonoma.edu

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Author Contributions:

Conceptualization: Owen A. Anfinson, Margo L. Odlum, Karsten Piepjohn, Eirini M. Poulaki
Data curation: Owen A. Anfinson, Daniel F. Stockli
Formal analysis: Owen A. Anfinson, Margo L. Odlum, Karsten Piepjohn, Eirini M. Poulaki, Grace E. Shephard, Daniel F. Stockli, Devin Levang, Maria A. Jensen
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Abstract During the Devonian, the Svalbard Archipelago lay at low latitudes, occupying a paleogeographic position at the intersection of Caledonian and Ellesmerian orogens. Provenance analysis, including detrital zircon U-Pb age studies, of Devonian (ca. 420–360 Ma) strata from the Andrée Land Basin, Svalbard, help reconstruct sediment sources to understand the assembly of the three basement provinces that make up Svalbard, which are presently separated by Devonian sedimentary basins and(or) faults with syn-to post-Devonian displacement. The studied Andrée Land Group strata, which are part of the North Atlantic's Old Red Sandstone, consist of the Early Devonian Wood Bay Formation and Middle to Late Devonian Mimerdalen subgroup. Paleocurrent indicators from Lower to lower-Middle Devonian strata record north-directed sediment transport. Detrital zircon U-Pb ages indicate a prominent "Caledonian" signal and include sources from Svalbard's Northwestern and(or) Southwestern basement provinces. In Middle and Upper Devonian strata, paleocurrents and detrital zircon ages record a shift to a predominantly eastern-northeastern provenance, likely from the uplifting Ny-Friesland block along the Billefjorden Fault Zone. Late Ediacaran-early Cambrian detrital zircons in the uppermost Planteryggen Formation (Frasnian) indicate extrabasinal sources possibly associated with the Timanian orogen of Northern Baltica. The combined provenance data suggest Svalbard may have already been assembled, similar to the modern block, with the Andrée Land Basin located between modern exposures of the Southwestern/Northwestern and the Northeastern basement provinces. Comparison of detrital zircon ages from Andrée Land Group strata with those from other circum Arctic Devonian strata provides constraints on Svalbard's paleogeographic position in the Devonian.

1. Introduction

Detrital zircon provenance analysis of Devonian strata in Svalbard (Beranek et al., 2020; Pettersson et al., 2010) and across other modern Arctic regions (Figure 1a; Detrital zircon data locations listed from East to West from the Prime Meridian): East Greenland (Slama et al., 2011); Canadian Arctic Islands (Anfinson, Leier, Embry, & Dewing, 2012; Anfinson, Leier, Gaschnig, et al., 2012), Northwest Canada (Beranek et al., 2010; Lemieux et al., 2011), Alexander terrane (Beranek et al., 2013; Tochilin et al., 2014; White et al., 2016), Seward Peninsula (Amato et al., 2009), New Siberian Islands (Ershova et al., 2015b), Northeast Siberia (Ershova et al., 2020), Severnaya Zemlya (Lorenz et al., 2008), Novaya Zemlya (Lorenz et al., 2013), Northern Baltica (Miller et al., 2011), and Western Norway (Templeton, 2015) provide an ever clearer picture of sediment source regions, plate tectonic setting, and help guide the paleogeographic framework of modern Arctic regions in the late Paleozoic (e.g., Colpron & Nelson, 2009; Domeier & Torsvik, 2014). Samples from Andrée Land Group strata in the Dickson Land on the island of Spitsbergen, Svalbard (Figures 1b and 2a), located between the NE and NW Basement Provinces, were collected, and provenance analysis of detrital zircon U-Pb ages was performed to further constrain Paleozoic paleogeographic models of modern Arctic terranes.

The Svalbard Archipelago, located to the northwest of the Barents Shelf, represents a series of strike-slip faulted terranes, which are presumably pieces of neighboring landmasses and orogenic belts, that were isolated and

Investigation: Owen A. Anfinson, Margo L. Odlum, Karsten Piepjohn, Eirini M. Poulaki, Grace E. Shephard, Devin Levang, Maria A. Jensen, Elena A. Pavlovskaia
Methodology: Owen A. Anfinson, Margo L. Odlum, Grace E. Shephard, Daniel F. Stockli
Project Administration: Owen A. Anfinson
Resources: Owen A. Anfinson, Margo L. Odlum
Supervision: Owen A. Anfinson, Margo L. Odlum
Validation: Owen A. Anfinson, Margo L. Odlum, Grace E. Shephard
Visualization: Owen A. Anfinson, Margo L. Odlum, Karsten Piepjohn, Eirini M. Poulaki, Grace E. Shephard
Writing – original draft: Owen A. Anfinson, Margo L. Odlum, Karsten Piepjohn, Eirini M. Poulaki, Grace E. Shephard, Daniel F. Stockli, Devin Levang, Maria A. Jensen
Writing – review & editing: Owen A. Anfinson, Margo L. Odlum, Karsten Piepjohn, Eirini M. Poulaki, Grace E. Shephard, Daniel F. Stockli, Devin Levang, Maria A. Jensen, Elena A. Pavlovskaia

subsequently assembled to their current position (Harland, 1971; Harland et al., 1997; Gasser & Andresen, 2013; Gee & Teben'kov, 2004; Ohta, 1994; Pettersson et al., 2010). Determining the paleogeographic location of Svalbard during the Devonian (~420–360 Ma) is a key component in solving the tectonic puzzle of how the disparate pieces of the modern Arctic fit together before being separated during the Cretaceous opening of the Amerasia Basin (Embry, 2000; Miller et al., 2018) and the Cenozoic opening of the Eurasian Basin (Døssing et al., 2013; Harland et al., 1997; Kristoffersen et al., 1990; Thórarinsson et al., 2015). Here, we examine the provenance of samples collected from Andrée Land Group strata, part of the Old Red Sandstone (ORS), using detrital zircon U-Pb age data and compare it to samples from other Devonian Arctic basins to better understand Svalbard's tectonic and paleogeographic evolution. Evidence of magmatic or tectonic activity can further constrain the provenance of these strata by allowing us to match those events with other tectonic events (e.g., the Svalbardian event as a correlative/extension of the Ellesmerian orogeny (e.g., Piepjohn, 2000)). We integrate detrital zircon U-Pb geochronology with measured paleocurrents from cross-bedded strata and imbricated clasts from conglomerates to help determine paleoflow directions and sediment provenance evolution. These data are added to the growing database of detrital zircon data from the Arctic and help fill a spatial and temporal data gap for an important geographic location, and time period, for reconstructing late Paleozoic positions of modern Arctic terranes.

2. Geologic Background

The Devonian is an important period in the tectonic history of the modern Arctic as it encompasses the end of the Caledonian orogeny, post-Caledonian collapse, the development of the ORS molasse basin, and the Late Devonian to early Carboniferous Ellesmerian/Svalbardian event. The Caledonian orogeny resulted from the collision of Baltica, Laurentia, and Avalonia in the Ordovician to Early Devonian (Gee et al., 2008; McKerrow et al., 2000; Roberts & Gee, 1985; Torsvik et al., 1996). The geologic remnants of the Caledonian orogen are well defined in the British Isles, Scandinavia, Greenland, and Svalbard (Dewey, 1969; Gasser, 2014; Gee & Teben'kov, 2004; McKerrow et al., 2000) and evidence of Caledonian age deformation, translation, and metamorphism is reported from the Pearya terrane of the Canadian Arctic Islands (McClelland et al., 2021; Trettin, 1987), Franz Joseph Land (Knudsen et al., 2019), southern Lomonosov Ridge (Rekant et al., 2019), Chukchi Borderland (Brumley et al., 2015), and North American Cordilleran terranes (Gehrels et al., 1999; Miller et al., 2011) (locations on Figure 1a). The Caledonian orogen has an observed along strike length of >3,500 km (likely much greater), and involved a complex, polyphase history of terrane amalgamation, oceanic crust subduction and obduction, arc magmatism, basement nappe formation, metamorphism, anatexis, strike-slip faulting and extensional deformation (Dewey, 1969; Gasser, 2014; Gee, 2015; McKerrow et al., 2000).

On Svalbard, the Caledonian orogeny affected wide areas of pre-Devonian basement rocks in the Northwestern and Northeastern basement provinces (Figure 1b). On both the eastern and western sides of the Devonian Andrée Land Basin, Caledonian deformation is characterized by E-W shortening, folding, cleavage-formation, and metamorphism (Harland et al., 1997). On Biscayarhalvøya and northern Ny-Friesland (Figure 1b), west-directed thrust sheets or nappe stacks are reported (e.g., Bazarnik et al., 2019; Gee & Teben'kov, 2004; Hellman et al., 2001; Labrousse et al., 2008; Witt-Nilsson et al., 1998). In a late stage of the Caledonian orogeny, the basement areas on both provinces were affected by intrusion of syn-tectonic granites and migmatization (Johansson et al., 2002, 2004). Finally, the large, N-S striking fault zones on Spitsbergen (Billefjorden Fault Zone, Eolussletta Shear Zone; Figure 1b) were reactivated as ductile, sinistral shear zones (Dallmann, 2015; Harland et al., 1974, 1997; Lyberis & Manby, 1999; Manby, 1990; Manby et al., 1994).

The termination of the Caledonian orogeny is marked by the emplacement of undeformed, post-tectonic granite intrusions in the late Silurian and earliest Devonian. The largest are the Hornemantoppen Granite (U-Pb 418 ± 1 Ma: Myhre et al., 2009) in the Northwestern Basement Province and the Newtontoppen Granite (K-Ar 385–406 Ma: Gayer et al., 1966; Rb-Sr 432 ± 10 Ma: Teben'kov et al., 1996; U-Pb 430 ± 0.7 Ma: Myhre, 2005) and Rijpfjorden Granitoid Suite (U-Pb 410 ± 15 Ma: Johansson et al., 2002) in the Northeastern Basement Province.

2.1. Post-Caledonian Old Red Sandstone

The Caledonian orogeny and intrusion of post-tectonic granites was followed by the development of Old Red Sandstone (ORS) basins on Svalbard during the latest Silurian (?) and Devonian (e.g., Dallmann & Piepjohn, 2020;

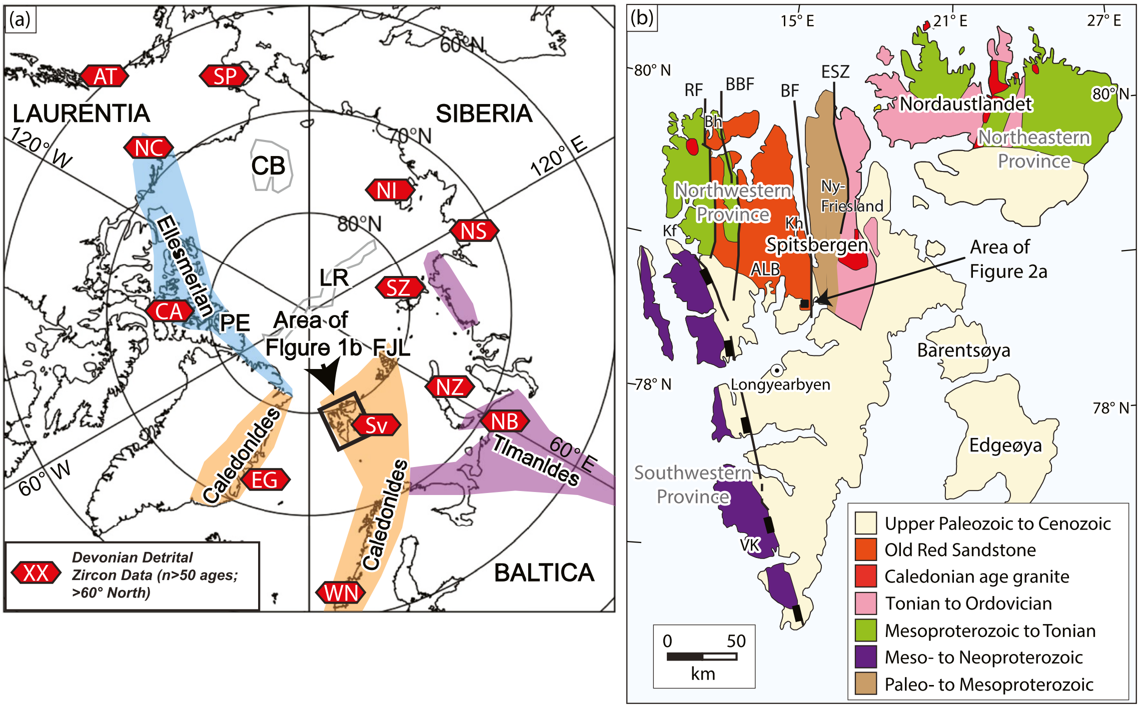

Figure 1. (a) Tectonic map of the modern Arctic depicting the general location of the Timanian, Caledonian, Ellesmerian orogenic belts, localities mentioned in the text, and existing Devonian detrital zircon data (map adapted from Colpron and Nelson [2009]). Detrital zircon data by location (East to West from Prime Meridian): EG, East Greenland (Slama et al., 2011); CA, Canadian Arctic Islands (Anfinson, Leier, Embry, & Dewing, 2012; Anfinson, Leier, Gaschnig, et al., 2012), NC, Northwest Canada (Beranek et al., 2010; Lemieux et al., 2011); AT, Alexander terrane (Beranek et al., 2013; Tochilin et al., 2014; White et al., 2016); SP, Seward Peninsula (Amato et al., 2009); NI, New Siberian Islands (Ershova et al., 2015a, 2015b; Ershova et al., 2018); NS, Northeast Siberia (Ershova et al., 2020); SZ, Severnaya Zemlya (Lorenz et al., 2008); NZ, Novaya Zemlya (Lorenz et al., 2013); NB, Northern Baltica (Miller et al., 2011); Sv, Svalbard (This study; Beranek et al., 2020; Pettersson et al., 2010); WN, Western Norway (Templeton, 2015). Geographic references: PE, Pearya terrane; LR, Lomonosov Ridge; CB, Chukchi Borderland; and FJL, Franz Joseph Land. (b) Geologic terrane map of Svalbard showing the location of the Northeastern, Northwestern, and Southwestern provinces and associated major tectonic elements including the Billefjorden Fault Zone (BFZ), Breibogen Fault (BBF), Raudfjorden Fault (RF), Eolussletta Shear Zone (ESZ), the Vimsodden-Kosibapasset shear zone (VK), and the Andrée Land Basin (ALB). Geographic references: Kh, Kronprinshoegda; Kf, Kongsfjorden; Bh, Biscayarhalvøya. Map adapted from Beranek et al. (2020) and based on the geologic map of Gee (2015).

Føyn & Heintz, 1943; Frebold, 1935; Friend, 1961; Gee & Moody-Stuart, 1966; Holtedahl, 1914; Murašov & Mokin, 1979; Orvin, 1940; Piepjohn, 1994; Piepjohn & Dallmann, 2014; Piepjohn et al., 2000; Suess, 1888; Vogt, 1938; Figure 1b). The ORS is mainly exposed in two areas in NW Spitsbergen, the Raudfjorden Trough and the Andrée Land Basin, with a number of smaller, isolated occurrences along the west coast and in the south of Spitsbergen (Dallmann & Piepjohn, 2020). The molasse deposits of the ORS on Spitsbergen can be divided into two major successions (Dallmann & Piepjohn, 2020; Manby & Lyberis, 1992; Piepjohn, 1994) which were controlled by initial tectonic subsidence (lower ORS succession) and subsequent thermal subsidence (upper ORS succession) (Manby & Lyberis, 1992). The greatest accumulated thickness of the ORS is estimated to be in the range of 8 km (Friend & Moody-Stuart, 1972).

2.1.1. Lower Old Red Succession (Siktefjellet and Red Bay Groups)

The development of the lower ORS succession was initiated by the formation of the small, isolated pull-apart basins with sandstone and conglomerate of the late Silurian (?) Siktefjellet Group (Friend et al., 1997; Gee & Moody-Stuart, 1966; McCann, 2000), which are only exposed in northern Haakon VII Land between Raudfjorden and Liefdefjorden. The Siktefjellet Group is in depositional and/or fault contact with the metamorphic basement (Friend et al., 1997). Basal ORS deposition is primarily fluvial sandstone with occasional conglomerates related to fault scarps created by transpression (Friend et al., 1997). Deposition of the Siktefjellet Group was terminated by sinistral strike-slip tectonics of the Haakonian Phase (ca. 420 Ma; Dallmann & Piepjohn, 2020; Gee, 1972; McCann, 2000). The second unit of the lower ORS succession is represented by ~3.5 km thick sandstone and conglomerate of the Lochkovian (earliest Devonian) Red Bay Group (Holtedahl, 1914), which are mainly exposed in the narrow, NNW-SSE trending Raudfjorden Trough between the Raudfjorden Fault in

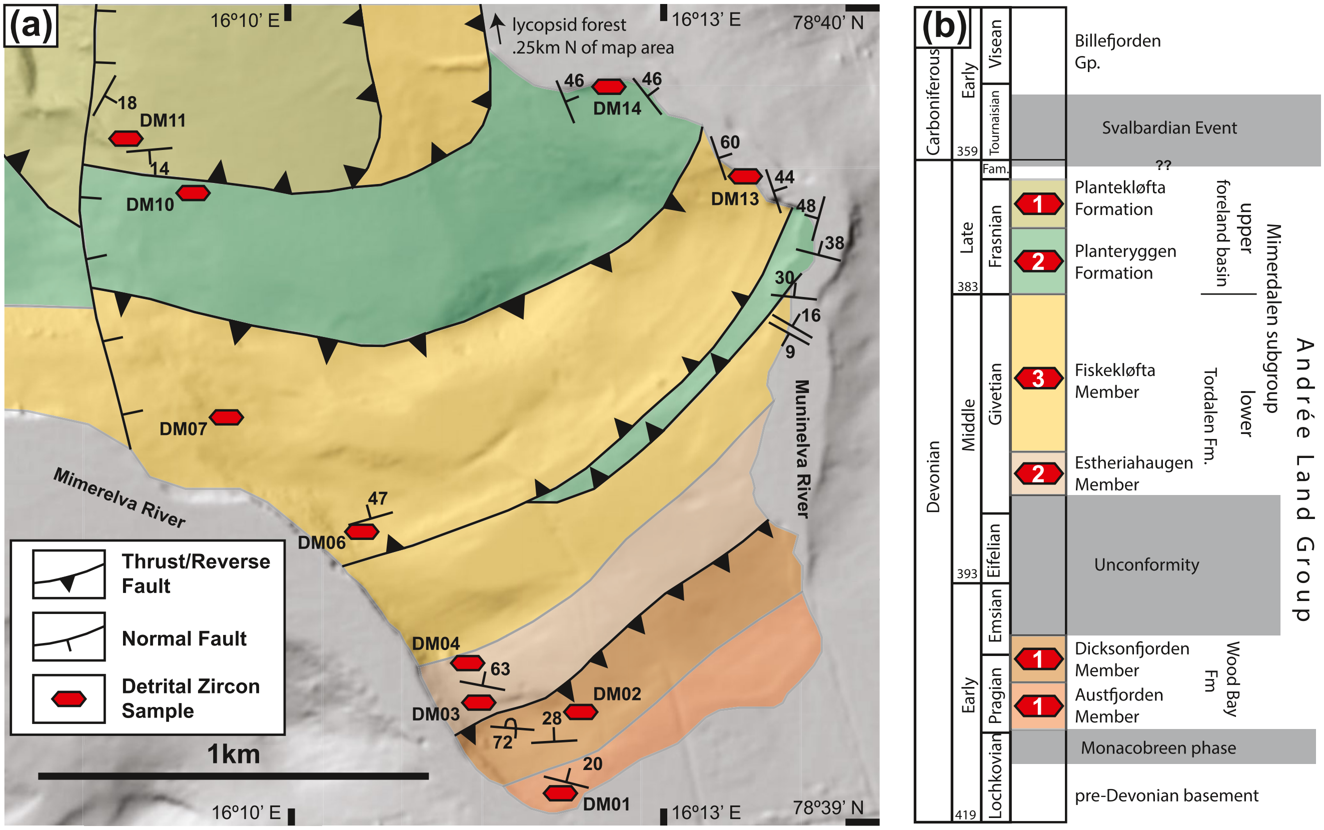

Figure 2. (a) Detrital zircon sample locations and geologic map of the Mimerdalen Subgroup at Estheriahaugen, Mimerdalen in Dickson Land on the island of Spitsbergen, Svalbard (Location of map area on Figure 1b). Modified from Michaelsen (1998), Bergh et al. (2011), Piepjohn and Dallmann (2014), and partially based on field observations. Geologic units are only depicted for the field area between the Muninelva and Mimerelva rivers. (b) Stratigraphic column of the Devonian Andrée Land Group modified from Piepjohn and Dallmann (2014) updated to include stratigraphic ages from Berry and Marshall (2015) for Upper Devonian strata. The number inside the zircon symbol indicates the number of detrital zircon samples from that unit.

the west and the Breibogen Fault in the east (Figure 1b; Dallmann & Piepjohn, 2020; Friend et al., 1997; Gee & Moody-Stuart, 1966; McCann, 2000). Red Bay Group strata sit unconformably on both Siktefjellet Group rocks and metamorphic basement (Friend et al., 1997). The deposition of the Red Bay Group was accompanied by syn-sedimentary sinistral strike-slip faulting and block rotation, which resulted in the inversion of the Red Bay Trough (McCann, 2000). The deposition of the lower ORS succession was terminated by renewed sinistral strike-slip faulting of the late Lochkovian (ca. 412 Ma) Monacobreen Phase (Dallmann & Piepjohn, 2020; McCann, 2000).

2.1.2. Upper Old Red Succession (Andrée Land-Group)

The upper ORS succession is represented by >5 km thickness of sandstone, siltstone, and minor conglomerate of the Pragian to Frasnian (Early to Late Devonian) Andrée Land Group (Harland et al., 1974), which are exposed in the Andrée Land Basin between the Breibogen Fault and Billefjorden Fault Zone on northern Spitsbergen (Figure 1b). The Andrée Land Basin lies between the Northwestern Basement Province in the west (Breibogen Fault: Gee & Moody-Stuart, 1966) and the Northeastern Basement Province in the east (Billefjorden Fault Zone: Harland et al., 1974) (Figure 1b). It should be noted that in the majority of the basin, the basement underneath the Andrée Land Basin is unknown. There is one location in southern Kronprinshøgda (Kh, Figure 1b), where the Andrée Land Group is sitting on Red Bay Group, but the exposure is very poor (see Dallmann & Piepjohn, 2020). There is also only a single outcrop where the unconformity of the Andrée Land Group is exposed, at Pretender Mountain SE of Kongsfjorden (Kf, Figure 1b), where the Andrée Land Group is underlain by basement rocks (McCann, 2000). However, Hellman et al. (1998) recognized that 1740 Ma boulders contained within the Siktefjellet Group increase in size toward the Breibogen-Bockfjorden fault and were likely sourced from the basement beneath the Andrée Land Basin. This was used as evidence supporting a connection between the NE and NW provinces during deposition of the Siktefjellet Group. The predominantly clastic rocks of the Andrée Land Basin are summarized in the Andrée Land Group (Harland et al., 1974), which is divided into the Wood Bay Formation (Murašov & Mokin, 1979), Gray Hoek Formation (Holtedahl, 1914), Wijde Bay Formation (Friend et al., 1966; Harland et al., 1974; Holtedahl, 1914), and the Mimerdalen Subgroup (Piepjohn & Dallmann, 2014).

The Wood Bay Formation represents the "typical" red bed facies of the ORS, with red, yellow and green fluvial sandstone, siltstone, and subordinate shale. It is more than 3 km thick (Friend & Moody-Stuart, 1972; Gee, 1972), and the age is Pragian to Emsian (Lower Devonian) (Friend, 1961; Friend et al., 1966; Føyn & Heintz, 1943). The depositional area of the Wood Bay Formation is characterized by the presence of long-lived river systems with general paleoflow directions toward the north (Friend & Moody-Stuart, 1972).

In the study area west of Billefjorden, the Wood Bay Formation is subdivided in the Austfjorden Member (Friend, 1961) and the Dicksonfjorden Member (Friend, 1961). The Austfjorden Member in the southeastern parts of the Andrée Land Basin is >800 m thick and consists of yellow to greenish sandstones. The Dicksonfjorden Member (Friend, 1961) represents the typical red bed facies of the ORS in the Andrée Land Basin consisting of red, fine-grained sandstones, siltstones and subordinate shale. It makes up the bulk of the Wood Bay Formation, from the base in western areas, and overlying (or interfingering with) the Austfjorden Member in eastern areas of the Andrée Land Basin.

The 1.1 km thick Gray Hoek Formation overlies the Wood Bay Formation and consists of basal limestone, green, gray and black shale, silt- and sandstone. The age is determined as late Emsian to Eifelian (Middle Devonian) by fish fauna (Føyn & Heintz, 1943; Heintz, 1937; Orvig, 1969). In northeastern Andrée Land, alternating black shale, dark-gray mudstone, gray siltstone and light-gray quartzitic sandstone of the 500–600 m thick Wijde Bay Formation of Givetian age (Middle Devonian) (Føyn & Heintz, 1943; Westoll, 1951; N.M. Petrosian in: Murašov & Mokin, 1979) are exposed.

The uppermost stratigraphic unit of the Andrée Land Group is the Mimerdalen Subgroup (Piepjohn & Dallmann, 2014), which is restricted to Dickson Land in the southeastern-most part of the Andrée Land Basin northeast of Billefjorden. It overlies the Wood Bay Formation (Dicksonfjorden Member) with a low-angle, erosional unconformity (Friend & Moody-Stuart, 1972) and is divided into the Tordalen Formation with the Estheriahaugen Member and Fiskekløfta Member (Friend, 1961), the Planteryggen Formation (Friend, 1961) with the Odinelva Member and Muninelva Member (Dallmann et al., 2004; Piepjohn & Dallmann, 2014), and the Plantekløfta Formation (Friend, 1961). Mimerdalen Subgroup strata are characterized by predominantly fluvial and alluvial fan deposits (Michaelsen, 1998; Piepjohn & Dallmann, 2014). Flaser bedding and marine ostracods indicate that the Tordalen Formation depositional area was at least temporarily affected by marine transgressions (Grewing, 1997).

After a period of tectonic quiescence during the deposition of the Wood Bay, Gray Hoek, and Wijde Bay formations, the Mimerdalen Subgroup contains the first substantial conglomerates since the deposition of coarse clastic deposits of the Red Bay Group in the Lochkovian. This indicates an important transition of the depositional regime from the wide-spread molasse facies of the Andrée Land Basin (Friend, 1961) to the onset of the Svalbardian orogeny. The onset of tectonic activity is supported by normal faults offsetting deposits of the Fiskekløfta Member, which are overlain by the Planteryggen Formation (Hugindalen Phase: Dallmann & Piepjohn, 2020) and by clasts in the conglomerates of the lower Planteryggen Formation, which indicate a reworking of the underlying Fiskekløfta Member. This phase of block-faulting is possibly related to uplift of areas east of the Billefjorden Fault Zone: conglomerate of the Plantekløfta Formation supposedly contain green sandstone pebbles of the Austfjorden Member indicating that the Lower Devonian cover east of the Billefjorden Fault Zone was already eroded, removed, and partly resedimented during the deposition of the Mimerdalen Subgroup (Friend, 1961; Piepjohn et al., 2000; Vogt, 1938). This is supported by the content of basement clasts in the lower Planteryggen Formation indicating uplift and erosion of the basement source areas in Ny Friesland east of the Billefjorden Fault Zone (Dißmann, 1997; Michaelsen, 1998). The narrow north-south trending trough of the Mimerdalen Subgroup parallel to the Billefjorden Fault Zone (BFZ) represents a foreland basin during initial uplift of the Ny Friesland High to the east (Dißmann, 1997; Piepjohn, 2000; Piepjohn & Dallmann, 2014; Piepjohn et al., 2000).

2.2. Post-Devonian Svalbardian Orogeny

The development of the ORS basins on Spitsbergen was terminated by uplift associated with the Tournaisian Svalbardian orogeny (e.g., Dallmann & Piepjohn, 2020; Holtedahl, 1914; Piepjohn, 2000; Piepjohn et al., 2000;

Vogt, 1928), which can be correlated with the Ellesmerian orogeny in North Greenland and Canadian Arctic (Christie, 1979; Dallmann & Piepjohn, 2020; Manby & Lyberis, 1992; McCann, 2000; Piepjohn, 2000; Piepjohn et al., 2015). The Svalbardian is characterized by several fold-and-thrust zones within the Devonian basins (e.g., the Dickson Land Fold-and-Thrust Zone within the field area; Piepjohn, 2000) and in the underlying Caledonian basement (Dallmann & Piepjohn, 2020; Piepjohn, 1994, 2000; Piepjohn et al., 2015).

The timing of Svalbardian deformation on Svalbard is debated. The ages of the youngest deformed Devonian rocks of the Mimerdalen Subgroup and the oldest undeformed rocks of the Billefjorden Group are essential for constraining the timing of the Svalbardian deformation on Svalbard. The age of the Mimerdalen Subgroup, especially of the Plantekløfta Formation, has been a matter of discussion. Most authors agree that the Plantekløfta Formation is older than early Carboniferous (e.g., Murašov & Mokin, 1979). However, while most authors have interpreted an early Famennian age (~370 Ma; Allen, 1965, 1973; Heintz, 1937; Tarlo, 1967; Vigran, 1964; Westoll, 1951) or a late Famennian age (~360 Ma; Pčelina et al., 1986; Piepjohn et al., 2000; Schweitzer, 1999), Berry and Marshall (2015) suggested an early Frasnian age (~380 Ma) based on the suggestion that earlier reports (e.g., Piepjohn et al., 2000) have misidentified Frasnian spores as Famennian (i.e., *Retispora lepidophyta*). With respect to the timing of the Svalbardian orogeny, a possible late Frasnian age of the Plantekløfta Formation does not consequently mean that this deformation took place in Famennian times. It just widens the time interval in which the Svalbardian deformation could have taken place, from post-late Frasnian to pre-Viséan. However, the existing age determinations in the Canadian Arctic Islands, in North Greenland, and on Prins Karls Forland suggest the Svalbardian/Ellesmerian orogeny occurred: (a) between the late Famennian and the Bashkirian on Melville Island (Harrison et al., 1995), (b) latest Devonian to earliest Carboniferous on Devon Island (Mayr et al., 1998), (c) Tournaisian on northern Ellesmere Island (Beauchamp et al., 2019), (d) Visean to Bashkirian in North Greenland (Springer & Friderichsen, 1994), (e) post-late Famennian to pre-Visean on Spitsbergen (Piepjohn et al., 2000), and (f) Tournasian on Prins Karls Forland (Kośmińska et al., 2020).

2.3. Tectonic Terranes

The Svalbard Archipelago can be divided into three major pre-Devonian provinces based on the different lithologies and basement rock assemblage ages and different tectonic and structural evolutions. These are the Southwestern Basement Province, the Northwestern Basement Province, and the Northeastern Basement Province (Figure 1b; e.g., Dallmann, 2015; Gee, 2015; Gee & Teben'kov, 2004; Gee et al., 1995, 2006; Harland et al., 1997; Majka & Kośmińska, 2017). Below, we discuss the basic geologic architecture of each province to provide context for our provenance and paleogeographic interpretations.

2.3.1. Northeastern Basement Province

The Northeastern Basement Province is situated east of the Devonian Andrée Land Basin and the Billefjorden Fault Zone, and can be subdivided into the Western Ny-Friesland terrane and the Nordaustlandet terrane (e.g., Dallmann, 2015; Gee & Teben'kov, 2004; Gee et al., 1995; Harland et al., 1997; Sandelin et al., 2001). The two terranes are separated by the Eolussletta Shear Zone (Figure 1b; Lyberis & Manby, 1999; Manby, 1990; Manby & Lyberis, 1992; Manby et al., 1994) or the "Veteranen Line" (Harland et al., 1992, 1997). The Western Ny-Friesland terrane contains the oldest rocks of Svalbard, with Paleoproterozoic high-grade metamorphic complexes of orthogneiss, migmatite and amphibolite intruded by granitoids and felsic meta-tuff with ages of c. 1750 and 1760 Ma (Bazarnik et al., 2019; Dallmann, 2015). The Mosselhalvøya Unit is characterized by Mesoproterozoic medium- to high-grade metamorphic supracrustal and igneous rocks previously referred to as the Planetfjella Group (Wallis, 1967). The entire succession bears evidence for deformation and metamorphism during the Caledonian orogeny (e.g., Gee & Page, 1994; Johansson et al., 1995).

The complex Nordaustlandet terrane consists of sedimentary, metamorphic, and igneous rocks. The oldest unit consists of Mesoproterozoic metasedimentary rocks of the Brennevinsfjorden Group and Helvetesflya Unit (Gee & Teben'kov, 1996; Gee et al., 1995; Teben'kov et al., 2002) which were intruded by 940–960 Ma Tonian granites (Gee et al., 1995; Teben'kov et al., 2002). The Brennevinsfjorden Group and Helvetesflya Unit are unconformably overlain by the Kapp Hansteen Group (Ohta, 1985) and the Svartrabbane Unit (Gee & Teben'kov, 1996; Teben'kov et al., 2002), respectively. The Helvetesflya and Svartrabbane units are unconformably overlain by >5,000 m thick sedimentary rocks of the Tonian Murchisonfjorden Supergroup (Dallmann et al., 2002; Flood et al., 1969; Kulling, 1934; Ohta, 1982; Teben'kov et al., 2002), which correspond to the Lomfjorden Supergroup west of

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Hinlopenstretet (Dallmann, 2015; Gee et al., 1995; Harland et al., 1992). The sedimentation continued through Cryogenian to Ordovician times (~720–440 Ma) (Hinlopenstretet Supergroup: Harland et al., 1966, 1997; Stouge et al., 2011). All rock units were deformed and metamorphosed at different degree from low-grade up to migmatization and anatexis, during the Caledonian orogeny, and intruded by Silurian (~440–425 Ma) post-tectonic granites (Gasser, 2014; McClelland et al., 2019; Teben'kov et al., 2002).

2.3.2. Northwestern Basement Province

The Northwestern Basement Province is separated from the Devonian Andrée Land Basin by the Breibogen Fault in the east, and can be subdivided into the Albert I Land and Biscayarhalvøya terranes (e.g., Dallmann, 2015; Harland et al., 1997). The Albert I Land terrane is dominated by the metasedimentary succession of the Krossfjorden Group (e.g., Abakumov, 1979; Gee & Hjelle, 1966; Hjelle, 1979) for which the protolith was deposited in the late Stenian to early Tonian (Pettersson, Teben'kov, et al., 2009). The Krossfjorden Group was intruded by a 995 Ma dyke (Pettersson, Teben'kov, et al., 2009) and Tonian granitoids (970–960 Ma: Gromet & Gee, 1998; Ohta et al., 2002; Pettersson, Pease, & Frei, 2009). The high-grade Smeerenburgfjorden Migmatite Complex is interpreted to be an equivalent of the Krossfjorden Group and is characterized by migmatization and anatectic granite genesis (434–417 Ma: Myhre et al., 2009; Ohta et al., 2002; Pettersson, Pease, & Frei, 2009; Pettersson, Teben'kov, et al., 2009). During the final stage of the Caledonian orogeny, the basement of the Albert I Land terrane was intruded by the undeformed Hornemantoppen batholith (418–414 Ma: Balašov et al., 1996; Hjelle, 1979; Myhre et al., 2009). The Biscayarhalvøya terrane is subdivided in to the metasedimentary successions of the Richarddalen Complex and the Biscayarfonna Group (e.g., Dallmann, 2015; Gromet & Gee, 1998; Harland et al., 1997; Ohta et al., 2003; Peucat et al., 1989). The Biscayarfonna Group has been correlated with the Krossfjorden Group by Harland et al. (1997) and was intruded by early Tonian granite (Ohta & Larionov, 1998). The Richarddalen Complex, the tectonically highest unit of the terrane, comprises lenses of Cryogenian eclogite, mafic and felsic gneiss formed under high pressure conditions (Elvevold et al., 2014; Gee & Hjelle, 1966; Peucat et al., 1989). Eclogite-facies metamorphism was followed by amphibolite-facies retrogression in Cambro–Ordovician times (Dallmeyer et al., 1990; Elvevold et al., 2014; Gromet & Gee, 1998; Ohta et al., 2003; Pettersson, Pease, & Frei, 2009; Peucat et al., 1989). ^{40}Ar/^{39}Ar amphibole ages of c. 429 and c. 437 Ma as well as muscovite and biotite ^{40}Ar/^{39}Ar and Rb–Sr ages of 430 to 400 Ma were interpreted as cooling ages after Caledonian amphibolite-facies metamorphism (Dallmeyer et al., 1990).

2.3.3. Southwestern Basement Province

The Southwestern Basement Province of Svalbard consists of Mesoproterozoic and Neoproterozoic basement rocks underlying the Cenozoic fold-thrust belt on the western edge of Spitsbergen (Bergh et al., 1997; Harland et al., 1997). Below the Torrelian Unconformity (ca. 640 Ma) the basement consists of Mesoproterozoic quartzite similar to that of the Krossfjorden Group of the Northwestern Basement Province. Detrital zircon age groups from Cryogenian basement strata of the Southwestern Province are predominately 1150–960 Ma, 1500–1300 Ma, and 1750–1600 Ma with few early Paleoproterozoic and older ages (Gasser & Andresen, 2013; Wala et al., 2021). This region also shares the Tonian magmatism experienced by both the Krossfjorden Group and the basement of the Nordaustlandet terrane, highlighting the broad extent of the shared tectonothermal history of the archipelago (Majka et al., 2014). Above the unconformity lies a series of sedimentary and low-grade metasedimentary rocks, capped by a thick unit of tillite that is linked to the Marinoan Glaciation (Gasser & Andresen, 2013; Wala et al., 2021). Rocks of the Southwestern Basement Province underwent extensive high-pressure metamorphism during the early stages of the Caledonian orogeny (ca. 470–420 Ma), highlighted by the blueschist/eclogite facies of the Vestgötabreen Complex (Dallmeyer et al., 1990), however, this is not representative of the entire Southwestern terrane, which has been shown to be a composite terrane of multiple peri-Baltican and peri-Laurentian crustal fragments (Wala et al., 2021).

2.4. Northeast Greenland

Pre-Devonian rocks of Northeasternmost Greenland developed along the Laurentian margin and were deformed in the Silurian as a result of continental collision with Baltica during the Caledonian orogeny (Gee, 2015; Higgins & Soper, 1995). In the late Devonian, northern Greenland experienced ultra-high pressure metamorphism and both sinistral and dextral translation, which is interpreted as accommodating margin parallel escape from the Caledonian orogen (Gilotti & McClelland, 2007). McClelland et al. (2021) suggest this strike slip system is truncated by the Canadian Arctic Transform System (CATS), providing a possible mechanism for transferring Caledonian rocks of Svalbard along the northern Greenland margin. The similarity of Neoproterozoic and Early Paleozoic stratigraphy and faunal assemblages found in both Svalbard's Northwestern and Northeastern Basement Provinces and that of the Northeast Greenland have long suggested a correlation of these regions (e.g., Gee, 2015). Lines of evidence that support this correlation include: (a) Cambro-Ordovician carbonate bank successions found on both northeastern Greenland and Svalbard contrast with coeval successions on the Fennoscandian Shield of Baltica (Gee, 2015), (b) Timing and degree of Caledonian and Precambrian metamorphism are similar in both regions (Dallmeyer et al., 1990; Gee & Teben'kov, 2004). (c) Structural correlations between west-directed thrust sheets of the Northeastern and Northwestern basement provinces and the upper allochthons of the northeast Greenland Caledonides (e.g., Gee, 2015; Gee & Teben'kov, 2004). Based on these correlations, the Northwestern and Northeastern basement provinces have been viewed as a continuation of the NE Greenland shelf and as such, suggest the ORS of Svalbard was developed in close proximity to NE Greenland.

3. Detrital Zircon Methods

All sandstone samples underwent conventional heavy-mineral separation techniques, including crushing, grinding, water tabling, magnetic, and heavy liquid separations. Detrital zircon grains were mounted on double-sided tape (tape mount) on a 1-inch acrylic disc without polishing. 120–140 grains were randomly selected for LA-ICP-MS analysis to avoid biases and to capture all major age components (>5%) (Vermeesch, 2004). All grains were depth-profiled at the UT Chron Geochronology facility at the University of Texas at Austin using a Photon Machines Analyte G2 ATLex 300si ArF 193 nm excimer laser equipped with a Helex 9 sample cell, combined with a Thermo Scientific™ Element 2™ single-collector, magnetic sector ICP-MS, following similar analytical protocols to Marsh and Stockli (2015). Thirty seconds of background was measured followed by 4 pre-ablation "cleaning" shots, then 15 s of washout to measure background, prior to 30 s of sample analysis. A 30 μm spot for each grain with a fluence of ∼4 J/cm^2, resulted in ∼15 μm deep ablation pits. For all U–Pb geochronologic analyses of detrital zircon the masses ^{202}Hg, ^{204}Pb, ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{232}Th, ^{235}U, and ^{238}U were measured. GJ1 was used as primary zircon standard (^{206}Pb/^{238}U 601.7 ± 1.3 Ma, ^{207}Pb/^{206}Pb 607 ± 4 Ma; Jackson et al., 2004) and interspersed every five unknown analyses for elemental and depth-dependent fractionation. Plesovice (337.1 ± 0.4 Ma; Sláma et al., 2008) was used as a secondary standard for quality control, yielding ^{206}Pb/^{238}U ages during this study of 338 ± 6 Ma, which is in agreement with the published age. No common-Pb correction was applied. Data reduction was performed using the IgorPro-based iolite 3.4 software (Paton et al., 2010) with the VizualAge data reduction scheme (Petrus & Kamber, 2012). All uncertainties are quoted at 2 sigma level, and age uncertainty of reference materials are not propagated. For ages younger than 850 Ma, ^{206}Pb/^{238}U ages are reported and grains were eliminated from text and data figures if there was more than 10% discordance between the ^{206}Pb/^{238}U age and the ^{207}Pb/^{235}U age or the ^{206}Pb/^{238}U age had more than 10% 2 sigma absolute error. For ages older than 850 Ma, ^{207}Pb/^{206}Pb ages are reported and grains were eliminated from text and figures if there was more than 20% discordance between ^{206}Pb/^{238}U age and ^{207}Pb/^{206}Pb age. We chose 850 Ma as our transition from ^{206}Pb/^{238}U ages to ^{207}Pb/^{206}Pb ages because the transition was outside of any major age group. Analytical data were visually inspected for common-Pb, inheritance, or Pb loss using the VizualAge live concordia function (Petrus & Kamber, 2012). Rejected ages are marked as "NA" in the "Best Age" column of Supporting Information S1.

4. Samples and Detrital Zircon U-Pb Age Results

4.1. Wood Bay Formation

4.1.1. Austfjorden Member

Sample DM01 was collected from the Austfjorden Member of the lower part of the Early Devonian Wood Bay Formation and is an arkosic sandstone, containing feldspar, quartz, and white mica (Table 1; Figures 2a and 2b). The strata of the Austfjorden Member contain abundant ripple marks (1–2 cm in scale) and the ripple laminations are consistent with previously recorded paleocurrent measurements suggesting transport from southwest to northeast (Friend & Moody-Stuart, 1972). Field observations of cross-bedded sandstone also showed a southwest to northeast paleocurrent orientation, similar to the overlying Dicksonfjorden Member (Figures 3a and 3b). The sample contains 110 accepted detrital zircon ages out of 131 age analyses and the ages range from

Table 1
Detrital Zircon Sample Numbers, Associated Formation and Member, Relative Age, and Geographic Coordinates

Sample #	Formation	Member	Relative age	Latitude	Longitude
OA19_DM01	Wood Bay	Austfjorden	Pragian	78.649438°	16.201969°
OA19_DM02	Wood Bay	Dickensonfjorden	Pragian	78.650815°	16.199599°
OA19_DM03	Tordalen	Estheriahaugen	Givetian	78.650818°	16.191658°
OA19_DM04	Tordalen	Estheriahaugen	Givetian	78.652009°	16.186957°
OA19_DM06	Tordalen	Fiskeklofta	Givetian	78.654092°	16.173733°
OA19_DM07	Tordalen	Fiskeklofta	Givetian	78.655605°	16.156510°
OA19_DM13	Tordalen	Fiskeklofta	Givetian	78.664181°	16.204225°
OA19_DM14	Planteryggen	Odinelva	Frasnian	78.664890°	16.186165°
OA19_DM10	Planteryggen	Muninelva	Frasnian	78.660057°	16.147336°
OA19_DM11	Planteklofta	Planteklofta	Frasnian	78.661067°	16.136242°

1867 to 386 Ma (Figure 4). The detrital zircon ages are primarily Silurian (443–422 Ma; 35%) and Ordovician (483–444 Ma; 30%). The sample contains secondary populations of Tonian (983–854 Ma; 10%), Cambrian (517–488 Ma; 6%), Devonian (417–386 Ma; 6%), Mesoproterozoic (1490–1011 Ma; 6%), and Paleoproterozoic (1867–1614 Ma; 4%) ages. There are three Cryogenian ages (663, 678, 679 Ma), and one Ediacaran age (601 Ma). One age (386.9 ± 5.4 Ma) is younger than the lower boundary of the reported depositional age (Pragian to Emsian; 411–393 Ma) of the Austfjorden Member and the rejection of that youngest age for assigning a new depositional age is discussed in the interpretations (Section 5.1).

4.1.2. Dicksonfjorden Member

Sample DM02 was collected from the Dicksonfjorden Member of the upper Wood Bay Formation (Table 1; Figures 2a and 2b) with similar arkosic sandstone lithology to the Austfjorden Member but a greater proportion of quartz and biotite mica. The Dicksonfjorden Member also displayed extensive 2D and 3D cross-bedding, up to 10 cm thick in scale, and indicates the depositional paleoflow was directed to the north (Figures 3a and 3b). The detrital zircon ages from the sample are mostly discordant with only 54 accepted detrital zircon ages out of 140 analyses (Figure 4). The ages range from 2687 to 423 Ma and contain primarily Mesoproterozoic (1587–1023 Ma; 52%) detrital zircon grains. The sample contains lesser amounts Silurian (443–423 Ma; 15%), Ordovician (481–444 Ma; 11%), Paleoproterozoic (2040–1630 Ma; 11%), and Cambrian (501–487; 3%) grains. There are single ages from the Cryogenian (675 Ma), Tonian (988 Ma), and Archean (2687 Ma).

4.2. Tordalen Formation

4.2.1. Estheriahaugen Member

Samples DM03 and DM04 were taken from the Estheriahaugen Member (Table 1; Figures 2a and 2b) and consist of gray and green colored siltstones and fine-grained sandstones that occasionally display crossbedding indicating a northeast directed paleoflow (Figure 3c). Lenses of conglomerate are interspersed throughout the sand and silt of the Estheriahaugen Member, predominantly composed of sub-angular to rounded clasts of green carbonate and white/pink quartz. The unit overlies a regional low-angle unconformity, highlighting an erosional period between the Pragian deposition of the Dicksonfjorden Member of the Wood Bay Formation and the Givetian (~385 Ma) strata of the Estheriahaugen Member of the Tordalen Formation (Friend, 1961).

Sample DM03 is from a sandstone unit within the lower Estheriahaugen Member. The sample contains 136 accepted detrital zircon ages out of 138 age analyses and the ages range from 2692 to 409 Ma (Figure 4). The detrital zircon ages are primarily Mesoproterozoic (1596–1001 Ma; 58%). The sample contains secondary populations of Silurian (442–419 Ma; 26%), Paleoproterozoic (2179–1602; 18%), and Ordovician (476–444 Ma; 13%) ages. From the Neoproterozoic there are 8% Tonian ages (986–786 Ma), two Cryogenian ages (703, 644), and one Ediacaran age (613 Ma). The sample also contains six Cambrian (539–490 Ma), two Archean (2692 and 2653 Ma), and two Devonian (417 Ma, 409) ages.

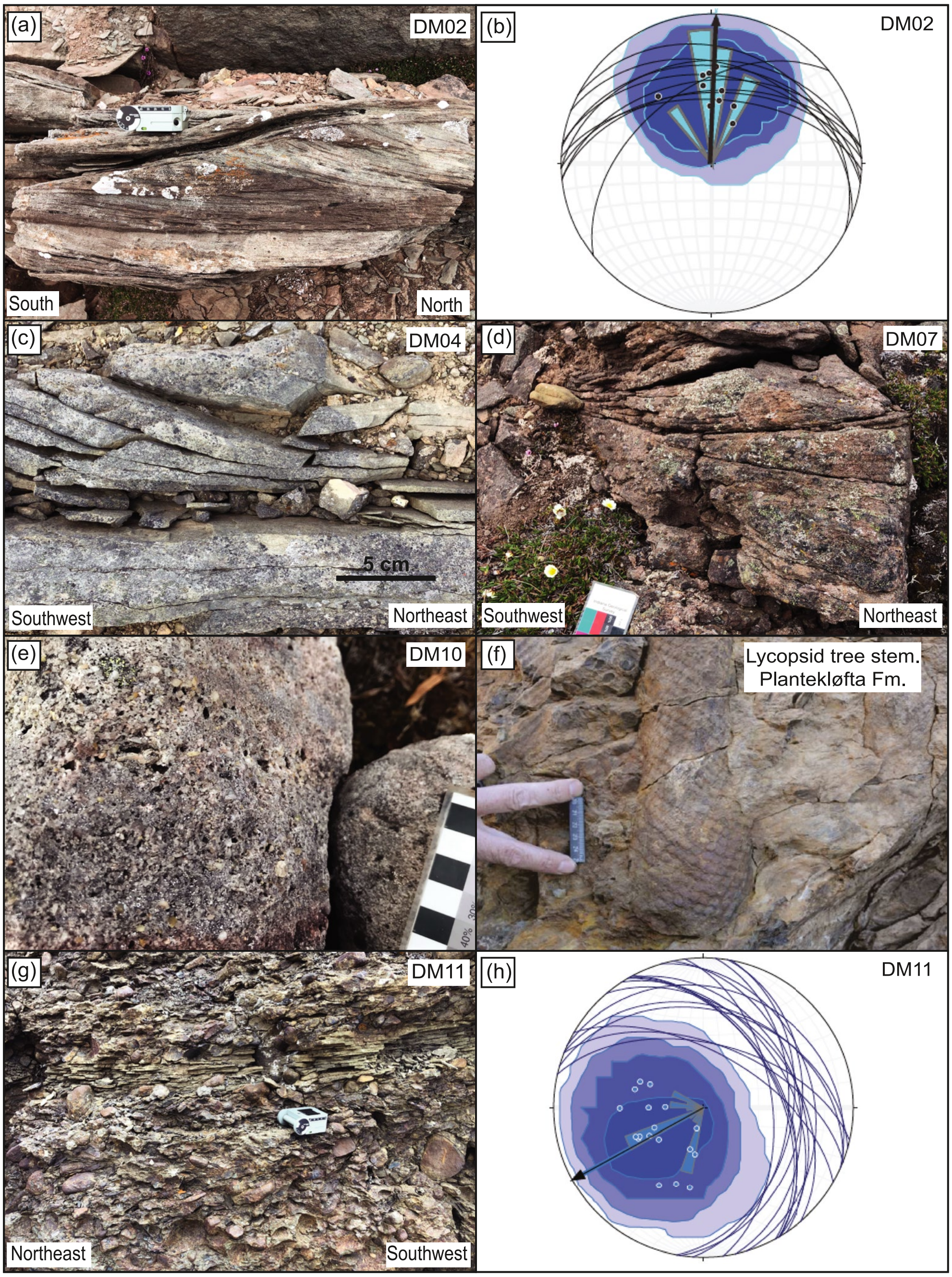

Figure 3. Sample pictures, field pictures, and paleocurrent measurements from the sampled section. (a) South to north directed crossbeds from sample location DM02 within the Dicksonfjorden Member of the Wood Bay Formation. (b) Paleocurrent rose diagram of crossbeds from the DM02 sample locality indicate a general south to north transport direction for the sandstones of the Dicksonfjorden Member of the Wood Bay Formation. (c) Southwest to northeast directed crossbedding from the DM04 sample locality within the Estheriahaugen Member of the Tordalen Formation (no paleocurrent data was collected). (d) Northeast to southwest directed crossbedding from the DM07 sample locality within the Fiskekløfta Member of the Tordalen Formation (no paleocurrent data was collected). (e) Quartz dominated oligomictic orthoconglomerate from the uppermost unit of the of Muninelva Member of the Planteryggen Formation. The unit was previously described as a 40 m thick succession of red conglomerate with up to cm size pebbles of red and white quartzite (Murašov & Mokin, 1979; Piepjohn & Dallmann, 2014). (f) Image from Berry and Marshall (2015) of a lycopsid tree stem (*Protolepidodendropsis*) from the Plantekløfta Formation (location noted on Figure 2a). The westward tilt of these fossil forests with respect to bedding orientation indicate debris flows transported sediment to the west (Berry & Marshall, 2015; Piepjohn, 2000). (g) Imbricated clasts within the Plantekløfta Formation from the DM11 sample locality. (h) Paleocurrent measurements of imbricated clasts from the DM11 sample locality indicate a general northeast to southwest transport direction for the conglomerates and sandstones of the Plantekløfta Formation.

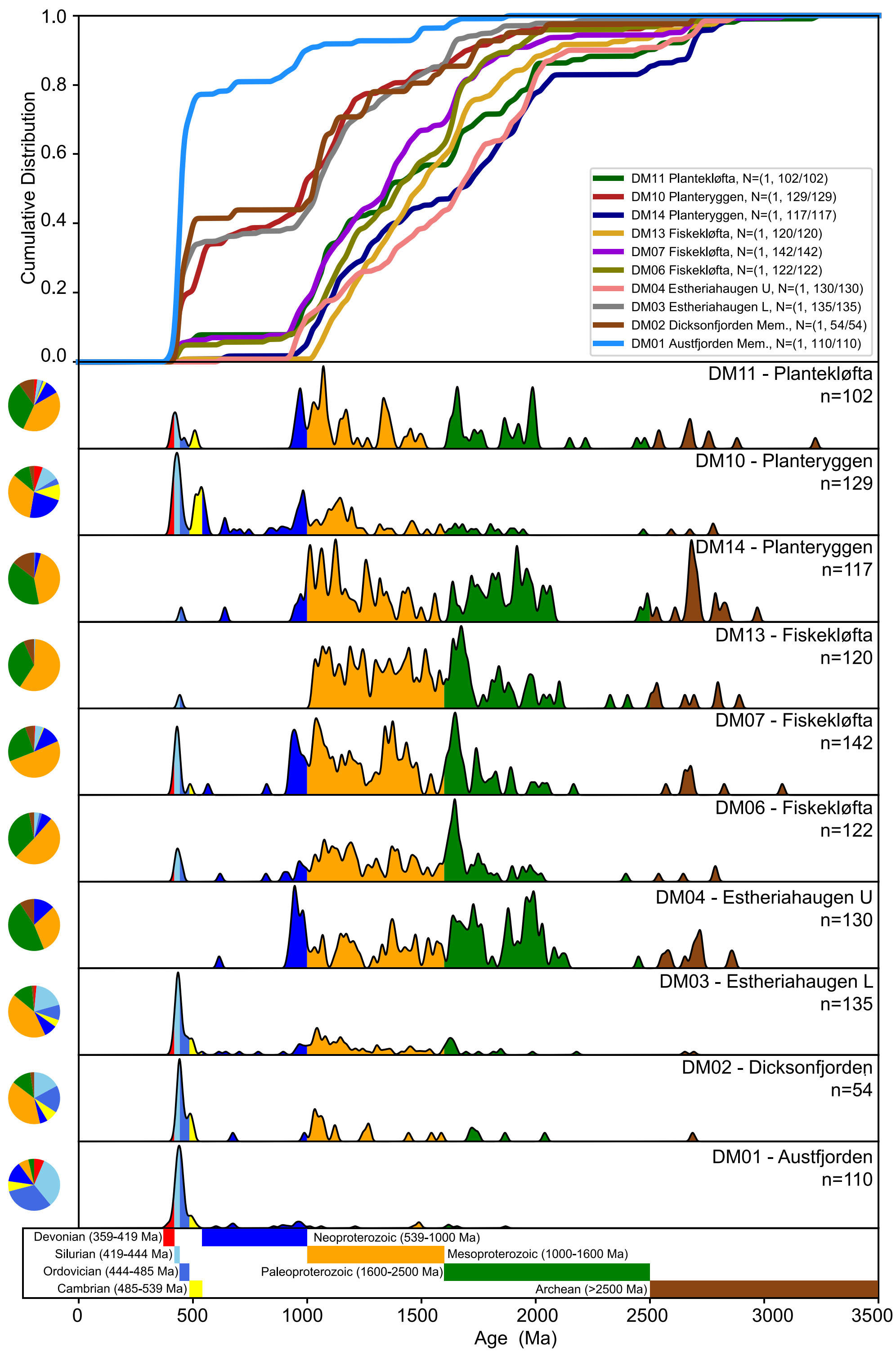

Figure 4. Kernel Density Estimate (KDE), Cumulative Distribution Plot (CDP), and pie diagrams for detrital zircon U-Pb ages from samples of the Andrée Land Group. Ages for pie diagrams correspond to the colored bars at the bottom of the KDE. Figure generated using detritalPy (Sharman et al., 2018).

Sample DM04 is stratigraphically higher in the Estheriahaugen Member than sample DM03. The sample contains 138 accepted detrital zircon ages out of 141 age analyses and the ages range from 3267 to 615 Ma (Figure 4). The detrital zircon ages are primarily Paleoproterozoic (2450–1628; 46%) and Mesoproterozoic (1592–1009 Ma; 31%) ages. The sample contains secondary populations of Tonian (988–920 Ma; 12%) and Archean (3267–2553 Ma; 11%) ages. There is a single Ediacaran age (615 Ma).

4.2.2. Fiskekløfta Member

Samples DM06, DM07, and DM13 were collected from sandstones of the Fiskekløfta Member (upper Tordalen Formation; Table 1; Figures 2a and 2b). This unit consists of black coalified mudstones and gray interbedded sandstones. Sample DM07 was collected from a crossbedded sandstone and although no quantitative paleocurrent measurements were made from this unit, field observations of the crossbeds orientation (Figure 3d) indicate a general northeast to southwest transport direction.

Sample DM06 contains 132 accepted detrital zircon ages out of 136 age analyses and the ages range from 3268 to 422 Ma (Figure 4). The detrital zircon ages are primarily Mesoproterozoic (1584–1002 Ma; 52%) and Paleoproterozoic (2395–1602 Ma; 35%). The sample contains secondary populations of Tonian (988–820 Ma; 5%), Archean (3268–2538 Ma; 4%), Silurian (435–422 Ma; 3%) ages. There are an additional two ages from the Ordovician (452 and 445 Ma) and a single Ediacaran age (619 Ma).

Sample DM07 contains 145 accepted detrital zircon ages out of 146 age analyses and the ages range from 3079 to 415 Ma (Figure 4). The detrital zircon ages are primarily Mesoproterozoic (1593–1005 Ma; 50%) and Paleoproterozoic (2166–1609 Ma; 26%). The sample contains secondary age groups of Tonian (999–823 Ma; 11%), Archean (3079–2570 Ma; 7%), and Silurian (441–423 Ma; 5%) ages. There are additional single ages from the Ediacaran (566 Ma), Cambrian (487 Ma), and Devonian (415 Ma).

Sample DM13 contains 127 accepted detrital zircon ages out of 132 age analyses and the ages range from 2891 to 442 Ma (Figure 4). The detrital zircon ages are primarily Mesoproterozoic (1584–1028 Ma; 58%) and Paleoproterozoic (2402–1608 Ma; 34%). The sample contains a secondary age group of Archean (2891–2505 Ma; 7%) ages. There are additional single ages from the Tonian (938 Ma) and Silurian (442 Ma).

4.3. Planteryggen Formation

Samples DM10 and DM14 were collected from the Frasnian Planteryggen Formation (Table 1; Figures 2a and 2b). The formation is divided into the lower Odinelva Member and the upper Muninelva Member (Piepjohn & Dallmann, 2014). The base of the Odinelva Member contains conglomerates characterized by 0.5–1 cm-scale rounded quartz clasts in a supported grain matrix with compositional layering of fine grain quartz which grades into sandstones in the upper parts of the formation. The base of the Muninelva Member is marked by two light green sandstones and conglomerates (Pčelina et al., 1986). The Muninelva member is primarily composed of gray and green siltstones and conglomerates with occasional clasts up to 4 cm (Pčelina et al., 1986; Piepjohn & Dallmann, 2014).

Sample DM14 is from a sandstone of the Odinelva Member and contains 132 accepted detrital zircon ages out of 134 age analyses (Figure 4). The ages range from 2970 to 448 Ma. The detrital zircon ages are primarily Paleoproterozoic (2491–1631 Ma; 40%), Mesoproterozoic (1561–1001 Ma; 39%), and Archean (2970–2529 Ma; 17%). The sample contains a secondary age group of Tonian (976–947; 3%) ages. There are additional single ages from the Cryogenian (639 Ma) and Ordovician (448 Ma).

Sample DM10 is from a quartz conglomerate from Muninelva Member (Figure 3e) and contains 137 accepted detrital zircon ages out of 150 age analyses and the ages range from 2778 to 403 Ma (Figure 4). The detrital zircon ages are primarily Mesoproterozoic (1586–1002 Ma; 34%). The sample contains secondary age groups of Tonian (992–745 Ma; 14%), Paleoproterozoic (2471–1621 Ma; 12%), Silurian (443–420 Ma; 11%), Cambrian (536–507 Ma; 10%), and Devonian (418–403 Ma; 5%) ages. Archean (2778–2577 Ma), Cryogenian (706–637 Ma) and Ediacaran (562–546 Ma) ages each represent 4% of the ages and there are 3% Ordovician (475–450 Ma) ages.

4.4. Plantekløfta Formation

The Plantekløfta Formation has intercalations of conglomerates, sandstones, mudstones, siltstones and contains important exposures of late Devonian lycopsid forests (Figure 3f; Berry & Marshall, 2015). Sample DM11 is from a sandstone lens laying in between conglomerate layers (Figure 3g) collected from the Plantekløfta Formation (Table 1; Figures 2a and 2b). The upper part of Plantekløfta Formation is composed of conglomerates that are dominated by shale intercalations. Conglomerates from this formation are characterized by 3–10 cm quartzite and shale clasts. This location is defined by clast imbrications with average dip direction toward SW (Figure 3h).

Sample DM11 contains 108 accepted detrital zircon ages out of 114 age analyses and the ages range from 3224 to 409 Ma (Figure 4). The detrital zircon ages are primarily Mesoproterozoic (1505–1004 Ma; 41%) and Paleoproterozoic (2477–1624 Ma; 34%). The sample contains a secondary age group of Archean (3224–2534 Ma; 9%) and Tonian (988–945; 8%) ages. There are three Silurian (432, 428, 422 Ma), two Cambrian (514 and 503 Ma), two Devonian (410 and 409 Ma) ages, and a single Ordovician (462 Ma) age.

5. Discussion

5.1. Provenance Interpretations

During deposition of the Wood Bay Formation there were stable tectonic conditions (following the Monacobreen Phase; Harland et al., 1997) and fluvial deposition kept pace with slow subsidence within the Andrée Land Basin (Dallmann, 2015; Dallmann & Piepjohn, 2020; Friend & Moody-Stuart, 1972). North-directed paleocurrents (Figures 3a and 3b) in the Pragian-Emsian Wood Bay Formation are consistent with previous studies (Friend & Moody-Stuart, 1972) and suggest sediment sources to the south-southwest of the Andrée Land Basin. There is a strong Early Ordovician-Early Devonian (ca. 480–410; herein referred to as "Caledonian") detrital zircon age component in the Austfjorden Member of the Wood Bay Formation where 77% of sample DM01 zircon is between an age range of 488–407 Ma. The Caledonian signal decreases upsection to 13% in the Dicksonfjorden Member. However, Tera-Wasserburg Concordia diagram intercepts (Figure 5b) indicate that DM02 has a significant number of discordant grains following two main trajectories with lower intercepts at ca. 960 and 440 Ma. The individual grain profiles ($^{207}Pb/^{206}Pb$, $^{206}Pb/^{238}U$) indicate that this is mainly the result of common lead, but lead loss and inheritance is also observed in some of the grains. The absence of Archean age grains and the minimal input of Meso- and Paleoproterozoic ages (10% in the Austfjorden Member) suggest a limited supply of sediment from old cratonic cores or reworked strata containing these ages. This contrasts significantly with a sample of the Wood Bay Formation from the central part of the Andrée Land Basin in southern Woodfjorden reported from Beranek et al. (2020) (sample GS11:10), which still has a large proportion of Caledonian ages but contains predominantly Paleoproterozoic ages (30%).

The abundant Caledonian detrital zircon ages in the Wood Bay samples, and the sample from the central part of the Andrée Land Basin in southeastern Woodfjorden (Beranek et al., 2020), are potentially sourced from granitoids that occur as discrete intrusions within the Northwestern Basement Province and have been dated to ca. 430–420 Ma (Gee & Teben'kov, 2004; Ohta et al., 2002). The Hornemantoppen Granite (U-Pb 418 ± 1 Ma: Myhre et al., 2009) in the Northwestern Basement Province is also a potential source for some of the younger Caledonian ages. Since paleocurrent data suggest that Wood Bay Formation river systems were derived from south and west of the Andrée Land Basin it is also worth investigating potential sources in the Southwestern Basement Province where, detrital zircon data from Cryogenian strata of the Southwestern Basement Province (Andresen & Gasser, 2014; Wala et al., 2021) show similar pre-Caledonian ages of 1150–960, 1500–1300, and 1750–1600 Ma with few early Paleoproterozoic and older ages. Similar ages occur in the upper Red Bay Group (Beranek et al., 2020) and we suggest that during this time the Andrée Land Basin strata were likely sourced from either Red Bay Group basins that were inverted by late Lochkovian Monacobreen Phase (Beranek et al., 2020; McCann, 2000) or directly from the basement within the Southwestern Basement Province. Caledonian age detrital zircon sources are more difficult to account for within current exposures of the Southwestern Basement Province as granitic intrusions of this age are mostly absent from the Southwestern Basement Province, however there is the potential that these intrusions are buried under extensive post-Devonian sedimentary cover to the south. It is also possible that Caledonian age detrital zircon ages were directly supplied from Northeast Greenland or the M'Clintock orogen within the Pearya terrane, where granitic intrusions of Silurian to Ordovician age are documented (e.g., Gee & Teben'kov, 2004; Majka et al., 2014; Trettin, 1987). The Southwestern Basement Province, as well as Pearya and Northeastern Greenland, also contain Tonian age granitoids (ca. 950–970 Ma; e.g., Gee & Teben'kov, 2004; Majka et al., 2014; Malone et al., 2019), which is another age signal present within the Wood Bay Formation. The suggestion that sources of sediment are within the Southwestern Basement Province indicates that the Southwestern and Northwestern basement provinces were already close to their present position during the deposition of the Wood Bay Formation. If this assumption is correct, it suggests that the basement provinces of Svalbard were juxtaposed between the late Caledonian sinistral strike-slip tectonics and the deposition of the Wood Bay Formation. The timing of juxtaposition of the Southwestern Basement Province with the Northwestern Basement Province has been a significant area of contention (e.g., Mazur et al., 2009). Micro-

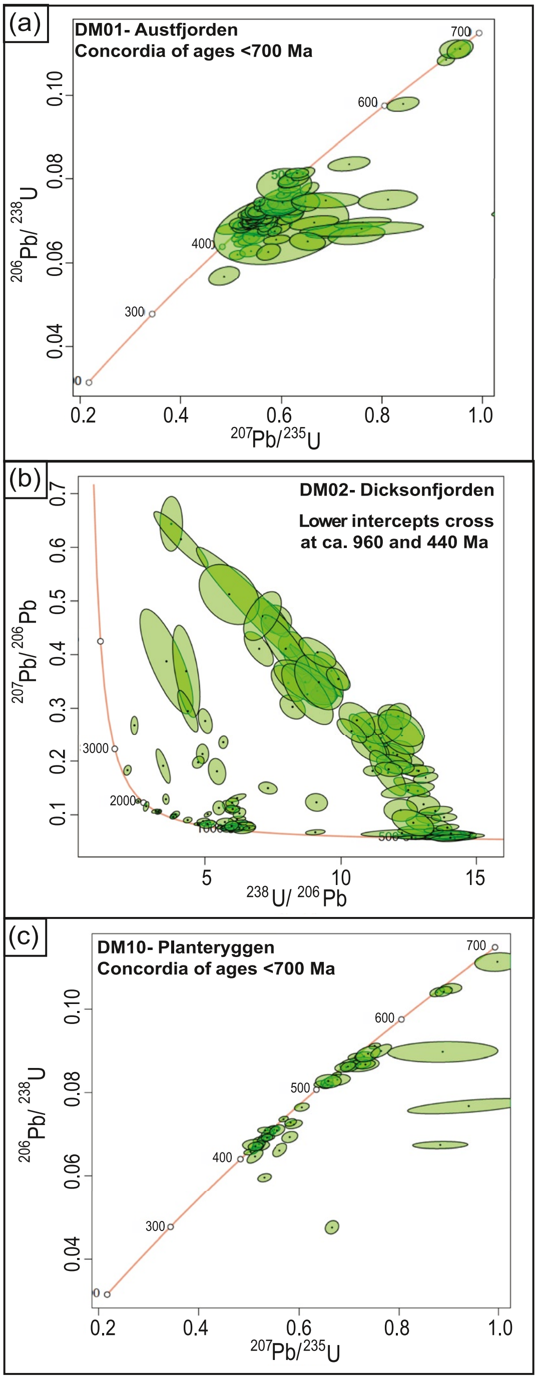

Figure 5. Wetherill Concordia and Tera Wasserburg Concordia diagrams generated using the IsoplotR software of Vermeesch (2018). (a) Concordia diagram for ages younger than 700 Ma from sample DM01. This depicts a single U-Pb age younger than the reported Austfjorden Member depositional age (Føyn & Heintz, 1943; Holtedahl, 1914; Piepjohn & Dallmann, 2014), but its location right of concordia suggests disturbance to the U-Pb system. (b) Tera Wasserburg Concordia diagram of DM02 depicting abundant discordance within the dated detrital zircon grains. The lower intercepts of the two trends cross concordia at ca. 960 and 440 Ma. (c) Concordia diagram for detrital zircon ages younger than 700 Ma from sample DM10 (Planteryggen Formation). The diagram highlights an important group of late Neoproterozoic to early Cambrian ages (706–507 Ma; 17% of sample) that vary from underlying units (discussed in Section 5.1).

structural analysis and $^{40}Ar/^{39}Ar$ muscovite geochronology by Faehnrich et al. (2020) suggests that movement along the Vimsodden-Kosibapasset Shear Zone (VKSZ) occurred in the late Silurian–Early Devonian and was contemporaneous with the beginning of the main phase of Caledonian continental collision. Although the VKSZ is not the major bounding structure of the Southwestern Basement Province, it does represent a major crustal

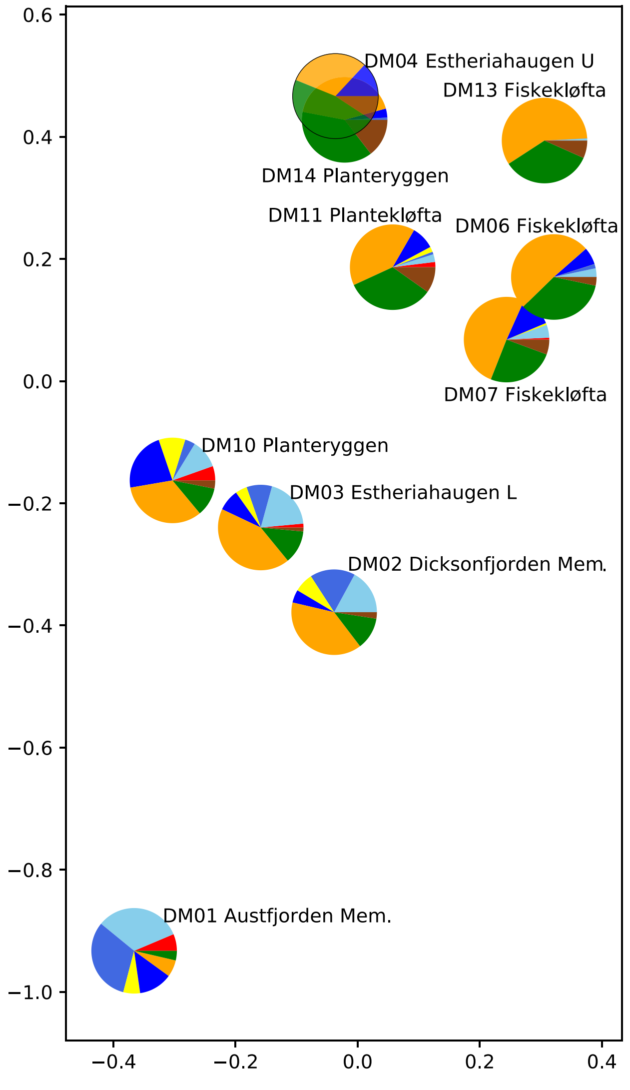

Figure 6. Multidimensional Scaling Plot (MDS) of all detrital zircon age data from samples of the Andrée Land Group. The MDS plot compares the statistical similarity of the samples to one another (using Kolmogorov-Smirnov test *D*-values to calculate differences) and includes pie diagrams with colors corresponding to the age ranges presented in Figure 4. Generated using the detritalPy software of Sharman et al. (2018) and based on methods described in Vermeesch (2018).

boundary with clear sinistral kinematic indicators (Mazur et al., 2009) and provides support that the Southwestern terrane and Northwestern terrane may have been in their current positions by the Early Devonian. Further research, constraining detrital zircon age signatures of Devonian strata of the Marietoppen Formation within the Southwestern Basement Province may shed light on this issue and aid in correlation of the units.

It should be noted that there is a single detrital zircon age (386.9 ± 5.4 Ma) in sample DMO2 that is younger than the reported Wood Bay Formation depositional age (Pragian-Emsian; 410–393 Ma; Føyn & Heintz, 1943; Holtedahl, 1914; Piepjohn, 2000). The concordia diagrams for the young age (Figure 5a) indicate the grain may have experienced some Pb loss and due to its lack of age overlap with other grains, we suggest this age does not constrain the depositional age of the unit.

The lower Estheriahaugan Member (DM03) is lithologically similar to the underlying Wood Bay Formation (Figures 4 and 6), and field observations of the steeply dipping cross-bedded strata, indicate a general northeast directed paleocurrent similar to the underlying Dicksonfjorden Member. Detrital zircon ages are also similar to the Dicksonfjorden Member and we suggest that these ages are primarily derived from reworking of the underlying Wood Bay Formation or has the same provenance as the Wood Bay Formation. Although paleocurrent directions from crossbed orientations in the upper Estheriahaugen Member (DM04) remain consistent with underlying units (Figure 3c), there is a clear shift in detrital zircon age signatures between the upper and lower Estheriahaugen Member of the Tordalen Formation (Figures 4 and 6). This shift is recorded by the lack of Caledonian age grains in sample DM04 and larger proportion of older ages, suggesting sediment was derived from a significantly older source region (99% of DM04 ages are older than 920 Ma) with ages as old as 3267 Ma (>600 Ma older than any age from underlying units). Although this contrast in detrital zircon ages versus paleocurrents is somewhat enigmatic, we suggest southerly derived river systems may have captured sediment derived from the uplifted Ny Friesland block to the east of the Billefjorden Fault Zone. This presents the possibility that there was a pulse of tectonic uplift in the east of the basin during deposition of the upper Estheriahaugen Member and indicates erosion of Meso- and Paleoproterozoic rocks of the Atomfjella Complex (Gee & Page, 1994) with short transports to the west into north flowing rivers of the Andrée Land Basin.

The three detrital zircon samples (DM06, DM07, DM13) from the Givetian Fiskekløfta Member exhibit a reintroduction of minor Caledonian age components, as well as a major paleocurrent reversal from underlying units to a southwest transport direction (Figure 3d). The detrital zircon age spectra from the three samples are similar to one another (Figure 6), with a dominant presence of Mesoproterozoic and Paleoproterozoic ages. The samples have 94% (DM06), 93% (DM07) and 99% (DM13) ages >900 Ma and few ages corresponding to the timing of the Caledonian orogen (DM06, 453–422 Ma, 5%; DM07, 441–415 Ma, 8%; DM13, 442 Ma, 1%). These ages are similar to basement ages of Ny Friesland where exposure of Neoarchean (ca. 2700 Ma) orthogneiss, Paleoproterozoic (ca. 1750 Ma) granitic gneiss (Hellman et al., 2001; Johansson et al., 1995), overlying Mesoproterozoic strata (intruded by ca. 1300 Ma mafic intrusions; Hellman & Witt-Nilsson, 1999), and younger subordinate metasedimentary strata have yielded detrital zircon ages as young as 1190 Ma (Gee & Hellman, 1996). Ny-Friesland also contains exposures of post-Caledonian granites intruded between 432 and 385 Ma (Gayer et al., 1966; Harland, 1958; Myhre, 2005; Teben'kov et al., 1996). These data align with previous sedimentologic and structural constraints (e.g., Piepjohn & Dallmann, 2014) suggesting that significant uplift of Ny-Friesland took place along the Billefjorden Fault Zone during deposition of the Fiskekløfta Member and had become the dominant sediment source region for the southeastern Andrée Land Basin in the Givetian.

Detrital zircon age groups from the Odinelva Member of the Planteryggen Formation, represented by sample DM14, are similar to underlying Fiskekløfta Member samples of the Tordalen Formation with a dominance of older ages (132 of 134 ages are >900 Ma). This indicates that Ny-Friesland was still the dominant source of sediment during this time.

Another major shift in sediment provenance is apparent within the Muninelva Member of the Planteryggen Formation, exhibited by the abundance of Caledonian ages (475–403 Ma; 19%) and Cryogenian-middle Cambrian (706–507; 17%) ages in sample DM10. Although the Caledonian ages are similar to those of underlying units and numerous authors have suggested derivation and reworking of the Fiskekløfta sandstone clasts into the Planteryggen Formation (Piepjohn & Dallmann, 2014; Piepjohn et al., 2000), the percentages and ages from the Cryogenian-middle Cambrian aged grains (Figure 5c) are different from that of the Fiskekløfta Member. There are considerably more Cambrian and late Ediacaran ages (561–507 Ma; $n = 18$) in sample DM10 compared to underlying units. We interpret these Neoproterozoic to early Paleozoic (~710–510 Ma) ages to be derived from a source not yet concretely identified but coeval with, and related to, the Timanide orogen and suggest the region is located to the east-northeast of the basin in the Late Devonian. In older strata of the northwest ORS (Siktefjellet, Red Bay, and lower Andrée Land groups), Beranek et al. (2020) suggested that Cambrian-Ordovician detrital zircon ages are ultimately compared to those from the Pearya terrane at the north coast of Ellesmere Island, where they are observed in abundance (Malone et al., 2019). However, sampled units from the Pearya terrane contain few 560–510 Ma detrital zircon ages and do not appear to correspond well with the main Timanian age peak from the Late Devonian strata of Canadian Arctic Islands (Anfinson, Leier, Embry, & Dewing, 2012; Anfinson, Leier, Gaschnig, et al., 2012) or the Middle and Late Devonian units of the Andrée Land Group. Evidence for Neoproterozoic to early Paleozoic (~710–520 Ma) magmatism is also found other Arctic terranes such as Arctic Alaska, the Farewell and Alexander terranes, but is lacking in the Canadian Arctic Islands and Alaska's north slope subterrane (e.g., McClelland et al., 2021). Within Svalbard, late Ediacaran to Cambrian $^{40}Ar/^{39}Ar$ ages are present in the Northwestern and Northeastern Basement provinces (Dallmeyer et al., 1990; Gayer et al., 1966), but this age group is notably absent from zircon U-Pb ages of schists and gneisses of the Northwestern Basement Province (Koglin et al., 2022). We suggest this 560–510 Ma detrital zircon age group is evidence of extrabasinal Timanian age sources northeast of Svalbard, but we have not yet concretely identified a source.

Our uppermost sample (DM11) in the Plantekløfta Formation is dominated by ages >900 Ma (3224–945; 93%) but contains two Cambrian ages (514 and 503 Ma) that are similar to the underlying Muninelva Member of the Planteryggen Formation. Pebbles of green sandstone in the conglomerates have been linked to the Austfjorden Member of the Wood Bay Formation (Friend, 1961; Piepjohn et al., 2000; Vogt, 1938) and paleocurrent data from the imbricated clasts (Figures 3g and 3h) indicate derivation from the northeast. We suggest this unit has sediment provenance similar to the underlying Planteryggen Formation and Fiskekløfta Member of the Tordalen Formation. Although the green sandstone clasts in conglomerates suggest reworking of the Austfjorden Member of the Wood Bay Formation, the detrital zircon ages are distinct from the Austfjorden Member (Figure 6) and therefore do not support this interpretation. We concur with previous interpretations that suggest that sediment sources for these upper units are within Ny Friesland and Nordaustlandet (i.e., Friend, 1961; Piepjohn et al., 2000; Vogt, 1938), but suggest the source of reworked pebbles is more likely from the Fiskekløfta Member of the Tordalen Formation or the Planteryggen Formation.

5.2. Devonian Detrital Zircon U-Pb Age Compilations and Implications for the Paleogeography of Svalbard

Detrital zircon U-Pb ages ($n = 6,806$) from 75 samples of Devonian strata within the modern circum Arctic (locations depicted in Figure 1a) were compiled to provide a framework for comparison with the Early (Figure 7), Middle (Figure 8), and Late (Figure 9) Devonian strata of the Andrée Land Basin. Although limitations exist for comparison of detrital zircon age groups for identifying sediment sources (e.g., Malkowski et al., 2019; Malusà et al., 2016), the use of these age groups for comparison of source regions, determining proximity to orogens, and reconstructing paleogeography has proven useful for Paleozoic and Mesozoic strata of the circum Arctic (e.g., Anfinson et al., 2016; Ershova et al., 2015b; McClelland et al., 2021; Miller et al., 2011, 2013). The majority of detrital zircon ages from within the Andrée Land Group strata are interpreted as being derived from within

Svalbard's current geographic boundaries. However, the compiled detrital zircon ages provide some indication of proximity to sediment sources of specific ages and their comparison, along with other geologic constraints, helped guide the general paleogeographic setting of the Andrée Land Basin discussed below and presented in Figure 10.

Detrital zircon ages were compiled from the following locations: (a) Early Devonian (Figure 7): Svalbard (this study; Beranek et al., 2020; Pettersson et al., 2010), Canadian Arctic Islands (Anfinson, Leier, Embry, & Dewing, 2012), New Siberian Islands (Ershova et al., 2018), Severnaya Zemlya (Lorenz et al., 2008), Alexander terrane (Beranek et al., 2013; Tochilin et al., 2014; White et al., 2016).; (b) Middle Devonian (Figure 8): Svalbard (this study; Beranek et al., 2020), Western Norway (Templeton, 2015, p. 3 representative samples out of 15), East Greenland (Slama et al., 2011), Canadian Arctic Islands (Anfinson, Leier, Embry, & Dewing, 2012; Anfinson, Leier, Gaschnig, et al., 2012), and the New Siberian Islands (Ershova et al., 2018). (c) Late Devonian (Figure 9): Svalbard (this study), East Greenland (Templeton, 2015), Canadian Arctic Islands (Anfinson, Leier, Embry, & Dewing, 2012; Anfinson, Leier, Gaschnig, et al., 2012), Northwest Canada (Beranek et al., 2010; Lemieux et al., 2011), New Siberian Islands (Ershova et al., 2015a, 2015b; Ershova et al., 2018), Seward Peninsula (Amato et al., 2009), Northeast Siberia (Ershova et al., 2020), Northern Baltica (Miller et al., 2011), Novaya Zemlya (Lorenz et al., 2013). No age filters were applied to the published data and the "Best Age" (i.e., accepted ages from authors) column was used when available. When "Best Age" was not given, we used the $^{206}Pb/^{238}U$ age for ages younger than 850 Ma, and the $^{207}Pb/^{206}Pb$ age for ages older than 850 Ma.

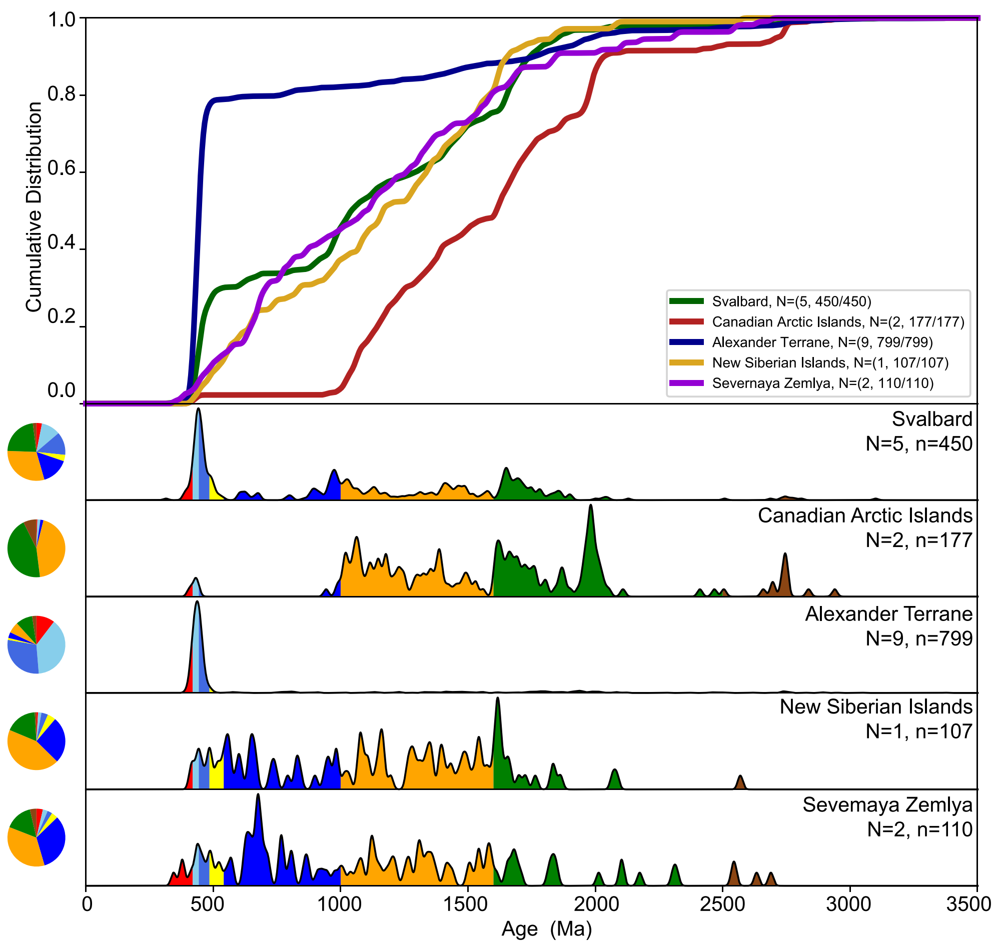

Figure 7. Detrital zircon comparison plot for Early Devonian samples from the circum Arctic. Locations referenced in Figure 1a and listed from Svalbard then progressively west. Age ranges for KDE and pie diagrams listed in Figure 4. Detrital zircon data sources: Svalbard (This study, Beranek et al., 2020; Pettersson et al., 2010), Canadian Arctic Islands (Anfinson, Leier, Embry, & Dewing, 2012), Alexander terrane (Beranek et al., 2013; Tochilin et al., 2014; White et al., 2016), New Siberian Islands (Ershova et al., 2018), and Severnaya Zemlya (Lorenz et al., 2008).

5.2.1. Early Devonian

Following collapse of the Caledonian orogen, development of the Red Bay Trough and Andrée Land Basin in the Early Devonian appears to be within a predominantly sinistral transpressional setting during juxtaposition of Svalbard's basement provinces (Harland et al., 1974, 1997; McCann, 2000). Sediment sources to the southeastern Andrée Land Basin strata were derived by fluvial systems from the south and southwest. The dominance of a primary detrital zircon age peak corresponding to the Caledonian orogen from the Lower Devonian strata of Svalbard (this study; Beranek et al., 2020; Pettersson et al., 2010) is rather unique in the modern circum Arctic (Figure 7). The exception is an overwhelming abundance of these Caledonian ages from the Lower Devonian strata of the Alexander terrane (Beranek et al., 2013; Tochilin et al., 2014; White et al., 2016), which led numerous authors to correlate this terrane with a northern continuation of the Caledonides (e.g., Beranek et al., 2012, 2013; Colpron & Nelson, 2009; Gehrels et al., 1996). Secondary Caledonian detrital zircon age peaks in Lower Devonian strata from the Franklinian Basin of the Canadian Arctic Islands are interpreted to be derived from the East Greenland Caledonides (Anfinson, Leier, Embry, & Dewing, 2012) and may also be partially recycled from underlying flysch deposits (Beranek et al., 2015). The Caledonian orogen is also supplying sediment to Lower Devonian strata of the New Siberian Islands (Ershova et al., 2018) and Severnaya Zemlya (Lorenz et al., 2008), but here the age signal is heavily influenced by ages associated with the Timanian orogen.

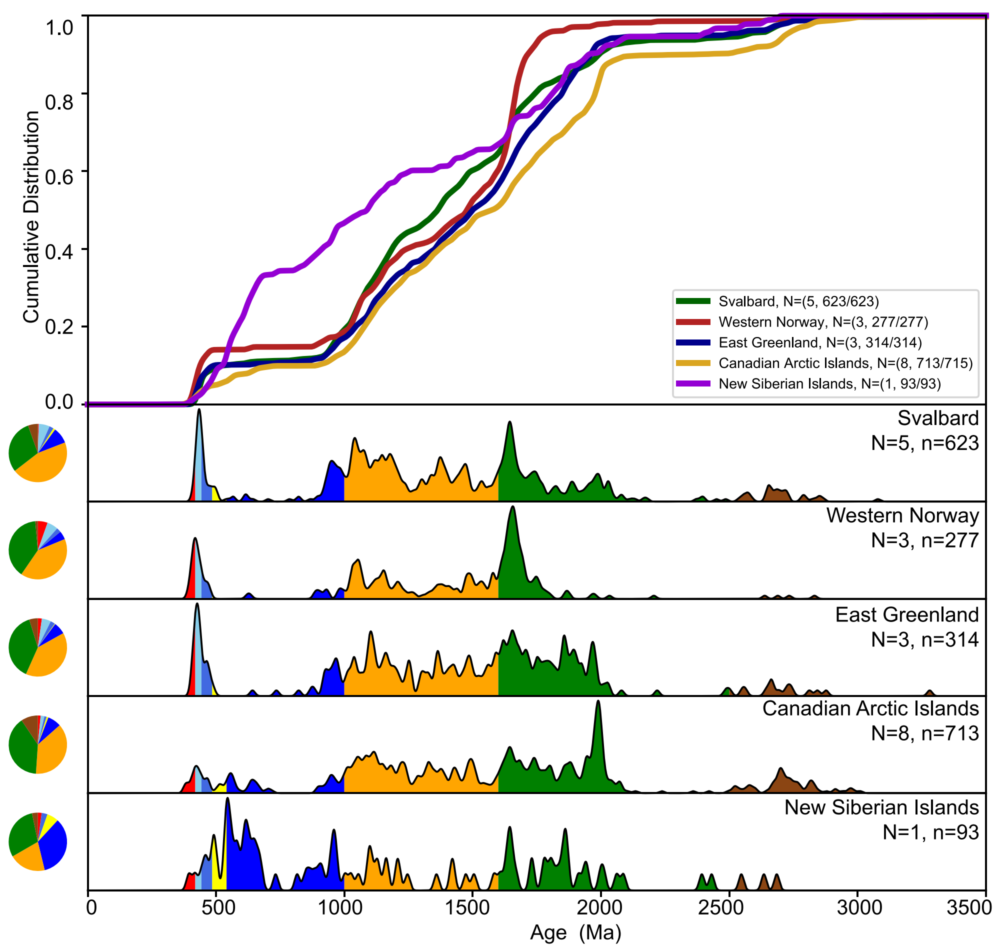

Figure 8. Detrital zircon comparison plot for Middle Devonian (Eifelian-Givetian) samples from the circum Arctic. Locations referenced in Figure 1a and listed from Svalbard then progressively west. Age ranges for KDE and pie diagrams listed in Figure 4. Detrital zircon data sources: Svalbard (This study, Beranek et al., 2020), Western Norway (Templeton, 2015, p. 3 representative samples out of 15), East Greenland (Slama et al., 2011), Canadian Arctic Islands (Anfinson, Leier, Embry, & Dewing, 2012; Anfinson, Leier, Gaschnig, et al., 2012), and the New Siberian Islands (Ershova et al., 2018).

5.2.2. Middle Devonian

Within Svalbard, the detrital zircon ages from Middle Devonian (Givetian) strata do not suggest any major shifts in provenance (Figure 4) and the lack of major depositional hiatuses at this time indicates relatively stable tectonic conditions (Piepjohn & Dallmann, 2014). This tectonic stability is similar to foreland basin conditions in the Canadian Arctic Islands where detrital zircon populations remain consistent throughout the Middle Devonian (Anfinson, Leier, Embry, & Dewing, 2012; Anfinson, Leier, Gaschnig, et al., 2012). The ages from the Middle Devonian strata of Svalbard are similar to those reported from East Greenland, with comparable age peaks at 430, 960, 1100, 1650, 1850, 1960, and 2700 Ma (Figure 8; Slama et al., 2011). Samples of Devonian ORS strata from the Hornelen Basin of Western Norway (Templeton, 2015, p. 3 representative samples out of 15) have many age spectra similarities to Svalbard (e.g., 430, 1100, and 1650 Ma), but contain a more prevalent late Paleoproterozoic age group and very few early Paleoproterozoic and Archean ages (a notable age group in Andrée Land Basin Middle Devonian strata; Figure 8). Samples from the Franklinian Basin of the Canadian Arctic Islands (Anfinson, Leier, Embry, & Dewing, 2012; Anfinson, Leier, Gaschnig, et al., 2012) are also comparable to Svalbard, but contain a much more prominent 2050 Ma age peak and seem to lack the prominent ca. 960 Ma age peak of Svalbard. The abundance of Timanian ages and presence of Caledonian ages from samples of Middle Devonian strata within the New Siberian Islands (Ershova et al., 2018) indicates that although this region is dominated by sources within the Timanian orogen, the New Siberian Islands are being supplied with sediment sources ultimately within the Caledonian orogen. Middle Devonian strata of the Andrée Land Basin in Svalbard are interpreted as being primarily derived locally from the uplift of the Northeastern Basement Province east of the Billefjorden Fault Zone, especially the Ny Friesland block. The Northeastern Basement Province uplift is caused by post Caledonian sinistral displacement and transpression within Svalbard (Harland et al., 1997).

5.2.3. Late Devonian

Upper Devonian strata are present over a much broader geographic distribution in the modern circum Arctic compared to that of Lower and Middle Devonian strata. These Upper Devonian strata have drawn increased attention from researchers due to potential bearing on the extent and timing of the Ellesmerian orogen (Anfinson, Leier, Embry, & Dewing, 2012; Anfinson, Leier, Gaschnig, et al., 2012; Beauchamp et al., 2019; Beranek et al., 2010; Dallmann & Piepjohn, 2020; Ershova et al., 2015a, 2015b; Lemieux et al., 2011; Piepjohn et al., 2000; Vogt, 1928; this study), and their preservation of important fossil assemblages including some of the first documented fossil forests from within studied Andrée Land Group strata from Svalbard (Figure 3f; Location noted on Figure 2a; Berry & Marshall, 2015).

The detrital zircon age spectra of Svalbard contain similarities (e.g., age peaks at ca. 430, 540, 650, 960, 1100, 1650, 1960, and 2700 Ma) to those of the Canadian Arctic Islands (Anfinson, Leier, Embry, & Dewing, 2012; Anfinson, Leier, Gaschnig, et al., 2012), NW Canada (Beranek et al., 2010; Lemieux et al., 2011), the New Siberian Islands (Ershova et al., 2015a, 2015b), and the Seward Peninsula of Alaska (Amato et al., 2009), but there are noticeable differences (Figure 9). Importantly, Late Devonian (358–383 Ma) detrital zircon ages are prevalent in Upper Devonian strata of the Canadian Arctic Islands (Anfinson, Leier, Embry, & Dewing, 2012; Anfinson, Leier, Gaschnig, et al., 2012), NW Canada (Beranek et al., 2010; Lemieux et al., 2011), northeast Siberia (Ershova et al., 2020), Severnaya Zemlya (Lorenz et al., 2008), and the Seward Peninsula (Amato et al., 2009), but are absent from the Andrée Land Basin, suggesting the basin is isolated from Late Devonian magmatic sources.

It is noted that the samples from Upper Devonian strata of Northeast Siberian likely have an unrelated source of Late Devonian detrital zircon ages compared to the other previously mentioned localities (Ershova et al., 2020). Upper Devonian strata from Novaya Zemlya lack Caledonian and younger ages and suggest they are more closely related to sediment sources within Siberia (Lorenz et al., 2013). Comparisons with Upper Devonian strata from the northeastern Baltican margin are difficult due to the low number of ages ($n = 52$; Miller et al., 2011), but a loose correlation to the age groups from Svalbard is apparent.

Notably, in late Devonian strata, there is increased abundance and more widespread distribution of Timanian detrital zircon ages (Figure 9), suggesting increased exhumation of, or catchment expansion into, Timanian aged detrital zircon sources. The Timanian ages have been useful in identifying new detrital sources in circum arctic strata (e.g., Anfinson, Leier, Embry, & Dewing, 2012; Anfinson, Leier, Gaschnig, et al., 2012; Beranek et al., 2010; Ershova et al., 2015a, 2015b). The exact sources of these Timanian ages are often difficult to place, but there is increasing evidence of widespread magmatism associated with the Timanide orogen and the involve-

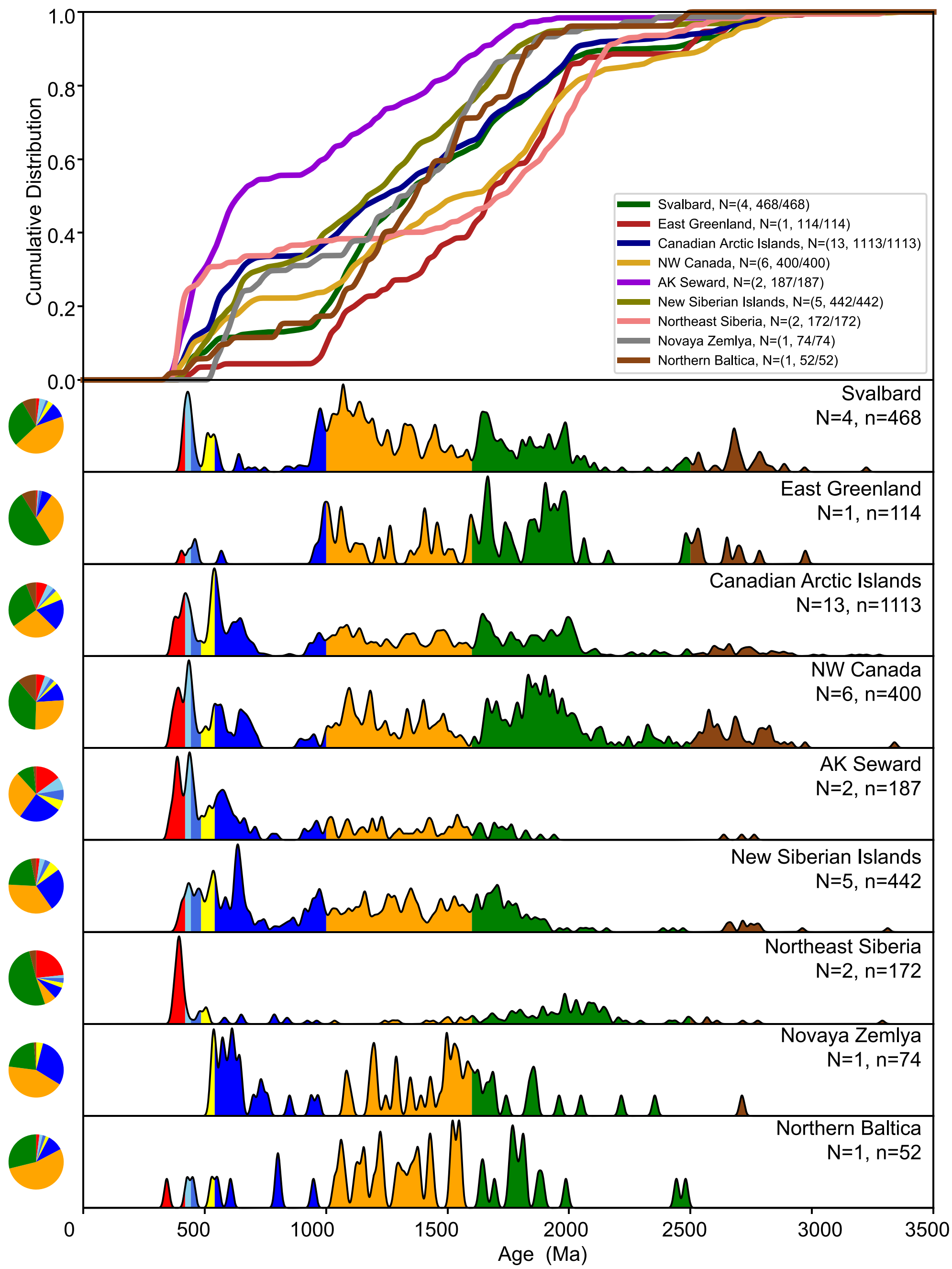

Figure 9. Detrital Zircon comparison plot for Late Devonian (Frasnian-Famennian) samples from the circum Arctic. Locations referenced in Figure 1a and listed from Svalbard then progressively west. Age ranges for KDE and pie diagrams listed in Figure 4. Detrital zircon data sources: Svalbard (This study), East Greenland (Templeton, 2015), Canadian Arctic Islands (Anfinson, Leier, Embry, & Dewing, 2012; Anfinson, Leier, Gaschnig, et al., 2012), Northwest Canada (Beranek et al., 2010; Lemieux et al., 2011), New Siberian Islands (Ershova et al., 2015a, 2015b), Seward Peninsula (Amato et al., 2009), Northeast Siberia (Ershova et al., 2020), Northern Baltica (Miller et al., 2011), Novaya Zemlya (Lorenz et al., 2013).

ment of regions not typically considered part of the sensu stricto Timanide Orogen (e.g., xenoliths in northeastern Greenland; Rosa et al., 2016). Within the late Devonian strata of the southeastern Andrée Land Basin, these Timanian ages are interpreted to be derived from Northeast due to paleocurrent indicators, such as crossbedding and imbricated conglomerate clasts (Figures 3g and 3h). Interestingly, this source region must also contain a significant source of early Archean (2800–3600 Ma) ages. Of the compiled 6,806 detrital zircon ages from all Devonian strata in the Arctic, the Middle and Upper Devonian strata sampled in this study (samples DM04, DM06, DM07, DM11, DM13, DM14) account for 19% of the Mesoarchean and Paleoarchean ages.

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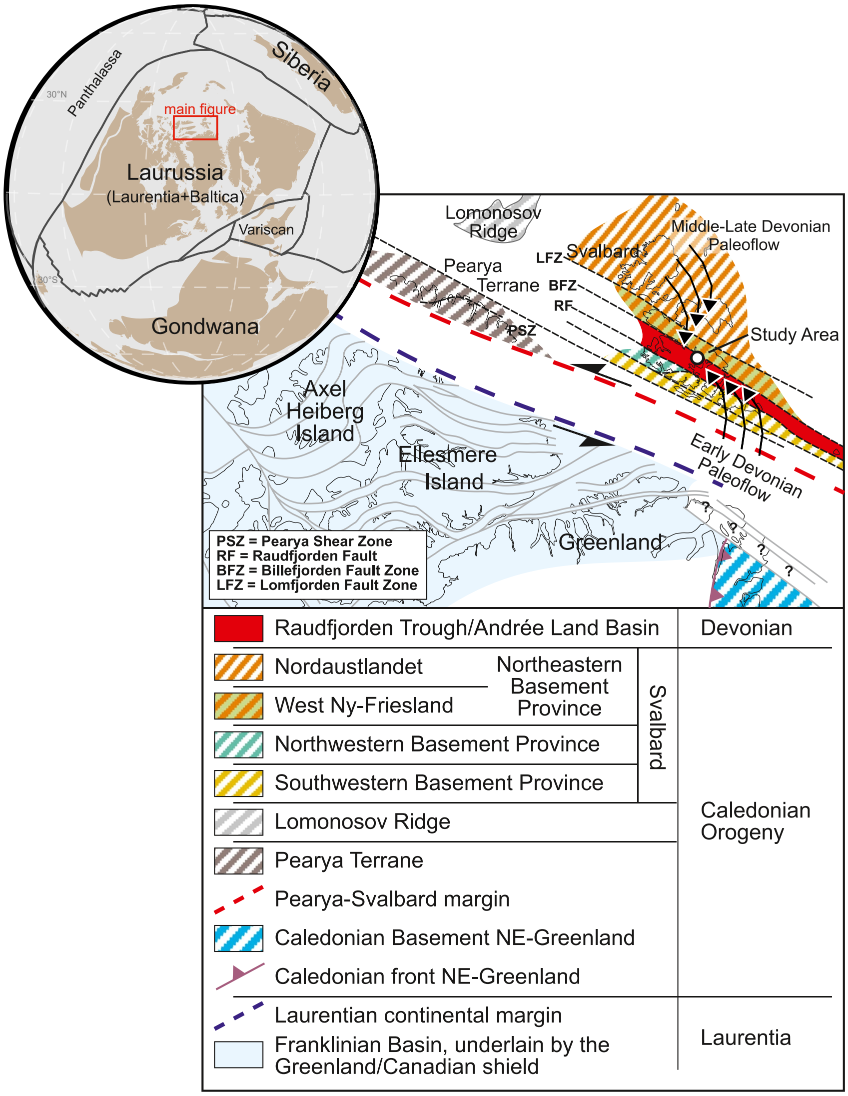

Figure 10. Paleogeographic reconstruction sketch. Globe inset is adapted from the global Paleozoic model of Domeier and Torsvik (2014) at 360 Ma, showing major plate boundaries and plates. The main panel depicts the possible relative situation of the involved blocks including the different basement provinces of Svalbard and position of the Andrée Land Basin in the Devonian. The reconstruction depicts the pre-Ellesmerian position of the involved blocks (Piepjohn et al., 2013; von Gosen et al., 2012) prior to ultimate transpression of Svalbard and Pearya with the Laurentian margin (e.g., Malone et al., 2019; McClelland et al., 2021). In order to account for relative motion between Greenland and the Svalbard margin, additional plate boundaries (which are not included in the global reconstruction of Domeier and Torsvik [2014]) are implied with the dashed lines. The distance of the gap between the Greenland and Svalbard margins is unknown and not drawn to scale but is meant to account for eventual shortening related to Late Devonian-Early Carboniferous Ellesmerian transpression. The sketch is based on von Gosen et al. (2012), Piepjohn et al. (2013), and the pre-Eurekan reconstruction published in Piepjohn et al. (2016).

5.3. Paleogeographic Reconstruction

The detrital zircon U-Pb ages, paleocurrent indicators, and provenance interpretations for sedimentary strata of the Andrée Land Basin are placed into a broader regional paleogeographic context (Figure 10). This regional reconstruction is mainly based on the pre-Eurekan interpretation of the relative positions of Pearya, the Lomonosov Ridge, and Svalbard with respect to the Canadian Arctic Archipelago and North Greenland by Piepjohn et al. (2016) (locations in Figure 1a). Figure 10 shows the pre-Ellesmerian position of the involved blocks (Piepjohn et al., 2013; von Gosen et al., 2012) prior to ultimate transpression of Svalbard and Pearya with the Laurentian margin (e.g., Malone et al., 2019; McClelland et al., 2021). This collisional process is still not entirely understood and possibly subject to a re-definition of the Ellesmerian orogen, and the delineation of new plate boundaries

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within Laurussia (or Laurentia/Baltica; Figure 10 inset). Both the Pearya terrane and Svalbard were affected by the post-Caledonian continuation of brittle sinistral strike-slip tectonics followed by orthogonal convergent shortening of the Ellesmerian orogeny proper (Piepjohn et al., 2000). The Siktefjellet, Red Bay, and possibly the lower Andrée Land groups are interpreted as being deposited in transpressional to transtensional conditions (e.g., Beranek et al., 2020), which started in Late Caledonian times with ductile sinistral shearing along the Billefjorden Fault Zone and Pearya Shear Zone and continued in the Early Devonian with brittle sinistral strike-slip faulting during the Haakonian and Monacobreen events (McCann, 2000). The deposition of the Andrée Land Group within the study area coincides with lateral tectonic movements of Svalbard and deposition in the basin ceased due to uplift from convergent Ellesmerian tectonic movements in the latest Devonian to earliest Carboniferous during the final translation and docking of Pearya/Svalbard to the continental margin of Laurentia.

6. Conclusions

Detrital zircon U-Pb geochronology, coupled with paleocurrent measurements from cross-bedded strata in sandstones and imbricated clasts of conglomerates, provide a holistic provenance analysis that help constrain the sediment sources and provenance evolution of the Old Red Sandstone in the Andrée Land Basin. In the Early Devonian, sediment sources were to the south of the basin and in the Middle-Late Devonian sources were to the east-northeast of the basin (Figure 10). Following collapse of the Caledonian orogen, development of the Andrée Land Basin in the Early Devonian appears to be within a predominantly sinistral transpressional setting during juxtaposition of Svalbard's basement provinces (Harland et al., 1974, 1997). There is a clear shift in detrital zircon U-Pb age signatures between the upper and lower Estheriahaugen Member of the Tordalen Formation which indicate uplift and exposure of sources east of the Billefjorden Fault Zone. Detrital zircon U-Pb ages from the Givetian Fiskekløfta Member of the Tordalen Formation and Frasnian Odinelva Member of the Planteryggen Formation do not appear to indicate any major shifts in provenance. In the Middle to Late Devonian, uplift of the Northeastern Basement Province, especially western Ny-Friesland along Billefjorden Fault Zone, controlled sediment sources east and northeast of the basin. Another major sediment provenance shift is apparent within the Muninelva Member of the Planteryggen Formation, where a relatively narrow range of Cambrian and late Ediacaran ages (507–561 Ma) indicates sources associated within the Timanian orogen. The Plantekløfta sediment provenance is similar to the underlying Planteryggen Formation.

The detrital zircon age comparisons of circum Arctic Devonian strata help provide insight on Svalbard's paleogeography throughout the Devonian. Previous detrital zircon provenance analysis on Devonian strata of the Raudfjorden Trough (Beranek et al., 2020), and our new detrital zircon data from the Andrée Land Basin, indicate that sediment was primarily locally derived (i.e., the source areas were located on the neighboring Southwestern/Northwestern and Northeastern basement provinces). This may indicate that the three basement provinces of Svalbard were already juxtaposed and situated in relative positions similar to their present position during the deposition of the Andrée Land Basin. This juxtaposition was related to the late Caledonian (ductile) and Early Devonian (brittle) sinistral strike-slip tectonics and also indicates that the sinistral movements potentially terminated near the end of deposition within the Andrée Land Group. This suggests that when the Ellesmerian convergent tectonics juxtaposed Pearya/Svalbard to the northern margin of Laurentia in the Late Devonian/early Carboniferous, Svalbard may have already been closely assembled to the block we know today with the Andrée Land Basin between the Southwestern/Northwestern and the Northeastern basement provinces. The suggestion that the Southwestern Basement Province may have been juxtaposed with the Northwestern and Northeastern basement provinces by the Devonian needs additional scrutiny, and we suggest complementary detrital zircon age data from the Devonian strata within the Southwestern Basement Province are necessary to provide additional insight. The compiled detrital zircon U-Pb data are unable to fully attest to which other continental blocks collided with the Laurentian margin except for Pearya/Svalbard. However, it is very likely that the southern part of Lomonosov Ridge, Chukchi Borderland, and North American Cordilleran terranes were either part of this block, or in close proximity to it, as indicated by abundant juvenile, arc derived, Ellesmerian age detrital zircon material within Carboniferous and younger strata within these regions (e.g., the Alexander terrane; Tochilin et al., 2014). The absence of these synorogenic Ellesmerian detrital zircon within the Andrée Land Basin suggests isolation from these sources in the Late Devonian.

Data Availability Statement

Data presented in this paper are available in Supporting Information S1 and are uploaded to the online Earthchem geochronology data repository (Geochron.org). To access the data use the below link and either search the map for the samples or use the sample names (i.e., OA19-DM01). http://www.geochron.org/detritalsearch.php.

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