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The Upper Devonian to Lower Carboniferous Billefjorden Group on Bjørnøya, Svalbard, and Its North-Eastern Greenlandic Provenance

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Keywords: detrital zircon provenance | LA-ICP-MS | Laurentia | Nordkapp formation | Røedvika formation

ABSTRACT

In this contribution, we document changes in detrital zircon ages in the upper Devonian (Famennian) to lower Carboniferous (Mississippian) Billefjorden Group on Bjørnøya, the southernmost island of Svalbard. This alluvial, coal-bearing clastic succession is widely distributed across the archipelago and the Barents Shelf. The sediments were deposited in subsidence-induced lowlands that formed just after regional post-Caledonian collapse-related extension, which created the classical 'Old Red Sandstone' basins during the Devonian, and prior to localised rift-basin development in the middle Carboniferous (Serpukhovian–Moscovian). Moreover, the succession is little affected by Ellesmerian compressional deformation, which occurred in the latest Devonian. However, little is known of the provenance and regional sediment routing in this tectonically transitional period between the post-Caledonian structuring events in the Devonian and the middle Carboniferous rifting. It has previously been invoked that a regional fault running parallel to the western Barents Shelf margin, the West Bjørnøya Fault, controlled sedimentation in the area. Here, we combine detrital zircon U–Pb ages and sedimentological data to investigate stratigraphic provenance variations and test whether tectonics controlled deposition of the Billefjorden Group on Bjørnøya. Sedimentological investigations demonstrate changes in fluvial style with intercalations between successions dominated by meandering channel fills and abundant overbank fines to sandstone-dominated sheet-like successions of braided stream origin. Palaeocurrent data show that two competing drainage directions accompany the changes in fluvial architecture. Northeasterly transport directions, recorded in the braided stream deposits, indicate possible fault-transverse drainage. The detrital zircon content in these deposits indicates sourcing from Caledonian terranes in Northeast Greenland. Northwest-oriented transport directions, measured in the meandering channel deposits, are inferred to represent axially positioned drainage systems. These may have been sourced from either Northeast Greenland, a more localised source, or Baltica. The latter would require long-distance sourcing, which, given the tectonic setting of the region, seems unlikely. Although our sedimentological observations point to syn-tectonic deposition, this is not clearly captured in the detrital zircon data, suggesting a common source for the Late Devonian–Mississippian fluvial systems of Bjørnøya. Thus, combined with previously published provenance data from Svalbard and Greenland, we demonstrate that the East Greenland Caledonides formed a long-lived and significant source area which provided sediments to nearby basins from the Devonian to the Early Cretaceous.

1 | Introduction

During the collapse of the Caledonian Orogen and the associated extensional collapse in the early–middle Devonian, several of the present-day Arctic regions were subsequently subject to periods of rifting and associated rift basin formation (Henriksen et al. 2011; Embry and Beauchamp 2019; Fyhn and Hopper 2021; Olaussen et al. 2024). In Svalbard, this culminated in the formation of the Billefjorden Trough in the middle Carboniferous, with rift climax in the Bashkirian (Gjelberg and Steel 1981; Johannessen and Steel 1992; Smyrak-Sikora et al. 2018). However, the Arctic also saw the development of several orogenic belts in the late Palaeozoic, such as the Ellesmerian and Uralian orogens (Embry 1988; Puchkov 1997; Piepjohn et al. 2015; Smelror and Petrov 2018). Collectively, the various structuring events created important local to supra-regional source terrains that, to variable degrees, have influenced the infill of all the major late Palaeozoic basins of the Arctic. Detrital zircon provenance analysis is one way to link sedimentary sinks to potential source areas and may thus aid in the reconstruction of sediment fairways, palaeogeography, and tectonic evolution of basins (e.g., Fedo, Sircomebe, and Rainbrid 2003; Koshnaw et al. 2019).

Bjørnøya, the southernmost island of the Svalbard Archipelago, lies on the central western margin of the Barents Shelf and thus holds a key position for investigating post-Caledonian and pre-Atlantic sediment routing in the region (Figure 1A). Particularly, the upper Devonian to lower Carboniferous (Mississippian) Billefjorden Group, which is exposed along the northern and eastern shores of the island, is interesting. This sedimentary succession post-dates both the Devonian 'Old Red Sandstone' successions on Spitsbergen and northeast Greenland and the Ellesmerian compressional tectonics (locally referred to as the Svalbardian event) but precedes the localised rift basin development across the area in the middle Carboniferous (Gjelberg and Steel 1981; Worsley et al. 2001; Henriksen et al. 2011; Smyrak-Sikora et al. 2018, 2021). As such, the Bjørnøya succession may shed light on the transitional period between these two important regional structuring events. The age of the lower part of the Billefjorden Group is well constrained on Bjørnøya by correlation of Late Devonian palynological assemblages from Europe and the Arctic (e.g., Lopes et al. 2021). The stratigraphy and depositional systems have been studied over the past century and are well established (Figure 1B,C) (Horn and Orvin 1928; Worsley and Edwards 1976; Gjelberg 1978, 1981; Dallmann 1999; Worsley et al. 2001; Worsley and Mørk 2008; Mørk, Gjelberg, and Worsley 2014; Janocha et al. 2024). On Bjørnøya, the Billefjorden Group comprises latest Devonian (Famennian) and early Carboniferous (Mississippian) coal-bearing siliciclastics that were deposited in an alluvial setting with low-lying floodplains transected by meandering and braided streams under humid climatic conditions (Figure 1C) (Horn and Orvin 1928; Gjelberg 1978, 1981; Gjelberg and Steel 1981; Worsley et al. 2001; Mørk, Gjelberg, and Worsley 2014). For most of the post-Caledonian succession in Svalbard, including Bjørnøya, provenance changes have been suggested based on sedimentological and petrographic observations, thus rarely being substantiated by zircon provenance data. As such, detrital zircon studies are scarce for much of the stratigraphy on Svalbard, albeit some exceptions exist. A limited number of studies deals with the detrital zircon age signature of the Devonian strata in northern Spitsbergen (Beranek, Gee, and Fisher 2020; Anfinson et al. 2022). Oordt et al. (2020) analysed some Palaeozoic strata in the Billefjorden area (central Spitsbergen), and Gasser and Andresen (2013) investigated the Mesoproterozoic to Carboniferous detrital zircon evolution in the St. Jonsfjorden area (western Spitsbergen), which included one sample from the Billefjorden Group. The latter sample yielded an abundance of Meso- and Paleoproterozoic zircons pointing to a source from northern to north-eastern Greenland. The Mesozoic platform (Pózer Bue and Andresen 2013; Gilmullina et al. 2021; Harstad et al. 2023) and Paleogene foreland basin strata have received far more attention (Elling et al. 2016; Petersen et al. 2016; Flowerdew et al. 2023). Collectively, these studies demonstrate that a wide range of Arctic terranes have variably contributed to the development of the sedimentary record in Svalbard, including terranes of Caledonian (Ordovician-earliest Devonian), Ellesmerian (Devonian) and Uralian (Permian–Triassic) affinities, as well as younger terranes such as the Eurekan fold and thrust belt (Paleogene).

Little is known about the source terranes of the Billefjorden Group on Bjørnøya or for equivalent upper Palaeozoic strata in surrounding basins. Previous studies have inferred a major fault west of Bjørnøya during the late Palaeozoic, referred to as the West Bjørnøya Fault, or the Palaeo-Hornsund Fault (Gjelberg and Steel 1981, 1983), a possible precursor to the supra-regional De Geer Zone, which may have originated from a Caledonian weakness zone (e.g., Faleide, Vågnes, and Gudlaugsson 1993; Doré et al. 2015). This lineament controlled sediment routing, accommodation space, and thus depositional style during the late Palaeozoic, particularly during the deposition of the Billefjorden Group alluvial sediments onwards from the Late Devonian (Gjelberg and Steel 1981, 1983). On Bjørnøya, the inferred fault-controlled sedimentation is evident in changing palaeocurrent directions and facies distribution, as well as stratigraphic variations in fluvial channel stacking patterns (Gjelberg 1981; Worsley and Mørk 2008; Mørk, Gjelberg, and Worsley 2014). Theoretically, significant changes in facies distribution and drainage directions may be accompanied by changing source provenance, as demonstrated in sedimentary basins elsewhere (Whitchurch et al. 2011; Foster-Baril and Stockli 2023). However, there have been no attempts to quantify provenance changes in the Billefjorden Group to demonstrate the influence of the fault on sediment routing and changing drainage dynamics, neither at local nor regional scale. This leads

Summary

- Cratonic source.
- Fault activity changes fluvial style and drainage direction but has no influence on source provenance.
- Direct correlation of detrital zircons to Northeast Greenland eclogite province.
- Northeast Grenlandic Caledonides acted as a long-lived catchment into to the Mesozoic.

us to our research questions: What were the source terranes for the Billefjorden Group on Bjørnøya? And did fault activity along the West Bjørnøya Fault influence the provenance signature of this alluvial succession?

In this study, we aim to answer these questions by combining conventional sedimentological field observations and detrital zircon provenance data from the upper Devonian–lower Carboniferous Billefjorden Group on Bjørnøya. The implication of our findings is discussed with respect to the late Palaeozoic regional palaeogeography and the tectonic evolution of the Arctic in the wake of the Caledonian collapse and prior to the Mesozoic to Cenozoic rifting that eventually resulted in the opening of the North Atlantic.

2 | Geologic Setting

2.1 | Tectonic Evolution

The present-day north-western corner of the Eurasian plate has undergone several orogenic and subsequent rifting events over its geologic history, which spans a period of more than 3 billion years, dating back to the Archean (Figure 2, Table 1). Some of the most prominent mountain building events in the region which pre-date deposition of the Billefjorden Group are the: (i) Grenvillian (Mesoproterozoic), (ii) the Timanian (Neoproterozoic), (iii) the Caledonian (early Palaeozoic) and (iv) the Ellesmerian (late Palaeozoic) orogens (Dallmann 2019).

The Grenvillian Orogeny was caused by continent–continent collision between Laurentia and Baltica in the Mesoproterozoic around 1300–900 Ma (Bingen et al. 2005, 2021; Pettersson,

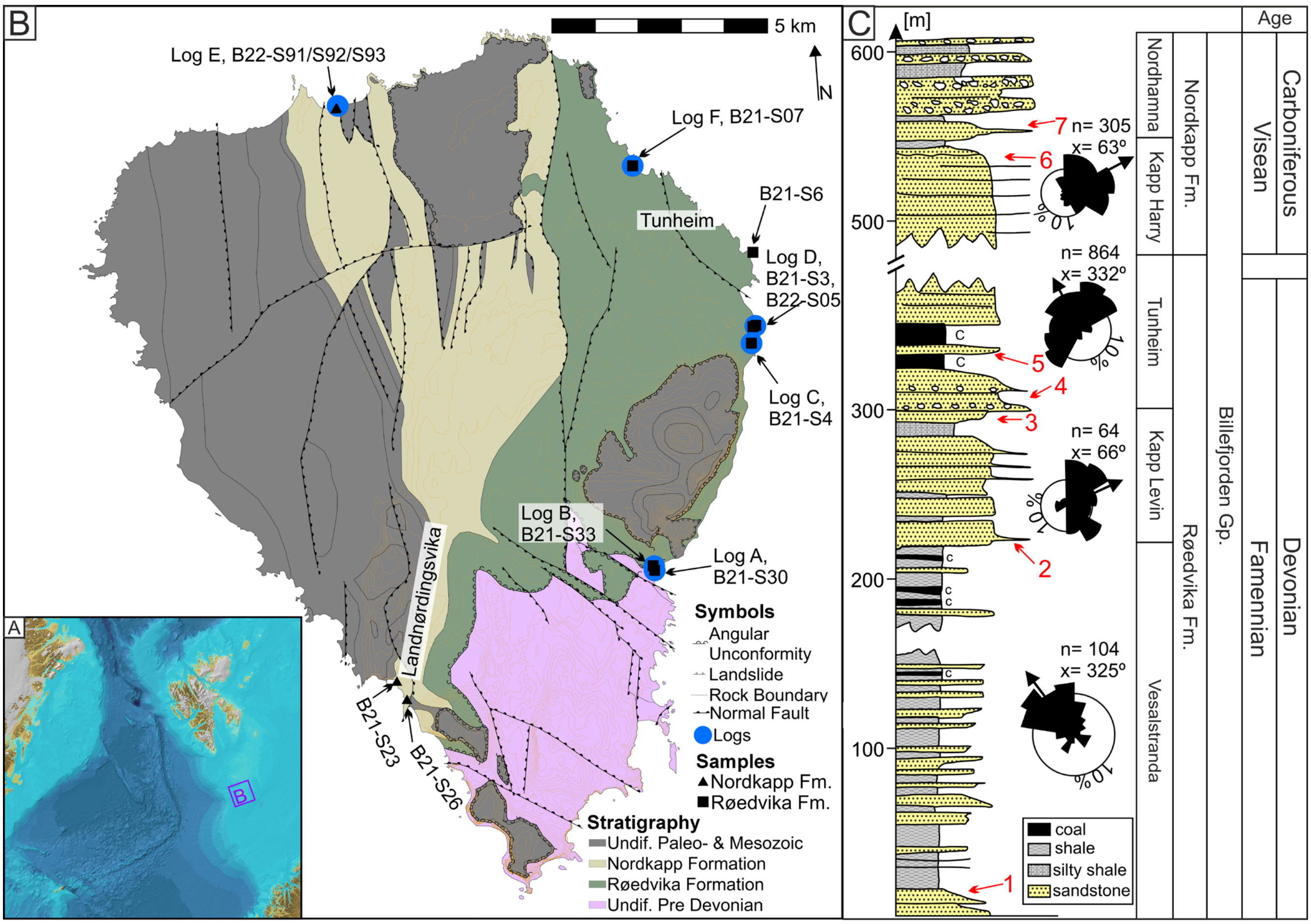

FIGURE 1 | Geographic, palaeogeographic and sedimentological overview of Bjørnøya. (A) Geographic overview of the Arctic with the outline of B marked in purple. Map modified from Jakobsson et al. (2012). (B) Geologic map of Bjørnøya with log and sample locations as well as outlines of digital outcrop models. Lithologic units in grey are those not studied in this contribution (Map modified after Dallmann and Krasil'Shchikov (1996)). (C) Composite stratigraphic log of the Billefjorden Group on Bjørnøya including rose diagrams for palaeocurrent readings for the individual members. Sampled intervals marked in red. 1—B21-S30/S33; 2—B21-S4; 3—B21-S3; 4—B22-S05; 5—B21-S6/S7; 6—B21-S26/B22-S93; 7—B21-S23/B22-S91/92. Stratigraphic log re-drawn after Gjelberg and Steel (1981), rose diagrams of palaeocurrent readings from Gjelberg (1981).

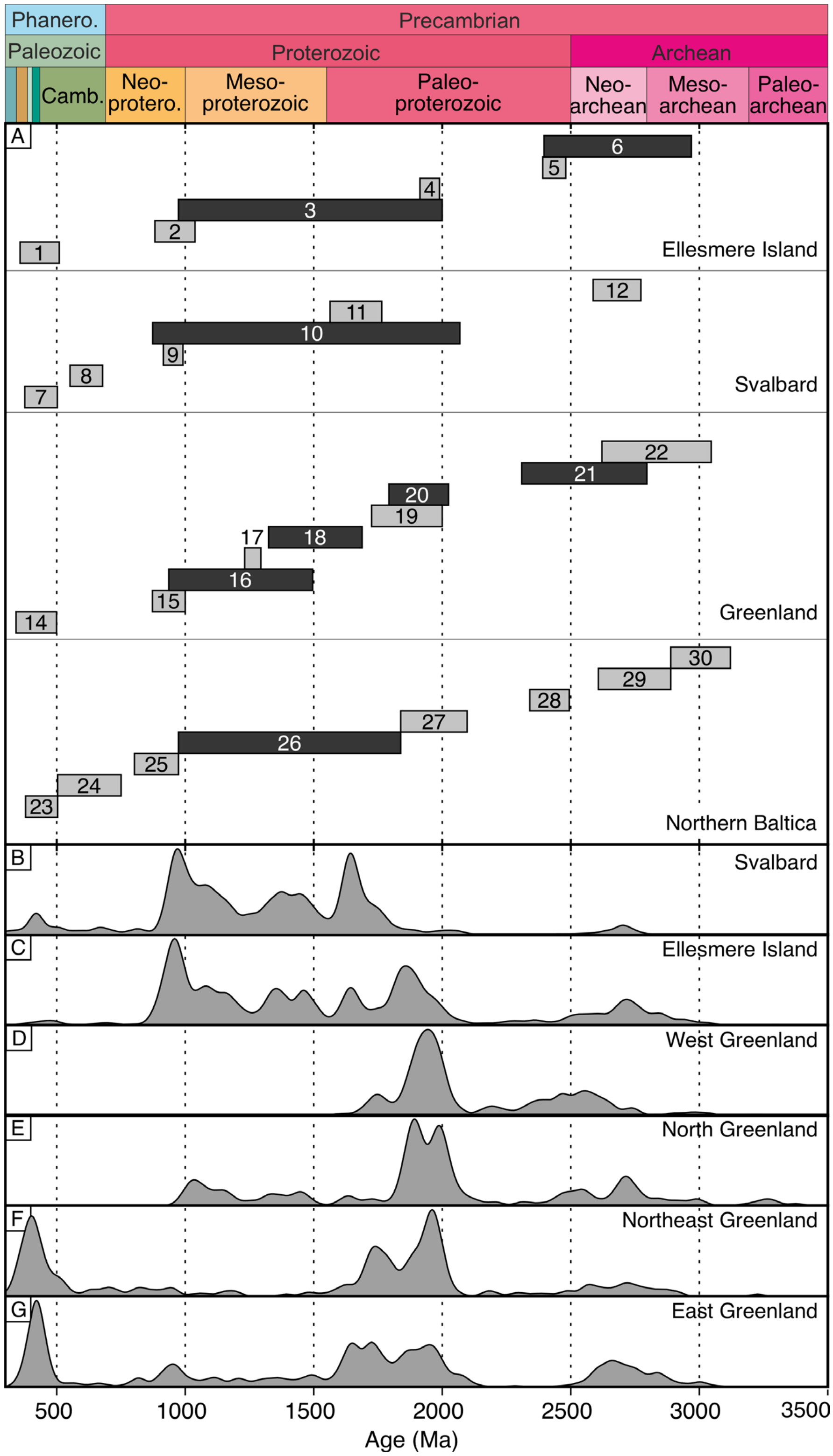

FIGURE 2 | Potential detrital zircon spectra for the different source areas. The KDE diagrams are a compilation of the available zircon U/Pb data referenced in Table 2. (A) represented zircon ages for the given source areas. Grey boxes symbolise igneous and metamorphic sources black boxes resemble detrital zircon sources. (B) KDE plot of all available zircon ages from Svalbard. (C) KDE plot of all available zircon ages from Ellesmere Island. (D) KDE plot of all available zircon ages from West Greenland. (E) KDE plot of all available zircon ages from North Greenland. (F) KDE plot of all available zircon ages from Northeast Greenland. (G) KDE plot of all available zircon ages from East Greenland. (Figure inspired from: Røhr, Andersen, and Dypvik 2008; Chronostratigraphic chart modified from: Cohen et al. 2013; updated).

TABLE 1 | Summary of the most relevant orogenic events recognised in the Arctic.

Age (Ma)	Orogen	Selected references
2000–1750	Ketilidian	Lahtinen, Garde, and Melezhik (2008), Henriksen et al. (2009)
2000–1750	Svecofennian	Åhäll and Larson (2000), Baltybaev (2013)
1900–1850	Nagssugtoqidian	Lahtinen, Garde, and Melezhik (2008), Henriksen et al. (2009)
1700–1500	Gothian	Åhäll and Gower (1997), Åhäll and Larson (2000), Roberts and Slagstad (2015)
1200–900	Grenville/Sveconorwegian	e.g., Lorenz et al. (2012), Bingen et al. (2021)
600–570	Timanian	Roberts and Siedlecka (2002), Kuznetsov et al. (2010)
500–390	Caledonian	e.g., McKerrow, Mac Niocaill, and Dewey (2000), Corfu, Gasser, and Chew (2014)
500–390	Ellesmerian	e.g., Piepjohn et al. (2015), Smelror and Petrov (2018), McClelland et al. (2023)
365–250	Uralian	e.g., Bea, Fershtater, and Montero (2002), Puchkov (2009)

Pease, and Frei 2009; Lorenz et al. 2012, 2013; Gee et al. 2015) during assembly of the supercontinent Rodinia (Li et al. 2008). On the Fennoscandian Shield, the Grenvillian Orogeny is referred to as the Sveconorwegian Orogeny. While Slagstad et al. (2013) propose that the Sveconorwegian Orogeny formed as an accretionary orogen, others suggest a continent–continent collision similar to the Grenvillian Orogeny (e.g., Möller and Andersson 2018; Bingen et al. 2021). Between 610 and 560 Ma, the Timanian Orogeny took place along the northeast margin of Baltica. Deformation related to this event is readily recognised in Arctic Russia and eastern Finnmark in North Norway (Roberts and Siedlecka 2002; Gee and Pease 2004). Timanian and post-Timanian magmatism are recorded in both northern Greenland and Arctic Russia (Pease et al. 2016; Rosa et al. 2016).

The Caledonian Orogeny, being one of the most prominent orogenic episodes of the entire North Atlantic region, controlled the development of the region during most of the Palaeozoic (500–390 Ma) (e.g., McKerrow, Mac Niocaill, and Dewey 2000; Corfu, Gasser, and Chew 2014). During the Caledonian Orogeny, Laurentia, Baltica and Avalonia collided because of the closure of the Iapetus Ocean and Tornquist Sea. The main phases of the Caledonian Orogeny occurred through the Silurian and Devonian (Trench and Torsvik 1992; Higgins, Soper, and Leslie 2000; McKerrow, Mac Niocaill, and Dewey 2000; Gasser and Andresen 2013; McClelland et al. 2023). The remnant of the Caledonian orogenic belt stretches from modern day northeast North America over Scotland and Norway all the way into the Arctic with branches in Greenland and Svalbard (McKerrow, Mac Niocaill, and Dewey 2000).

The Ellesmerian Orogeny followed slightly after the Caledonian Orogeny in the Late Devonian to Carboniferous (Piepjohn et al. 2015; McClelland et al. 2023). At its peak, the Ellesmerian orogenic belt stretched from northern Canada in the west to Svalbard in the east (Embry 1988; Higgins, Soper, and Leslie 2000; Piepjohn et al. 2000, 2015; Smelror and Petrov 2018; McClelland et al. 2023). In Svalbard, structuring associated with the Ellesmerian deformation occurred in the Late Devonian and is referred to as the Svalbardian event which has folded parts of the Devonian succession on Spitsbergen, particularly in proximity to older, long-lived lineaments (Piepjohn et al. 2000; Dallmann and Piepjohn 2020, 2024).

At the end of the Caledonian Orogeny, late orogenic collapse-related extension influenced the region, forming fault-bounded basins on the Barents Shelf, Svalbard, East Greenland, as well as on the west coast of Norway by backsliding of the Caledonian nappe complexes (e.g., Larsen and Bengaard 1991; Gudlaugsson et al. 1998; Osmundsen and Andersen 2001; Larsen, Olsen, and Clack 2008; Henriksen et al. 2011; Gernigon et al. 2014; Worsley 2016; Klitzke et al. 2019).

Regional subsidence and local basin formation recommenced during the Late Devonian to Mississippian (Gudlaugsson et al. 1998). It has been demonstrated that the position and orientation of these basins on the Barents Shelf is linked to an inherited Caledonian or Timanian structural grain, depending on their geographic location (e.g., Gudlaugsson et al. 1998; Gernigon et al. 2014; Klitzke et al. 2019; Hassaan et al. 2020). In the case of Bjørnøya and the Stappen High, a north–south-oriented Caledonian structural trend is evident (e.g., Braathen et al. 1999; Worsley et al. 2001). By the latest Devonian, Bjørnøya held an equatorial position. Extensive post-Caledonian subsidence-induced lowlands spanned large parts of the Barents Shelf and the Svalbard Platform and were possibly segmented by multiple faults, Figure 3E,F) (Gudlaugsson et al. 1998; Worsley 2016; Klitzke et al. 2019; Marshall, Tel'nova, and Berry 2019; Hassaan et al. 2020; Blakey 2021; Lopes et al. 2021). Subsidence resulting in the development of these lowlands may either have been induced by lithospheric stretching during incipient rifting (which peaked in the middle Carboniferous), reactivation and backsliding of

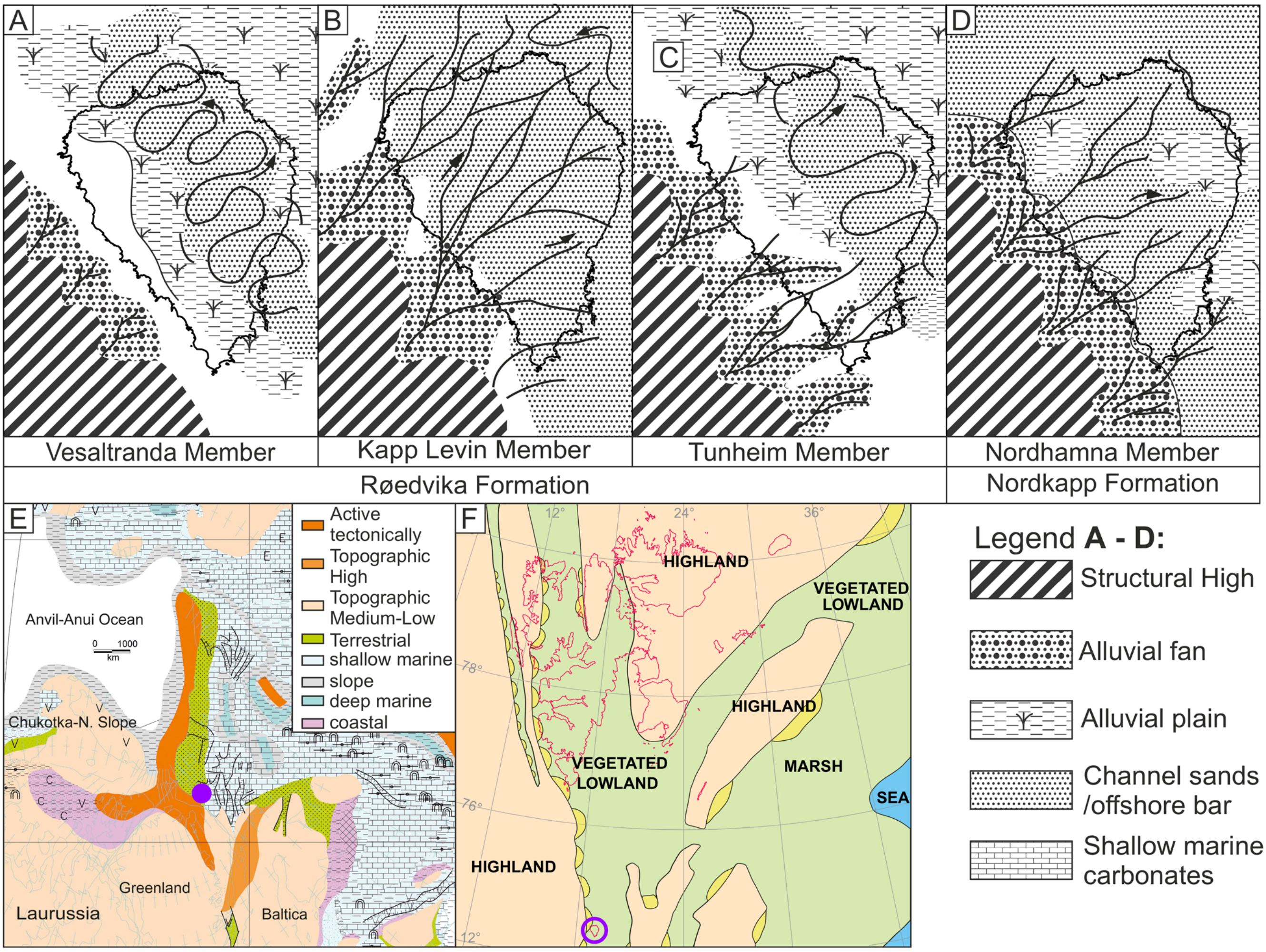

FIGURE 3 | Palaeogeographic reconstructions of the Billefjorden Group. (A–C) Palaeogeographic reconstructions of the Vesalstranda, Kapp Levin and Tunheim Members of the Røedvika Formation on Bjørnøya (modified from: Gjelberg 1981). (D) Palaeogeographic reconstruction of the Nordhamna Member (Nordkapp Formation) (modified from: Gjelberg 1981). (E) Regional palaeogeographic reconstruction at approximately 370 Ma (modified from: Golonka 2020). (F) Palaeogeographic reconstruction of Svalbard during the Viséan (modified from: Dallmann 2019).

Caledonian thrusts, or it may record continued subsidence and flexuring along Caledonian structures (Gudlaugsson et al. 1998; Stemmerik and Worsley 2005; Smelror et al. 2009; Henriksen et al. 2011). In the Wandel Sea Basin of Northeast Greenland, Mississippian (Viséan) basin development and accumulation of alluvial sediments, which is age equivalent to the Nordkapp Formation, have been attributed to initial rifting in the northern North Atlantic region (Dalhoff and Stemmerik 2000).

Following the closure of the Iapetus Ocean and the resulting Caledonian Orogeny, Laurentia and Baltica merged to form Laurussia, with Svalbard remaining connected to northeast Greenland and northeast Canada (Ellesmere Island) until break-up and opening of the North Atlantic Ocean in the Cenozoic (Domeier and Torsvik 2014; Golonka 2020; Blakey 2021).

2.2 | Source Terranes

The palaeogeographical location of terranes are important to identify potential source provinces for sedimentary units. Many of the Precambrian cratons and orogenic belts surrounding the Barents Shelf may have acted as potential source areas for the terrestrial siliciclastics and detrital zircons of the Billefjorden Group on Bjørnøya. This includes various terranes on the northern margin of Laurentia and the northern margin of the East European Craton (i.e., the palaeo-continent Baltica, Figure 4) (Gaál and Gorbatschev 1987; Lorenz et al. 2013; Pózer Bue and Andresen 2013). Figures 2 and 4 and Table 2 summarise source areas for detrital zircons which we assume is most relevant for this study, including major orogenic belts (Gaál and Gorbatschev 1987; Lorenz et al. 2013; Pózer Bue and Andresen 2013). In addition, due to fault-related uplift, exhumed basement rocks and recycling of meta-sedimentary strata may also be considered as potential local sources.

2.3 | Sedimentology and Stratigraphy

The age of the Billefjorden Group deposits on Bjørnøya spans the Late Devonian (Famennian) to Mississippian (Kaiser 1970; Lopes et al. 2021). The deposits are exclusively terrestrial and accumulated in humid wetlands east of the proposed West

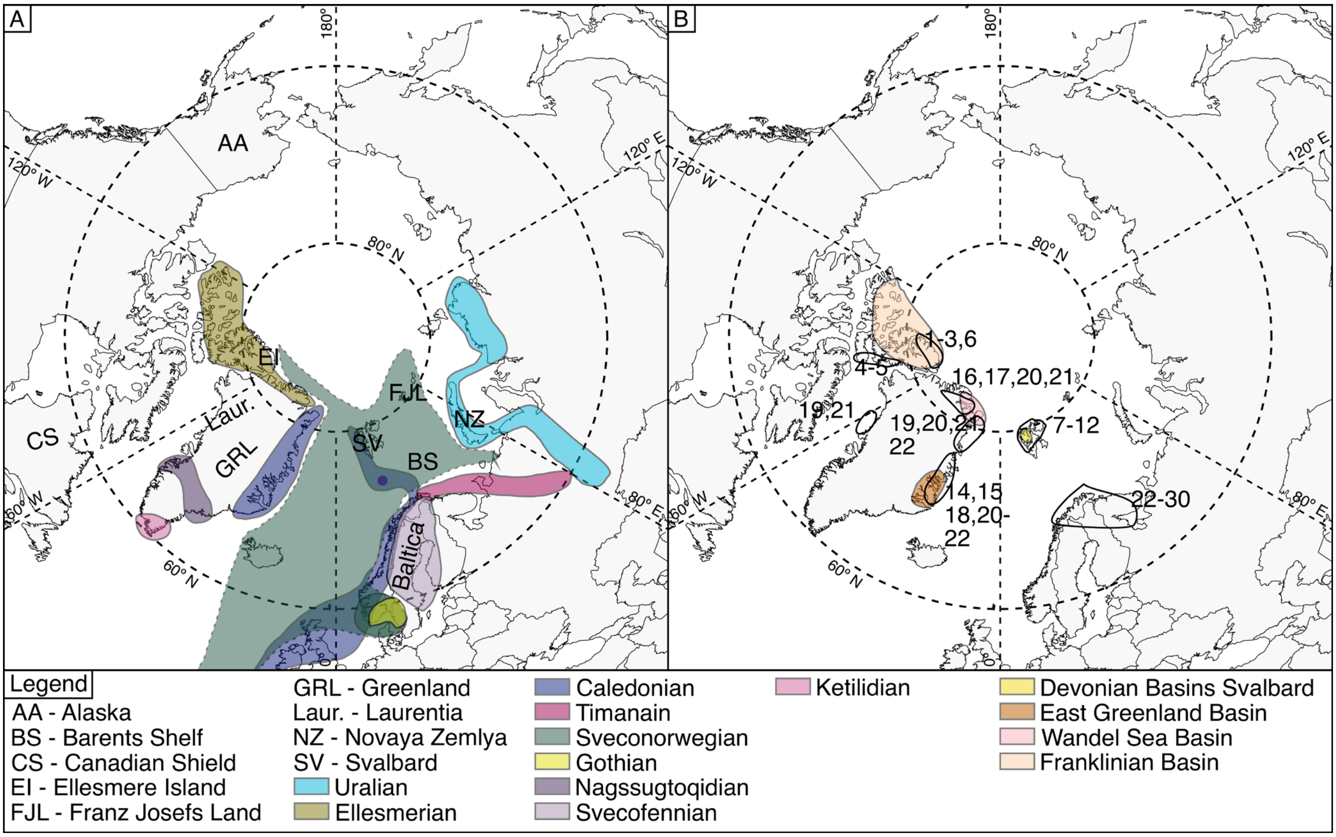

FIGURE 4 | Arctic Centred maps showing orogens, basins, and potential zircon source areas. (A) Most relevant orogenic events of northeast Laurentia and Baltica and most important place names. (B) Coloured are Devonian and Carboniferous basins. Black circles indicate potential source areas. The numbers refer to the potential source areas. For details and references, please see Table 2 and Figure 2.

Bjørnøya Fault (Figure 3) (Horn and Orvin 1928; Gjelberg 1981; Gjelberg and Steel 1981; Worsley et al. 2001; Mørk, Gjelberg, and Worsley 2014; Janocha et al. 2024). The group comprises the basal Røedvika Formation and the overlying Nordkapp Formation (Gjelberg 1981; Gjelberg and Steel 1981; Worsley et al. 2001; Mørk, Gjelberg, and Worsley 2014), and thickens from approximately 220 m in the southwest of the island (measured in an old coal exploration bore hole west of Ellasjøen) to 590 m in outcrops on the east coast (Horn and Orvin 1928; Gjelberg 1981; Gjelberg and Steel 1981). The southward thinning of the group has been proposed to be an effect of syn-tectonic deposition (Gjelberg 1981). The apparent thickness variation may also be less pronounced than previously thought, as the bore hole, from which the old thickness estimate was derived, was drilled in a structurally complex area (see Horn and Orvin 1928). Recent observations from the coastal cliff at the very southern tip of the island show thick developments of both the Røedvika and Nordkapp formations (Grundvåg et al. 2023).

Several exhumed Devonian basins, for which formation is generally linked to the collapse of the Caledonides, occur across the modern-day Arctic, including basins on Svalbard, Greenland, Norway, Canada and Alaska. Most of these basins host several kilometre thick successions predominantly consisting of alluvial sandstones, conglomerates and mudstones assigned to the 'Old Red Sandstone' succession (e.g., Friend and Williams 2000; Piepjohn et al. 2000; Anfinson, Leier, Embry, et al. 2012; Blakey 2021). Devonian-aged coal-bearing terrestrial deposits are reported from Canada, North Greenland and Bjørnøya (Goodarzi and Goodbody 1990; Janocha et al. 2024), suggesting periods of humid climate and the development of vegetated lowlands across the region despite the dominant arid climate characterising the period.

The Røedvika Formation is of Famennian age (Figure 1C) (Lopes et al. 2021) and is divided into three members: the Vesalstranda (Figures 1C and 3A), Kapp Levin (Figures 1C and 3B) and Tunheim members (Figures 1C and 3C) (Gjelberg 1978, 1981). The Røedvika Formation thickens from a minimum of 100 m in the southwest at Landnørdingsvika (in an incomplete section) to 360 m in the northeast near Tunheim (Horn and Orvin 1928; Gjelberg 1981; Worsley et al. 2001; Mørk, Gjelberg, and Worsley 2014). During deposition of the Vesalstranda Member, the area was characterised by meandering streams transecting a low-lying, alluvial plain (Figure 1C). Palaeocurrent data suggest a northwest directed drainage system (Figures 1C and 3A) (Gjelberg 1981; Gjelberg and Steel 1981; Worsley et al. 2001; Mørk, Gjelberg, and Worsley 2014). The overlying Kapp Levin Member records a shift to a braided stream setting with an east to dominantly north-easterly drainage (Figures 1C and 3B) (Gjelberg 1981; Gjelberg and Steel 1981; Worsley et al. 2001; Mørk, Gjelberg, and Worsley 2014). The base of the Tunheim Member is represented by a prominent conglomerate horizon, referred to as the Rifleodden Conglomerate. The Tunheim Member records a shift back to a northwest-directed drainage with large meandering streams running across an alluvial plain (Figures 1C and 3C) (Gjelberg 1981; Gjelberg and Steel 1981; Worsley et al. 2001; Mørk, Gjelberg, and Worsley 2014).

TABLE 2 | Potential zircon source areas for the Billefjorden Group on Bjørnøya.

#	Age (Ma)	Dated Material	Location	Selected references
1	500–450	Intrusions	Ellesmere Island, Canada	Trettin, Parrish, and Loveridge (1987)
2	1100–900	Crystalline basement	Ellesmere Island, Canada	Trettin, Parrish, and Loveridge (1987), Malone et al. (2017)
3	2000–950	Neoproterozoic & Cambrian meta−/sediments	Ellesmere Island, Canada	Hadlari, Davis, and Dewing (2014), Malone et al. (2014)
4	2000–1900	Intrusions	Southern Ellesmere Island, Canada	Frisch and Hunt (1988), Gilotti et al. (2018)
5	2500–2400	Paleoproterozoic intrusion	Devon Island, Canada	Frisch and Hunt (1988), Nutman et al. (2008)
6	3000–2400	Neoproterozoic meta−/sediments	Ellesmere Island, Canada	Hadlari, Davis, and Dewing (2014), Malone et al. (2014)
7	450–410	Caledonian granites	Svalbard	Johansson et al. (2002), Johansson et al. (2004), Myhre, Corfu, and Andresen (2009)
8	670–620	Intrusion	Svalbard	Peucat et al. (1989), Johansson et al. (2002), Beranek, Gee, and Fisher (2020)
9	1200–950	Grenvillian/Sveconorwegian granites & deformation	Svalbard	Balašov et al. (1995), Johansson et al. (2000), Johansson et al. (2002), Johansson et al. (2004), Myhre, Corfu, and Andresen (2009)
10	2000–900	Detrital zircons	Svalbard	Johansson et al. (2000), Pettersson, Pease, and Frei (2009), Gasser and Andresen (2013), Beranek, Gee, and Fisher (2020)
11	1750–1600	Basement	Nordaustlandet, Svalbard	Johansson (2001), Johansson et al. (2002)
12	2710	Quartz monzonite	Ny-Friesland, Svalbard	Hellman, Gee, and Witt-Nilsson (2001)
14	460–360	Caledonian	East Greenland	Kalsbeek et al. (1999), Watt, Kinny, and Friderichsen (2000), Gilotti, Nutman, and Brueckner (2004), Gilotti and McClelland (2005), Augland et al. (2011), Corfu and Hartz (2011)
15	1100–920	Grenvillian/Sveconorwegian granites & inherited zircons	East Greenland	Strachan, Nutman, and Friderichsen (1995), Watt, Kinny, and Friderichsen (2000), Kirkland et al. (2009)
16	1500–950	Detrital zircons	North Greenland	Kirkland et al. (2009)
17	1380	Zig-Zag Dal basalts	North Greenland	Kalsbeek and Jepsen (1984), Upton et al. (2005)

(Continues)

TABLE 2 | (Continued)

#	Age (Ma)	Dated Material	Location	Selected references
18	1700–1400	Detrital zircons	East Greenland	Kalsbeek, Nutman, and Taylor (1993), Strachan, Nutman, and Friderichsen (1995), Watt, Kinny, and Friderichsen (2000), Kirkland et al. (2009)
19	2000–1700	Intrusions	West & northeast Greenland	Kalsbeek et al. (1999), Watt, Kinny, and Friderichsen (2000), Thrane et al. (2005), Nutman et al. (2008)
20	2000–1750	Paleoproterozoic gneisses, crystalline basement	North & east Greenland	Kalsbeek, Nutman, and Taylor (1993), Nutman and Kalsbeek (1994), Kalsbeek et al. (1999), Thrane (2002), Kirkland et al. (2009)
21	2800–2300	Detrital zircons	Greenland	Nutman and Kalsbeek (1994), Kalsbeek et al. (1999), Nutman et al. (2008), Kirkland et al. (2009)
22	3000–2700	Gneiss (Archean protolith), detrital zircons	Northeast and east Greenland	Tucker, Dallmeyer, and Strachan (1993), Nutman and Kalsbeek (1994), Thrane (2002), Kirkland et al. (2009)
23	500–400	Caledonian, Kalak Nappe Complex	Northernmost Norway	Corfu, Ravna, and Kullerud (2003), Corfu (2004b), Kirkland, Daly, and Whitehouse (2005), Barnes et al. (2007), Kirkland, Daly, and Whitehouse (2008), Augland et al. (2012)
24	710–502	Metamorphic events, Kalak Nappe Complex	Northernmost Norway	Paulsson and Andréasson (2002), Kirkland, Stephen Daly, and Whitehouse (2007)
25	980–840	Intrusives, Kalak Nappe Complex	Northernmost Norway	Paulsson and Andréasson (2002), Kirkland, Stephen Daly, and Whitehouse (2007), Agyei-Dwarko, Augland, and Andresen (2012), Augland et al. (2014)
26	1700–1000	Inherited zircon grains and intrusions	Northernmost Norway	Paulsson and Andréasson (2002), Corfu, Bergh, Kullerud, et al. (2003), Kirkland, Daly, and Whitehouse (2005), Kirkland, Stephen Daly, and Whitehouse (2007)
27	2060–1700	Granitoids, Keivitsa-Kuetsjarvi-Umba (LIP), Pechanga-Onega (LIP)	Lofoten (Norway) and Kola Peninsula (Russia)	Daly et al. (2001), Corfu (2004a), Rehnström and Corfu (2004), Ernst and Bleeker (2010), Martin et al. (2013)

(Continues)

TABLE 2 | (Continued)

#	Age (Ma)	Dated Material	Location	Selected references
28	2478–2394	Plutons, Baltic Large Igneous Province (BLIP)	Kola Peninsula, Russia	Levchenkov et al. (1995), Ernst and Buchan (2001), Ernst (2014)
29	2903–2650	Plutons	Varanger (Norway) and Kola (Russia) Peninsula	Levchenkov et al. (1995), Corfu, Bergh, Kullerud, et al. (2003), Höltä et al. (2008)
30	3100–2900	Belomorian Belt	Kola Peninsula, Russia	Bibikova et al. (2004)

The overlying Nordkapp Formation has been assigned a Viséan age (Kaiser 1970; Lopes et al. 2021). The thickness of the unit ranges from minimum 110 m in the southwest (in the previously mentioned bore hole west of Ellasjøen) to 230 m in the north (Horn and Orvin 1928), and the unit is divided into the Kapp Harry and the Nordhamna Members (Figures 1C and 3D). Both members consist of cross-stratified sandstones, occasional mudstones and subordinate conglomerates, inferred to represent braided stream deposits of an alluvial fan complex that built north-eastwards into the basin (Gjelberg 1981; Gjelberg and Steel 1981; Worsley et al. 2001; Worsley and Mørk 2008). Large-scale soft-sediment deformation structures are evident throughout the succession and point to tectonic activity during, or shortly after, deposition (Worsley and Edwards 1976; Gjelberg 1981; Gjelberg and Steel 1981; Worsley et al. 2001; Worsley and Mørk 2008; Mørk, Gjelberg, and Worsley 2014). A gradual transgression under arid climatic conditions is inferred for the deposits of the Gipsdalen Group overlying the Billefjorden Group (Gjelberg 1981; Gjelberg and Steel 1981; Worsley et al. 2001).

3 | Methods and Data Set

The main objectives of our two field campaigns to Bjørnøya were to investigate the sedimentology of the Billefjorden Group, particularly focusing on previously reported changes in depositional styles between its various stratigraphic units, as well as collecting samples for detrital zircon geochronology to explore potential changes in source terrains and sediment routing. Thus, to provide a stratigraphic framework for the detrital zircon analysis, we logged c. 220 m of strata of the Røedvika and Nordkapp Formations wherever accessible along the steep and rugged coastal cliffs of Bjørnøya (see Figure 1B for location and Figure 5 for a selection of logs). The sedimentary logs were measured bed-by-bed at decimetre-scale and include descriptions of lithology, grain size, sorting, sedimentary structures and trace fossils (Figure 5). In addition, we collected an extensive data set of photographs to accompany the logged sections (see Figures 6 and 7 for representative outcrop photos). A total of 12 samples were collected for detrital zircon provenance analysis, spanning all the lithostratigraphic subunits of the two formations of the Billefjorden Group (see data presented in Figure 9 and Table 3, Figure 1 for sampling location and Figure 5 for stratigraphic levels). A subset of eight samples was used for petrographic thin section analysis (Figure 8, Table 3).

When it comes to detrital zircon provenance, common limitations are sampling bias, zircon recycling, mineral fertility, hydraulic fractionation and statistical adequacy (Vermeesch 2004; Lawrence et al. 2011; Malusà et al. 2013; Malusà, Resentini, and Garzanti 2016; Flowerdew et al. 2019; Andersen et al. 2022; Lowey 2024).

To perform the detrital zircon provenance analysis, we first carried out conventional heavy-mineral separation on all samples. This included: crushing, grinding, water tabling as well as magnetic and heavy liquid separation. The actual zircon analyses were carried out at the UT Chron Geochronology facilities at the University of Texas. To avoid any bias and to capture all major age components, we randomly selected 120 grains per sample (Vermeesch 2004). The analytical protocol we followed is based

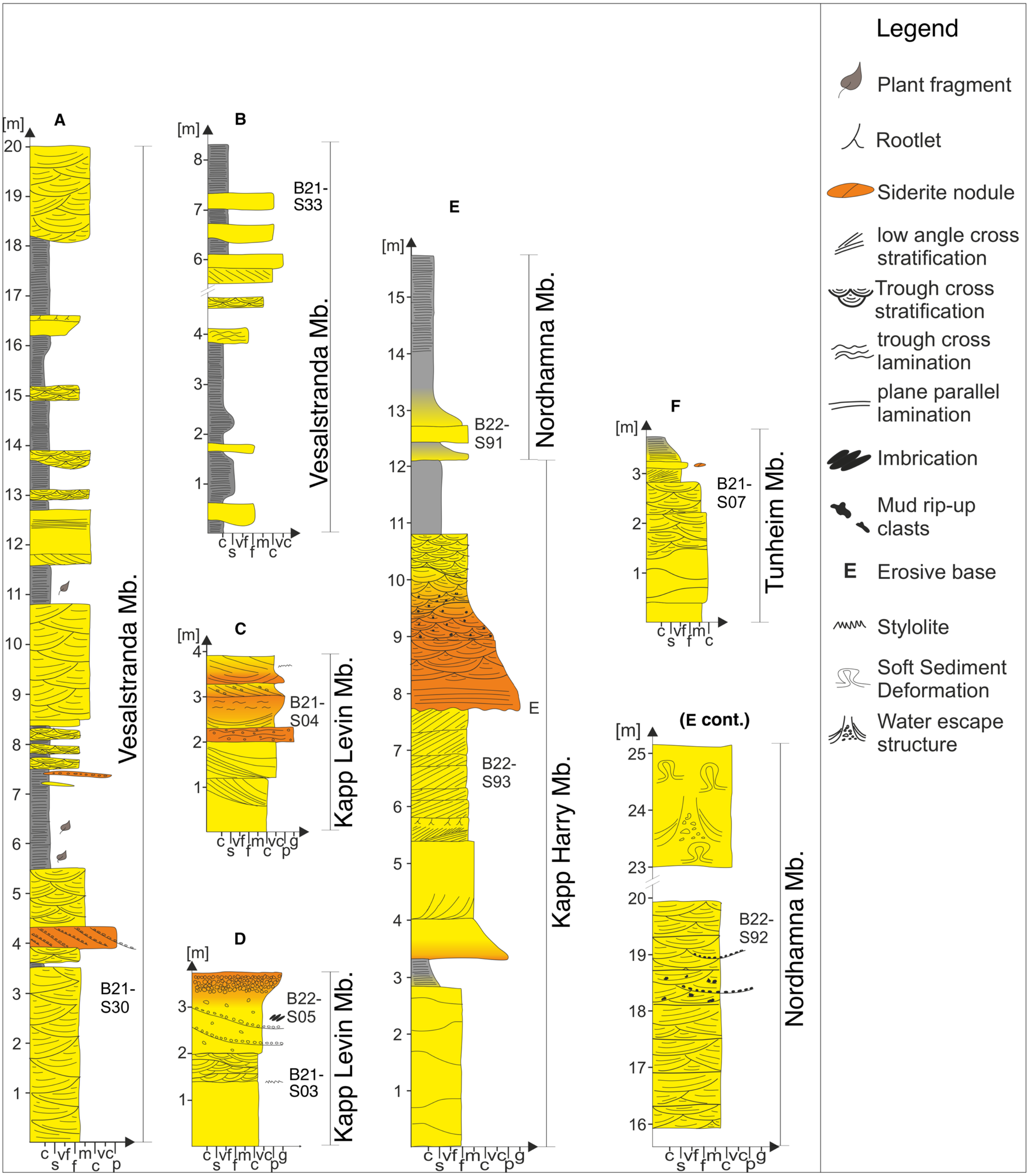

FIGURE 5 | Stratigraphic logs of sampling locations of the Røedvika and Nordkapp formations along the north and east coast of Bjørnøya. (A) Log A of the Vesalstranda Member logged at Røedvika. (B) Log B is a logged section of the Vesalstranda Member at Røedvika. (C) Log C is a logged section of the Kapp Levin Member logged at Rifleodden. (D) Log D is a logged section of the Kapp Levin Member logged at Rifleodden. (E) Log E is a logged section of the Nordkapp Formation logged at Nordhamna. (F) Log F is a logged section of the Tunheim Member logged at Jacobsenodden. For locations of the stratigraphic logs, refer to Figure 1.

on Marsh and Stockli (2015), and Anfinson et al. (2022). To transition between $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ ages, we chose 850 Ma as this age lies outside any major age mode in our samples. For ages younger than 850 Ma, $^{206}Pb/^{238}U$ ages are reported, while for older grains, the $^{207}Pb/^{206}Pb$ age is reported. Uncertainties are given at 2 sigma level. We disregarded grains based on discordance and error thresholds. The thresholds for younger than 850 Ma grains are greater than 10% discordance between

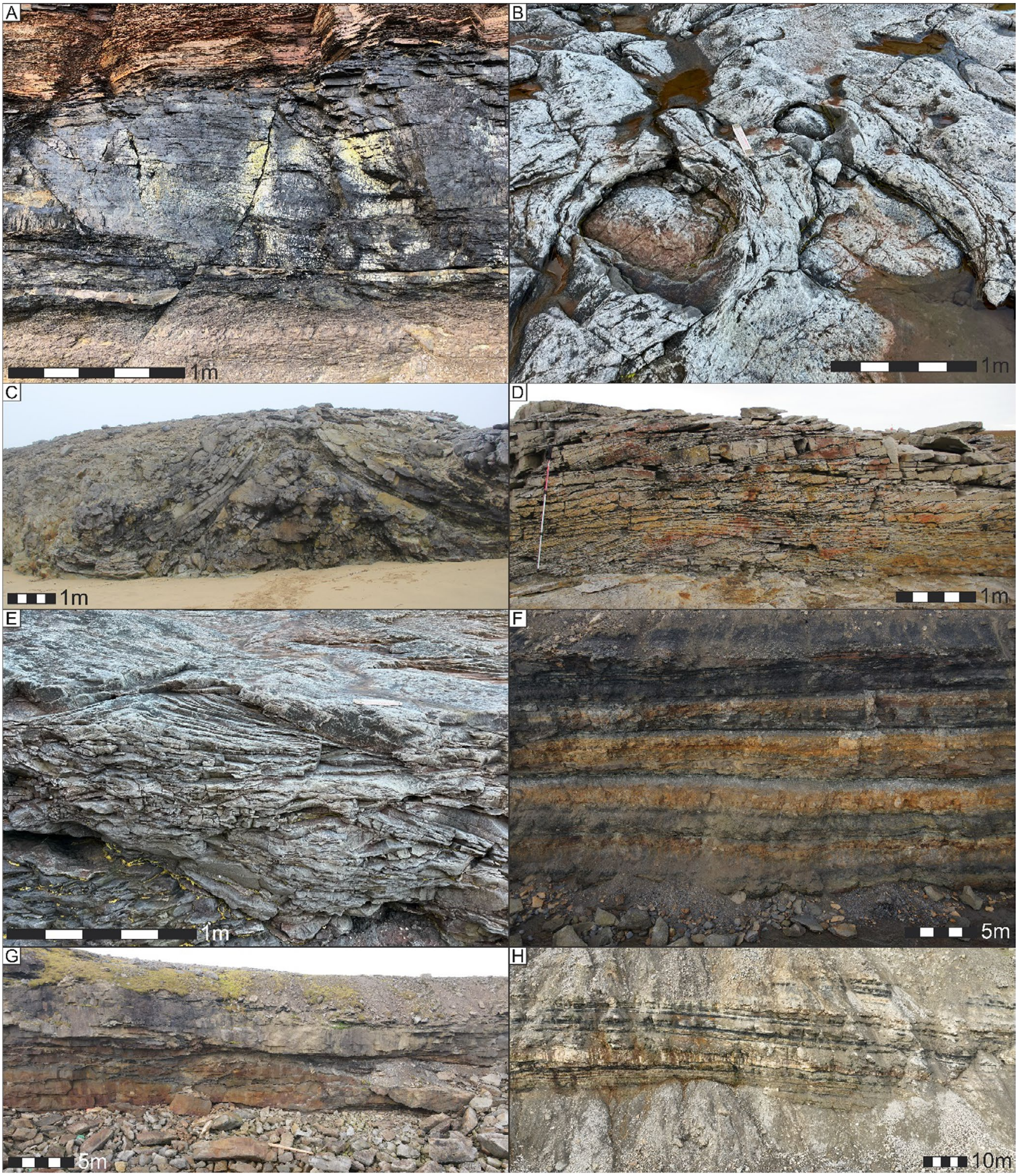

FIGURE 6 | (A) Syn-sedimentary fault in a coal seam of the Tunheim Member terminating at the top of the coal seam. (B) Soft sediment deformation (SSD) features on the top surface of a sandstone layer in the Tunheim Member. (C) Large-scale SSD in the Nordkapp Formation. (D) Tabular cross-bedded sandstone of the Nordkapp Formation. (E) Trough cross-bedded sandstone of the Tunheim Member. (F) Overbank and coal deposits of the Tunheim Member. (G) Meandering channel sandstone body of the Kapp Levin Member. (H) Vesalstranda Member showing thin coal seams, silty overbank and sandy channel deposits.

$^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ages or if the $^{206}Pb/^{238}U$ age error is more than 10%. For older grains, the threshold is greater than 10% discordance between the $^{206}Pb/^{238}U$ and the $^{207}Pb/^{206}Pb$ ages. Rejected ages are marked with 'NA' in the 'Best age' and 'Best age error' column of Supporting Information S1. The data have also been uploaded to the geochronological repository

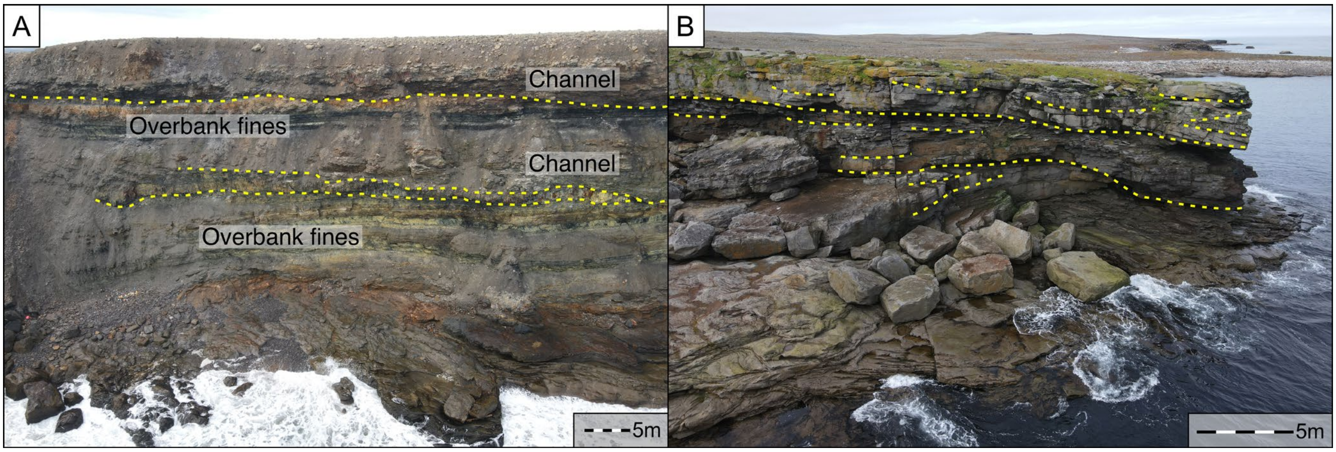

FIGURE 7 | Different fluvial systems operated during the deposition of the Billefjorden Group on Svalbard, as evident by the variability in fluvial architectures and sandstone content. Highlighted with yellow stippled lines are the channel bases. (A) Meandering channel fill within fine-grained overbank deposits. Example representative for channel bodies of the Vesalstranda and Tunheim members of the Røedvika Formation. (B) Cross-cutting, sandstone-dominated channel bodies of an interpreted braided stream channel system. Example representative for the Kapp Levin Member of the Røedvika Formation and the Nordkapp Formation.

TABLE 3 | Analysed samples, their corresponding stratigraphic unit, lithology, sampling location and petrography.

Sample	Formation	Member	Age	Lithology	Latitude	Longitude	Petrography
B21-S30	Røedvika	Vesalstranda	Famennian	f sst	74.400929° N	19.173261° E	Yes
B21-S33	Røedvika	Vesalstranda	Famennian	f-m sst	74.401900° N	19.172366° E	Yes
B21-S4	Røedvika	Kapp Levin	Famennian	f sst	74.446537° N	19.260266° E	Yes
B21-S3	Røedvika	Kapp Levin	Famennian	f-m sst	74.449941° N	19.262402° E	Yes
B22-S05	Røedvika	Kapp Levin	Famennian	CGL	74.450158° N	19.264637° E	No
B21-S6	Røedvika	Tunheim	Famennian	f-m sst	74.465329° N	19.266490° E	Yes
B21-S7	Røedvika	Tunheim	Famennian	vf sst	74.484979° N	19.178234° E	Yes
B21-S26	Nordkapp	Kapp Harry	Visean	f sst	74.377881° N	18.976018° E	Yes
B22-S93	Nordkapp	Kapp Harry	Visean	m sst	74.501389° N	18.952166° E	No
B22-S91	Nordkapp	Nordhamna	Visean	m sst	74.501212° N	18.951384° E	No
B22-S92	Nordkapp	Nordhamna	Visean	m-c sst	74.501212° N	18.951384° E	No
B21-S23	Nordkapp	Nordhamna	Visean	c-vc sst	74.381798° N	18.969173° E	Yes

Note: The ages in the age column are from Kaiser (1970) and Lopes et al. (2021) and are based on palynology.
Abbreviations: CGL, conglomerate; c-vc sst, coarse to very coarse sandstone; f sst, fine sandstone; f-m sst, fine to medium sandstone; m sst, medium sandstone; m-c sst, medium to coarse sandstone; vf sst, very fine sandstone.

geochron.org. Optical imagery of the analysed zircons with their respective ages can be found in the Supporting Information. To plot the kernel density estimate plots (KDE), cumulative distribution plot (CDP), multidimensional scale plot (MDS) and pie plots (see Figures 9, 10 and 11) of the zircon age distributions, we used detritalPy version 1.3 (Sharman, Sharman, and Sylvester 2018).

4 | Results

Because our sedimentary logs and sample collection span all the stratigraphic units of the Billefjorden Group on Bjørnøya, our data set should, in principle, account for the previously reported stratigraphic variations in palaeocurrent directions and fluvial styles within the Billefjorden Group (see Gjelberg 1981; Mørk, Gjelberg, and Worsley 2014). The effects of lateral facies variations across the basin, however, cannot be sampled and accounted for in a representative manner, which is commonly done in many other sedimentary basins (e.g., Fonneland et al. 2004; Dobbs et al. 2022). This is due to the gently dipping nature of the strata combined with outcrop limitations (e.g., steepness, accessibility, lack of exposures in the interior of the island etc.) and the limited size of Bjørnøya (20×15km) which inhibit detailed sampling laterally across the basin. However,

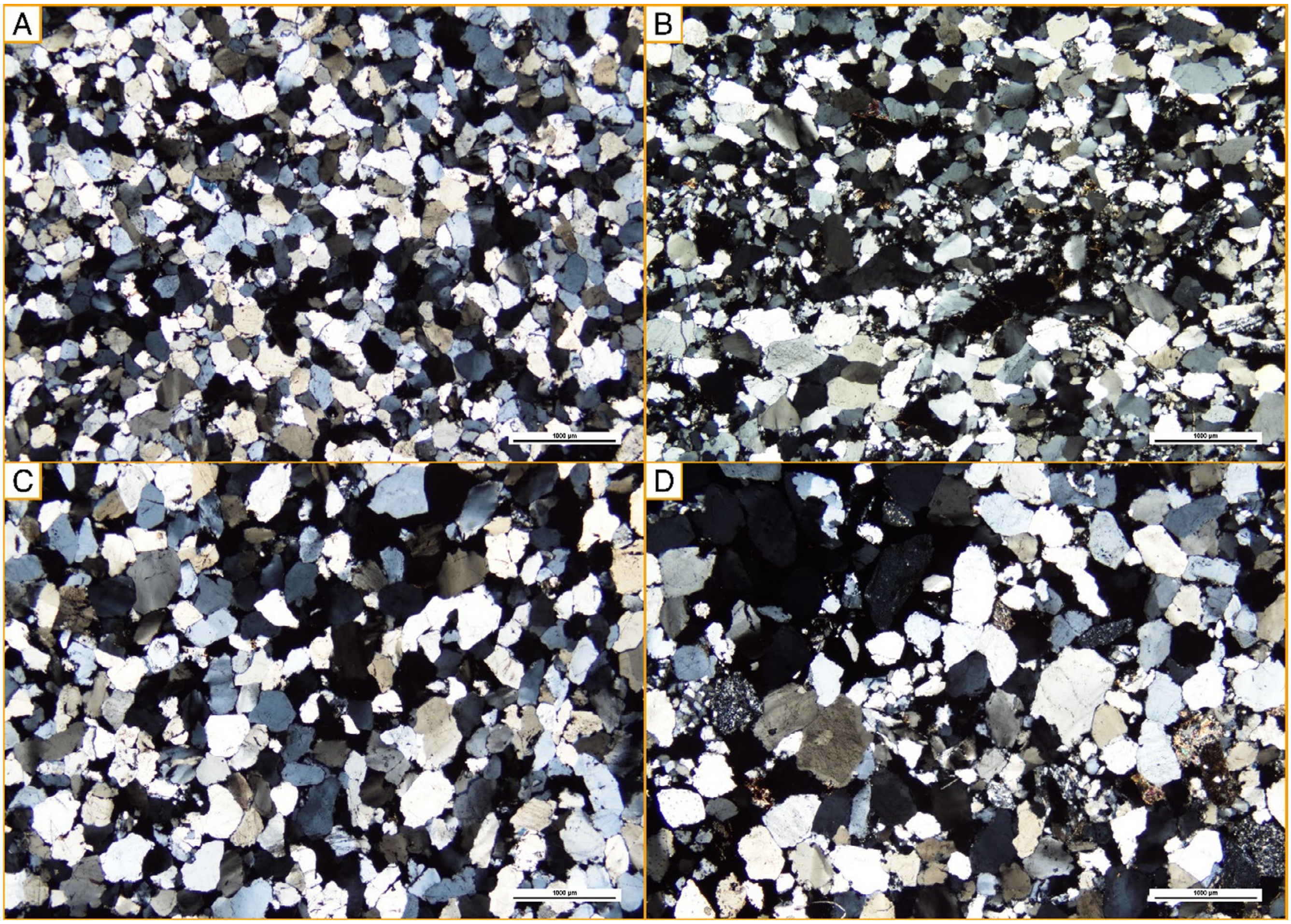

FIGURE 8 | Thin section images through cross-polarised light. All samples are mature sandstones with distinct quartz overgrowth and are dominated by monocrystalline quartz. (A) Sample B21-S33, Vesalstranda Member (Røedvika Formation); (B) Sample B21-S3, Kapp Levin Member (Røedvika Formation); (C) Sample B21-S6, Tunheim Member (Røedvika Formation); (D) B21- S23, Nordhamna Member (Nordkapp Formation).

given the small outcrop window, significant lateral variations are not expected, neither in terms of major facies shifts nor detrital zircon contents.

4.1 | Sedimentological Analysis

The logged sections typically consist of erosively based, fine- to coarse-grained, planar and trough cross-bedded sandstone units of variable thicknesses (typically ranging between 1 m and 15 m), which commonly exhibit blocky to weakly fining upward grain size motifs (Figures 5 and 6). Large-scale lateral accretion surfaces and internal truncations occur (Figure 6D,G). In places, some units exhibit plane-parallel stratification and subordinate current-ripple cross-lamination, whereas convolute bedding or other dewatering structures of assorted sizes (some being at meter scale) are locally abundant (Figure 6B,C). Pervasively soft sediment deformed horizons involving multiple beds are relatively common, particularly in the Nordkapp Formation. Small-scale faults with decimetre to metre-scale offset and which display bed thickening towards the fault planes have been recognised in a few cases (Figure 6B). Locally, various plant and tree fragments, as well as horizons of mudstone intraclasts or lithic conglomerates occur within the sandstones, the latter predominantly forming basal lags demarcating the erosive base of cross-bedded sandstone units.

In terms of thicknesses, external geometries, stacking patterns and relative sandstone to mudstone ratios, two principal types of erosively based sandstone units have been recognised (here referred to as types I and II). The first type rarely exceeds 10 m in thickness, typically exhibits lenticular geometries with smooth concave upward or stepped basal surfaces and intermittently displays lateral accretion surfaces within (Figure 7). These units tend to show fining upward trends and commonly intercalate with siltstone-rich heterolithics or mudstone-dominated units with thicknesses of 1–10 m (occasionally more). Collectively these deposits form several tens to hundreds of metres thick, mudstone-dominated successions (e.g., in the Vesalstranda Member), which host and encapsulate the erosively based sandstones (Figures 6 and 7). Coal seams, occasionally exceeding a thickness of 1 m, commonly occur within these fine-grained deposits, including the renowned A-Coal of the Tunheim Member mined during the 1920s (Figure 6) (Horn and Orvin 1928; Gjelberg 1981; Worsley et al. 2001; Mørk, Gjelberg, and Worsley 2014; Janocha et al. 2024). Thin sandstone beds, some exhibiting rootlets, also occur locally within the fine-grained units, and may occasionally form sheet-like, coarsening and thickening upward units of a few metre thickness.

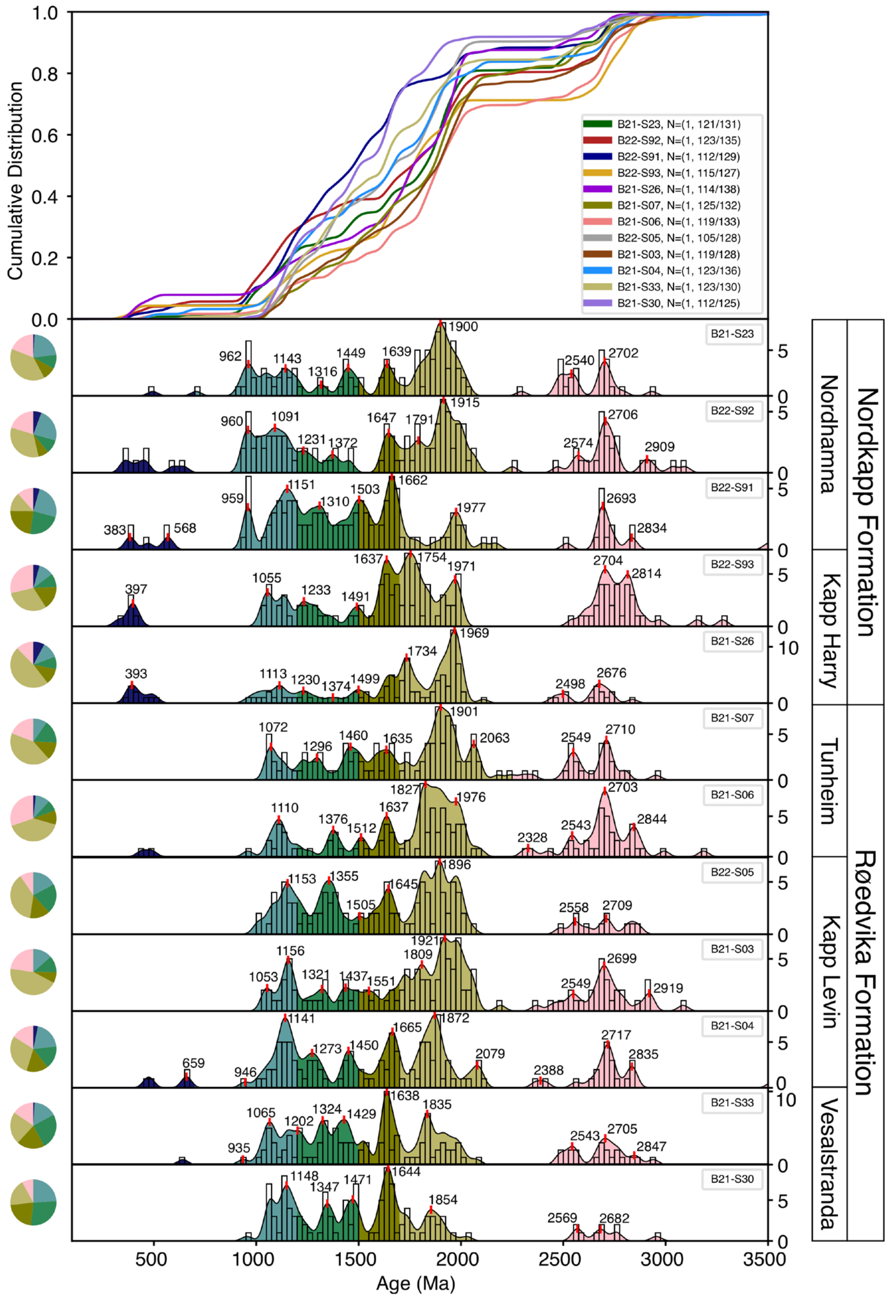

FIGURE 9 | Cumulative distribution plot (CDP), kernel density estimate (KDE) and pie diagrams for the detrital zircon age distribution of the Billefjorden Group on Bjørnøya. The colours of the pie diagrams correspond to the same colours as those of the KDE plots. Colouring of the KDE plots: 0–700 Ma—midnight blue, 700–1200 Ma—cadet blue, 1200–1500 Ma—sea green, 1500–1700 Ma—olive, 1700–2250 Ma—dark khaki, 2250–4000 Ma—pink.

The second type of erosively based sandstone units (type II) have flat to undulating bases and form more laterally persistent (at the scale of the outcrops), sheet-like units with thicknesses up to several tens to hundreds of metres (e.g., the Kapp Harry Member of the Nordkapp Formation; Figures 6 and 7). Internally, they are characterised by multiple truncation surfaces demarcated by conglomerate lags up to a few decimetres thick, which defines vertically stacked and amalgamated, planar cross-bedded subunits of variable thicknesses (typically between 2 and 15 m, with individual set thicknesses ranging from 0.2 to 2 m). Fine-grained intercalations are rarely associated with the type II sandstone units, albeit being more common in the Nordhamna Member on the northern coast of Bjørnøya.

Based on our detailed stratigraphic logging and facies description, we interpret the investigated Billefjorden Group strata to represent terrestrial and fluvial deposits, including channel fills of meandering (type I) and braided streams (type II), as well as inter-channel sandstone sheets and overbank fines (Figures 5, 6 and 7), in line with previous work (Horn and Orvin 1928; Gjelberg 1978, 1981; Gjelberg and Steel 1981; Worsley et al. 2001;

Mørk, Gjelberg, and Worsley 2014). A more thorough interpretation and discussion on the depositional system, including the repeated changes in palaeocurrent directions and fluvial styles between the various lithostratigraphic subunits, is provided in the discussion (Section 5).

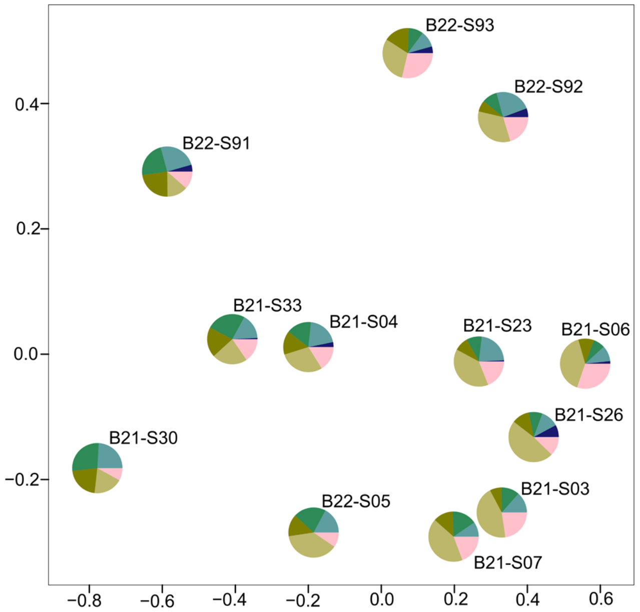

FIGURE 10 | MDS plot showing the dissimilarities between the samples were similar samples cluster together. The colours correspond to the age modes in Figure 7.

4.2 | Detrital Zircon Analysis

The CDP of the detrital zircon ages is strikingly similar for all samples (Figure 9). For most samples, 70% of the detrital zircons give ages between 1000 and 2000 Ma. The MDS plot in Figure 10 shows the dissimilarities between the samples and clusters together similar samples. The detrital zircon age distribution over time is seen in the KDE diagrams (Figure 9).

Our detrital zircon age distribution over time is polymodal (Figure 9). The youngest mode (300–500 Ma) is apparent in seven of the samples but missing in Samples B21-S30, B21-S03, B22-S05 and B21-S07. Other important age modes are 900–1100 Ma, 1100–1500 Ma, 1500–1700 Ma, 1700–2000 Ma and 2400–2900 Ma. The modes are chosen based on important orogenic phases and visual grouping of important zircon age groups. All modes are represented with variable intensities across all samples. The peaks in the KDE plot can be linked to potential source areas and will be discussed in the following section.

4.3 | Petrography

The eight thin sections selected for petrographic analysis show a clear dominance of monocrystalline quartz grains. All samples contain some few grains of chert and individual grains of polycrystalline quartz. The remaining pore space is often coated by clay minerals. Generally, all samples have experienced extensive quartz overgrowth. In individual samples, we were able to observe single zircons (Figure 8).

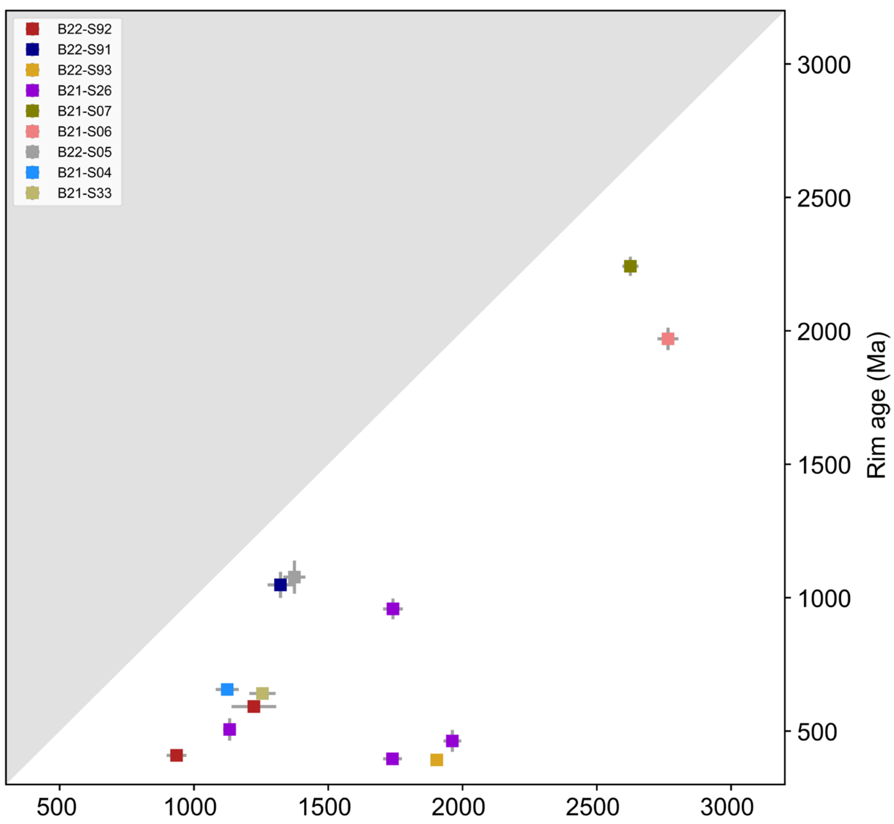

FIGURE 11 | Rim versus core plot showing ages of zircon overgrowth rims and the ages of the inherited core. The rim ages stem from zircon overgrowth during re-heating of the original zircon and can often be related to metamorphic events.

5 | Discussion

5.1 | Depositional Environments and Drainage Directions

The sedimentary strata of the Vesalstranda and Tunheim members of the Røedvika Formation, which are both dominated by type I erosively based sandstone units characterised by fining upward trends, lateral accretion surfaces, and which occurs within thick mudstone-rich successions, thus exhibit features consistent with deposition in meandering fluvial channels and on adjacent low-lying inter-channel alluvial (flood) plains (see also Gjelberg 1978, 1981). Similar meandering channel systems occur among others in the Upper Devonian of East Greenland (Olsen and Larsen 1993). The abundance of fine-grained deposits and the single-story nature of the sandstone channel fills is typical of high accommodation fluvial systems (Shanley and McCabe 1992). In contrast, the much thinner (c. 75 m), sheet-like Kapp Levin Member, which is sandwiched between the other two units, is dominated by type II sandstone units characterised by stacks of planar cross-bedded sets and multiple internal truncation surfaces, and thus exhibit features consistent with deposition in a braidplain setting (Gjelberg 1978, 1981). Such laterally extensive fluvial systems of limited thicknesses points towards a drastic decrease in vertical accommodation space (Shanley and McCabe 1992; Martinsen et al. 1999; Grundvåg and Skorgenes 2022). The sedimentological characteristics and sandstone-dominated nature of the Nordkapp Formation, mostly being composed of amalgamated type II sandstone units, are also typical of braided stream deposits (Gjelberg 1981). However, its extensive thickness (c. 230 m) is not consistent with a low accommodation space setting. As such, it is suggested here that the unit was deposited in a period of significant upland erosion and concurrent high rates of basin subsidence, pointing to syn-tectonic deposition for the Nordkapp Formation. This is supported by the abundance of soft sediment deformation structures in the unit, including pervasively deformed horizons spanning multiple beds, as well as the overall northward stratal thickening. Similar interpretations have been proposed for thick, cross-bedded fluvial sandstone sheets located near structural lineaments elsewhere (Grundvåg and Skorgenes 2022). Additionally, Ryan et al. (2023) argue for an extensional regime during the Late Palaeozoic on Bjørnøya and the Stappen High.

Based on > 1300 dip-azimuth readings of forests in the cross-bedded sandstones (summarised in Figure 1C), previous work has documented a change from an averaged north-north-westerly drainage direction in the interpreted meandering channel fills of the Vesalstranda Member (104 readings, with an average of 323°) to an averaged east-north-easterly drainage direction in the overlying braided stream deposits of the Kapp Levin Member (64 readings, with an average of 66° N), before changing back to an averaged north-north-westerly drainage direction in the meandering channel fills of the Tunheim Member (864 readings, with an average of 332°) (Figure 3) (Gjelberg 1978, 1981; Gjelberg and Steel 1981; Worsley et al. 2001; Mørk, Gjelberg, and Worsley 2014). Interestingly, the overlying Nordkapp Formation, dominated by braided stream deposits, records yet another change back to an averaged north-easterly drainage direction (305 readings, with an average of 65°) (Gjelberg 1981; Mørk, Gjelberg, and Worsley 2014). Although some of the variability in the data set can be attributed to lateral migration of high-sinuosity channel belts or changing migration directions of fluvial dunes and bars, the systematic stratigraphic change in averaged palaeocurrent directions may suggest drainage response to allogenic forcing, such as fault-induced uplift and subsidence. It is widely known that tectonics directly influence fluvial drainage systems, and particularly alluvial architecture (Gawthorpe and Leeder 2000; Schumm, Holbrook, and Dumont 2000; Bridge 2006). Land surface gradients may be altered due to fault activity, which may affect channel patterns and concurrently force rivers to divert, and differential subsidence, for example, may influence the stacking style and distribution of both fluvial channels and overbank fines (Bridge and Mackey 1993; Olsen and Larsen 1993; Ryseth 2000). It is therefore intriguing that the recurrent changes in palaeocurrent patterns coincide with alternations between the two principally distinctive styles of fluvial architectures documented here (i.e., the type I and II sandstone bodies; Figure 7). One explanation could be competing axial and transverse fluvial drainage, possibly controlled by fault-controlled topographic changes, which is a common sedimentary response to fault activity in extensional basins (Gawthorpe and Leeder 2000). In periods of high subsidence rates and low basin gradients, axially positioned meandering channels dominated (i.e., the Vesalstranda and Tunheim members), whereas periods of footwall uplift resulted in less vertical accommodation space and higher depositional gradients in the basin, which favoured the development of alluvial fans with braided streams oriented near perpendicular to the fault (i.e., the Kapp Levin Member). The thickness of the Nordkapp Formation deviates slightly from these models and may indicate a situation of high, yet balanced rates of sediment influx and basin subsidence, giving rise to an aggradationally stacked succession of braided stream deposits. Alternatively, both the changing fluvial styles and palaeocurrent directions record climatic forcing, which control source area erosion and sediment supply, combined with intrinsic factors (Bridge 2006). It has also been demonstrated that astronomical forcing of the climate can impact discharge and consequently channel sinuosity (e.g., Olsen 1990). However, it is beyond the scope of this study to investigate such relationships. Syn-sedimentary faults, which previously have not been reported in the Røedvika Formation (see also examples provided in Grundvåg et al. 2023), and abundant decimetre- to metre-scale soft sediment deformation structures, commonly involving multiple beds in both the Røedvika and Nordkapp formations (Figure 6) could point towards recurrent seismically induced liquefaction, which collectively is compatible with syn-tectonic deposition for the entire succession. Similar interpretations have also been postulated for this type of features in inferred tectonically active, fault-bounded basins elsewhere (e.g., Plaziat, Purser, and Philobbos 1988; Rossetti 2002; Grundvåg and Skorgenes 2022). The proximity to a fault, such as the inferred West Bjørnøya Fault suggested by Gjelberg and Steel (1981, 1983), may thus offer a viable explanation for the abundant deformation, alluvial architectures and palaeocurrent directions. Interestingly, Rotevatn et al. (2018) reported K-Ar ages from dating of illite from fault gouge samples in northern East Greenland and found evidence of an earliest Mississippian (or older rift initiation phase). In addition, extension and block faulting in the Late Devonian to Mississippian resulted in the formation of several NW-SE oriented half grabens on the Barents Shelf (e.g., Gudlaugsson et al. 1998; Klitzke et al. 2019; Hassaan et al. 2020). Several of these faults and basins exploited inherited Caledonian and locally Timanian basement fabrics during the Late Devonian to Mississippian regional extension event. It has, for example, been suggested that the supra-regional De Geer Zone, which runs just west of Bjørnøya, was initiated already in the Palaeozoic during the Caledonian Orogeny, following a zone of weakness (Faleide, Vågnes, and Gudlaugsson 1993; Gresseth et al. 2021). As such, given the regional framework and the sedimentological characteristics of the investigated succession, it does not seem unlikely that a fault system existed west of Bjørnøya during the Late Devonian to Mississippian, thereby controlling subsidence and sedimentation rates in the basin. Elsewhere, such fault activity has been shown to alter the drainage pattern of fluvial systems, and in extreme cases, also completely changing the catchment area and thus the resulting detrital zircon composition of the fluvial sediments in the basin (e.g., Whitchurch et al. 2011; Foster-Baril and Stockli 2023). Basin inversion may yield similar sedimentary response and drainage reversals (e.g., Olsen 1993). However, we see no signs of compressional tectonics (of Late Devonian to Mississippian age) in the investigated succession, albeit the slight northward thickening of the group can be interpreted because of tectonically induced, syn-sedimentary uplift of the Caledonian basement high exposed in the southern part of the island.

5.2 | Petrographic Considerations

The petrographic study of eight selected samples (Table 3) has shown a dominance of monocrystalline quartz (Figure 8). Thus, with the thin sections, we demonstrate that the mineralogical composition remains nearly identical throughout the entire stratigraphic succession (Figure 8). Similar results have previously been reported by Gjelberg (1978, 1981). The petrography shows that the sampled sandstones are mature and potentially indicate that the sediments have been subject to long transport distances and long exposure, as well as pointing to a source area yielding erosional products predominantly consisting of quartz grains. The quartz overgrowth is a result of deep burial, adhering to the long and complex burial history of the Stappen High (e.g., Worsley et al. 2001). Because of the similarity between all the samples, which clearly indicate a similar type of source area for the entire succession, they cannot be used to infer provenance changes.

5.3 | Source Areas

Multiple studies have shown that zircons of different ages and sources may have different sizes (e.g., Pirkle and Podmeyer 1993). Deposition of grains transported by a flowing medium is size and density dependent. In fluvial systems, flow velocity to a large part determines which grain size fraction is deposited at any given time (e.g., Rubatto, Williams, and Buick 2001; Corfu, Hanchar, Hoskin, et al. 2003). As a result, zircons with a certain grain size may be deposited together with the sand fraction of similar size or density. This process may lead to peak mismatch, or even the complete lack of age populations in some samples (Lawrence et al. 2011; Malusà, Resentini, and Garzanti 2016). We do not possess a full hydraulic data set, but we aimed to sample sandstones of similar grain sizes to minimise the effects of hydraulic fractionation (Table 3). However, this do not exclude the possibility that some of the peak mismatches and potentially missing age modes are the result of hydraulic fractionation rather than changes in source area. All the analysed samples have a broad spread in their detrital zircon age modes. However, a series of age modes can be recognised in our data, these are (from youngest to oldest): (i) 300–600 Ma (Palaeozoic—latest Neoproterozoic), (ii) 900–1200 Ma (latest Mesoproterozoic—earliest Neoproterozoic), (iii) 1200–1500 Ma (Mesoproterozoic), (iv) 1500–1700 Ma (latest Paleoproterozoic—earliest Mesoproterozoic), (v) 1700–2000 Ma (Paleoproterozoic), (vi) 2400–2900 Ma (Archean—earliest Paleoproterozoic). Prominent missing age intervals in the data set are 600–900 Ma, 2000–2400 Ma, and > 3000 Ma. As such, potential source areas are many and include Archean to Palaeozoic terrains on Svalbard, the Canadian Arctic Islands, Greenland and Baltica (Figures 2 and 4, Table 2).

i. The 300–500 Ma age mode has potential Palaeozoic source areas on Svalbard, the Canadian Arctic Islands, Greenland, and Baltica and comprises mainly zircons related to the Caledonian and Ellesmerian orogenic events (Trettin, Parrish, and Loveridge 1987; Watt, Kinny, and Friderichsen 2000; Corfu, Ravna, and Kullerud 2003; Johansson et al. 2004) (Table 2). In our samples, this age mode is rare in the Røedvika Formation, albeit a minor mode is recognised in the samples of the Nordkapp Formation. Even though this age mode is only minor in our samples it serves as a good indicator for source provenance. Especially ages younger than 400 Ma which are present in the samples of the Nordkapp Formation (Figure 9). Sources for zircons younger than 400 Ma are mostly found in the East Greenland Caledonides (Kalsbeek, Nutman, and Taylor 1993; Gilotti, Nutman, and Brueckner 2004). Late Devonian dolerite dykes in North Norway yield zircons younger than 400 Ma (Roberts 2011), but given the distance between the source and the sink, as well as their localised and scattered occurrences, they are disregarded as a major contributor.

ii. The age mode from 900 to 1200 Ma (latest Mesoproterozoic—earliest Neoproterozoic) is a major age mode in most samples (Figure 9). The peaks and intensities of this age mode vary across the samples. While all samples exhibit zircon ages between 1000 and 1200 Ma, the stratigraphically youngest samples B22-S91/S92 & B21-S23 additionally exhibit zircons of around 960 Ma. The overall Mesoproterozoic age mode (900–1200 Ma) can be attributed to the Grenvillian and the associated Sveconorwegian orogens (Lorenz et al. 2012; Bingen et al. 2021). The latter is restricted to the southern parts of Sweden and Norway (e.g., Bingen et al. 2021). In Greenland, Svalbard, the Canadian Arctic Islands and Baltica, zircons of this age mode may be derived from Neoproterozoic to Cambrian sedimentary successions, as well as smaller intrusions (e.g., Watt, Kinny, and Friderichsen 2000; Paulsson and Andréasson 2002; Johansson et al. 2004; Kirkland et al. 2009; Pettersson, Pease, and Frei 2009; Malone et al. 2017).

iii. The 1200–1500 Ma (Mesoproterozoic) age mode is apparent in all samples with varying peaks and intensities (Figure 9). Crystalline basement yielding these ages is lacking across the discussed source terranes, but detrital modes are found in pre-Devonian sedimentary sequences in Greenland (Figure 2) (e.g., Watt, Kinny, and Friderichsen 2000; Paulsson and Andréasson 2002). The 1380 Ma old flood basalts of the Zig-Zag Dal Basalts are missing in our sample set, despite their great extent and their proximity to Bjørnøya during the Devonian. This is not surprising as flood basalts are too silica-poor to crystallize zircons and therefore, consequently, lack zircons (Upton et al. 2005; Shumlyanskyy et al. 2016).

iv. The 1500–1700 Ma (latest Palaeoproterozoic—earliest Mesoproterozoic), age mode is present in all samples, albeit with varying peaks and intensities. Potential source areas for this age mode exist in Svalbard, Greenland and Baltica (Figure 2) (e.g., Watt, Kinny, and Friderichsen 2000; Johansson et al. 2002; Paulsson and Andréasson 2002). This mode corresponds, agewise, to the Gothian Orogen, which is most prominent in southeast Sweden (Åhäll and Gower 1997; Åhäll and Larson 2000; Roberts and Slagstad 2015). However, given the distance, this terrane is not considered here.

v. The most dominant age mode in most samples is Palaeoproterozoic zircons with ages between 1700 and 2000 Ma (Figure 9). Potential source areas are located on the Canadian Arctic Islands, Greenland and Baltica (Figure 2) (e.g., Frisch and Hunt 1988; Kalsbeek, Nutman, and Taylor 1993; Daly et al. 2001). Prominent orogenic events of this age are the Svecofennian Orogeny and the Trans-Scandinavian Intrusive Belt on Baltica, and the Ketilidian and Nagssugtoqidian orogenies in Greenland (Åhäll and Larson 2000; Lahtinen, Garde, and Melezhik 2008; Henriksen et al. 2009; Baltybaev 2013).

vi. The last prominent zircon age mode in our sample is that spanning 2400–2900 Ma (Archean—earliest Paleoproterozoic). Most samples show prominent peaks around 2500 Ma, 2700 Ma and 2900 Ma (Figure 9). Potential source areas for this age mode occur in Svalbard, Greenland and Baltica (Figure 2) (e.g., Nutman and Kalsbeek 1994; Levchenkov et al. 1995; Hellman, Gee, and Witt-Nilsson 2001). The distinct Archean peaks (i.e., those older > 2500 Ma) correspond well with the detrital zircon spectrum of metasandstones reported in Greenland (Kalsbeek et al. 1999). On north-eastern Svalbard, a quartz monzonite within a Caledonian thrust sheet yields zircon ages of c. 2700 Ma (Neoarchean) (Hellman, Gee, and Witt-Nilsson 2001).

A potential local source unit that hitherto has not been but should be considered is the Ediacaran (Neoproterozoic) Sørhamna Formation. Quartzites of this unit are variably exposed in scattered outcrops within the otherwise highly metamorphic basement on Bjørnøya. Similar-aged meta−/sandstones exposed in North Norway have yielded significant Mesoproterozoic age peaks (Roberts and Siedlecka 2012; Zhang, Roberts, and Pease 2016). However, because the quartzites of the Sørhamna Formation have not yet been studied in detail, neither for their petrography nor detrital zircon composition, they can at best be considered as a potential source with unconstrained detrital zircon ages.

The Canadian Arctic Islands, the northern Svalbard Archipelago, Greenland and Baltica all comprise terranes yielding the broad zircon age spectrum observed in our samples. The spectrum of Mesoproterozoic zircons is predominately found in meta−/sedimentary strata (e.g., Kirkland, Stephen Daly, and Whitehouse 2007; Kirkland et al. 2009; Gasser and Andresen 2013; Hadlari, Davis, and Dewing 2014). Palaeozoic, Neoproterozoic, Palaeoproterozoic and Archean zircons all have potential direct source areas (e.g., Trettin, Parrish, and Loveridge 1987; Levchenkov et al. 1995; Kalsbeek et al. 1999; Watt, Kinny, and Friderichsen 2000; Hellman, Gee, and Witt-Nilsson 2001; Johansson et al. 2002; Corfu, Ravna, and Kullerud 2003; Kirkland, Stephen Daly, and Whitehouse 2007; Nutman et al. 2008; Kirkland et al. 2009; Malone et al. 2017; Gilotti et al. 2018).

The broad zircon age spectrum that we record may thus suggest the presence of a large cratonic catchment and/or recycling of older sedimentary basin strata. As discussed above, the exposed basement of the all the terranes provides mainly Palaeozoic, Paleoproterozoic and Archean age modes while Mesoproterozoic age groups are mainly attributed to older sedimentary units. Multiple scenarios for the source of Mesoproterozoic zircons in the Billefjorden Group on Bjørnøya are therefore possible:

i. Local contributions from Mesoproterozoic basement rocks hidden beneath younger (Palaeozoic) sedimentary strata on the island itself or occurring elsewhere in the subsurface of the Stappen High (the submerged structural high on which Bjørnøya is located). We regard this scenario less likely as no Mesoproterozoic basement exposures are recorded in any of the discussed terranes.

ii. Long distance transport of Mesoproterozoic zircons from sources in the southern parts of Greenland, Norway or Sweden. This scenario also seems unlikely given the long distance and given the many fault-bounded basins and local highs any transported sediment must have bypassed on its way to Bjørnøya.

iii. From an unknown Mesoproterozoic terrane for example hidden beneath the present Greenland Ice Sheet.

iv. Recycling of older (Precambrian) sedimentary sequences exposed in the East Greenland Caledonides (e.g., Watt, Kinny, and Friderichsen 2000) and on Svalbard (e.g., Gasser and Andresen 2013; Beranek, Gee, and Fisher 2020), or less likely, in northern Norway (Roberts and Siedlecka 2012; Zhang, Roberts, and Pease 2016). In addition, a potential local source is the Sørhamna Formation, as already discussed.

Apparent differences across the samples are mostly seen in varying intensities of certain age modes. Lower intensities of the 1200–1500 Ma age mode correspond to higher intensities in the 1700–2000 Ma age mode. We argue that samples with a dominant 1700–2000 Ma age mode were mainly sourced from basement rocks in the Northeast Greenland Caledonides (Figures 4 and 12). This Palaeoproterozoic dominance could be related to a source originating from the Northeast Greenland eclogite province as shown for the locally derived Carboniferous Sortebakker Formation in the Wandel Sea Basin (McClelland et al. 2016), which was located near Bjørnøya in the Palaeozoic. Conversely, we attribute the Mesoproterozoic age signature to the recycling of Neoproterozoic-aged metasedimentary units of northern Greenland, as inferred for other Devonian basins in the Arctic (Slama et al. 2011; Anfinson, Leier, Embry, et al. 2012; Anfinson, Leier, Gaschnig, 2012; Malone et al. 2019). Additionally, the elevated Archean age modes in our samples correspond well to basement and pre-Cambrian metasedimentary units within the East Greenland Caledonides (Kalsbeek et al. 1999).

The most diagnostic for our study are age groups (i) (300–500 Ma) and (ii) (900–1200 Ma). Both age groups have few source localities across the discussed terranes (Table 2). The lack of sources yielding zircon ages younger than 400 Ma in the Basement Provinces of Svalbard, the Canadian Arctic Islands and Baltica indicates that the sediments were supplied from other source areas (also not considering the Late Devonian dolerite dykes in North Norway), at least during the deposition of the Nordkapp Formation in the earliest Mississippian. The East Greenland Caledonides, on the contrary, have proven sources for these ages (Gilotti, Nutman, and Brueckner 2004).

Rim and core ages are an additional tool to pinpoint sources which contributed to the Billefjorden Group sediments of Bjørnøya. Specifically for combinations of Caledonian (Palaeozoic; ~380 Ma) rims with Mesoproterozoic or Paleoproterozoic cores (~1300 Ma and ~1900 Ma; Figure 11), we were able to determine point sources in northeast Greenland that contributed to the Billefjorden Group on Bjørnøya. These point sources are in the Southern Liverpool Land Eclogite Terrane and the Northeast Greenland Eclogite Province (see Gilotti, Nutman, and Brueckner 2004; Corfu and Hartz 2011).

The Billefjorden Group on Bjørnøya displays slight variability in the detrital zircon spectra throughout the succession. Based on the minor changes in detrital zircon spectra across the samples and the large variability of detrital zircon ages within each sample, we argue for a continued sourcing from a cratonic source terrane. Based on the previously published palaeocurrent directions (Gjelberg 1981; Gjelberg and Steel 1981; Worsley et al. 2001; Mørk, Gjelberg, and Worsley 2014), both northern Baltica and Northeast Greenland are potential source areas for the Billefjorden Group on Bjørnøya. While the palaeocurrent data suggest a shift in drainage direction, the detrital zircon data do not indicate a change in provenance. The clear correlation of Caledonian aged detrital zircons from the Nordkapp Formation to metamorphic point sources in Northeast Greenland, thus confirms sediment sourcing from the northeast Greenland Caledonides (Figure 12). Further evidence for a Northeast Greenlandic source is the geographic proximity to Bjørnøya during the Late Devonian and early Carboniferous (Domeier and Torsvik 2014; Golonka 2020; Blakey 2021).

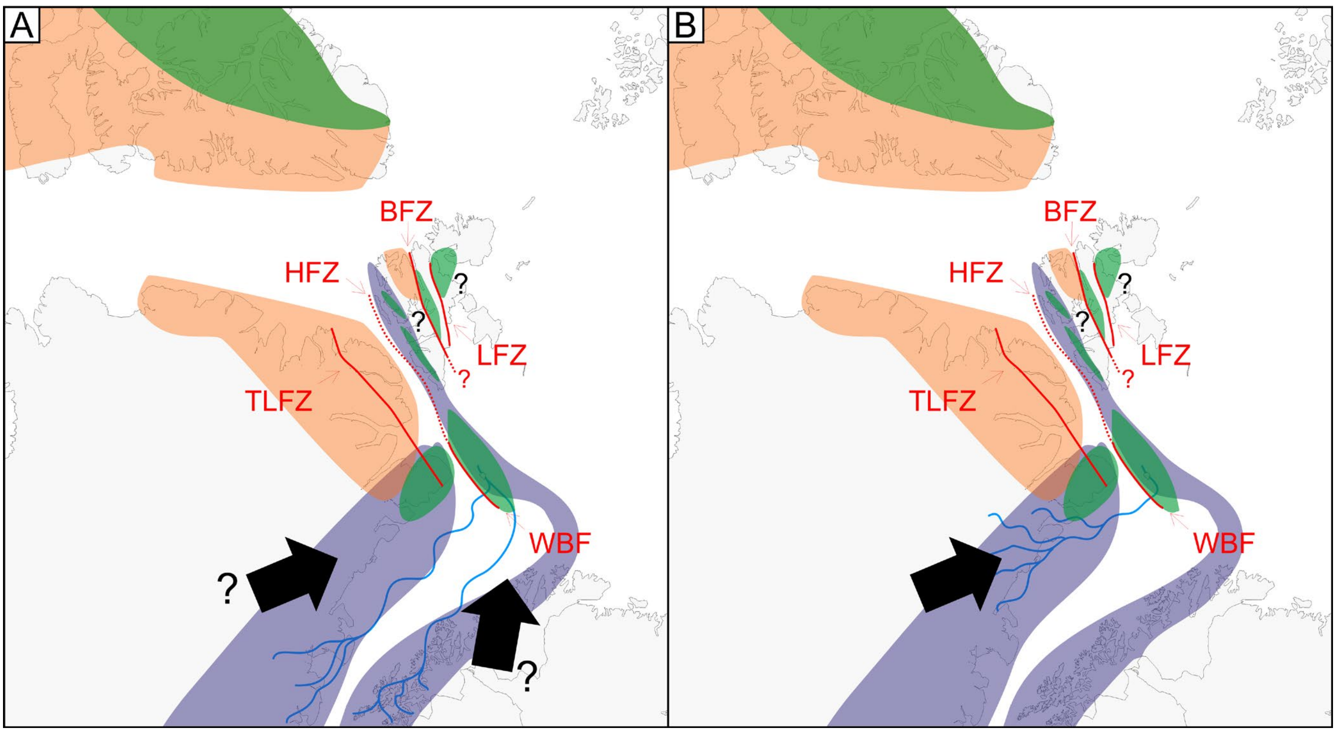

FIGURE 12 | Palaeogeographic maps of the Arctic showing the modern-day coastlines of Svalbard, Bjørnøya, northern Greenland, Ellesmere Island, and north-eastern Scandinavia (Baltica). (A) Potential source areas for the inferred axial meandering streams of the Vesalstranda and Tunheim members. (B) Source area in northeast Greenland for the inferred transverse braided streams of the Nordkapp Formation. The palaeogeographic reconstruction is based on Domeier and Torsvik (2014) and Blakey (2021). Blue highlights a potential fluvial network connecting the source area in northeast Greenland to Bjørnøya. The black arrow indicates the main direction of sediment transport. Orange: Old Red Sandstone Basins; Green: Carboniferous Troughs; Purple: Outline of the Caledonides. BFZ, Billefjorden Fault Zone; HFZ, Hornsund Fault Zone; LFZ, Lomfjorden Fault Zone; TLFZ, Trolle Land Fault Zone; WBF, West Bjørnøya Fault.

5.4 | Arctic Devonian and Carboniferous Basins

Several 'Old Red Sandstone' continental basins developed across the Arctic during the Devonian (Friend and Williams 2000). Here, we compare our sample set to adjacent basins located in Greenland, Spitsbergen and the Canadian Arctic Islands (Figure 13).

Only one sample of the Billefjorden Group on Spitsbergen has previously been analysed for its detrital zircon provenance (Figure 13) (Gasser and Andresen 2013). Intriguingly, the authors found that the sediments were most likely sourced from northern Greenland, recording the same major zircon age modes as in our data set. However, some major differences are evident in our sample set. Both the pronounced Archean ages around 2.7 Ga and major contributions of Paleoproterozoic ages between 1.7 and 2.0 Ga are not as distinct in sample S6-73-582 of Gasser and Andresen (2013) collected in the St. Jonsfjorden Trough on Spitsbergen (Figure 13). Detrital zircon provenance studies of the Devonian 'Old Red Sandstone' basins on Svalbard, on the contrary, show that the sediments, predominately, were derived from local sources (Beranek, Gee, and Fisher 2020; Anfinson et al. 2022).

Analysed samples derived from the Devonian to Carboniferous basins of East and Northeast Greenland, as well as from the Franklinian Basin on Ellesmere Island, show very similar detrital zircon age spectres as reported here (Figure 13). The Northeast Greenland Caledonides have previously been inferred as the main source for the sedimentary strata in these basins (Slama et al. 2011; Anfinson, Leier, Embry, et al. 2012; Anfinson, Leier, Gaschnig, 2012; Hadlari, Davis, and Dewing 2014; Malone et al. 2019). More specifically, the Northeast Greenland eclogite province, which yields distinct 1750 Ma and 1900–2000 Ma peaks, acted as a local source for the early Carboniferous strata of the Wandel Sea Basin in Northeast Greenland (McClelland et al. 2016). Interestingly, this basin fill strata is very similar to the Nordkapp Formation in terms of its Viséan age and sandstone-dominated alluvial facies (Dalhoff and Stemmerik 2000). Here, we demonstrate that the broad detrital zircon age spectrum of the Nordkapp Formation contains similar age peaks similar to those of the Carboniferous strata in the Wandel Sea Basin (Figure 9) (McClelland et al. 2016).

As such, we postulate that the East Greenland Caledonides, including old basement rocks in the orogenic wedge, as well as its underlying, exposed basement, formed a long-lived source area. Literary being the same for Triassic strata on western Spitsbergen, as well as for Cretaceous strata in the Wandel Sea Basin and Spitsbergen (Figure 12) (Røhr, Andersen, and Dypvik 2008; Pózer Bue and Andresen 2013; Grundvåg et al. 2019). This points to a regionally important source area, which has contributed to the infill of several Arctic basins throughout the Palaeozoic and Mesozoic.

5.5 | Palaeogeography

Palaeogeographical reconstructions show that Svalbard, including Bjørnøya, was situated at the north-eastern corner of Greenland during the Late Devonian and early Carboniferous (Domeier and Torsvik 2014; Golonka 2020; Blakey 2021) (Figure 12). More specifically, some reconstructions place Spitsbergen near Peary

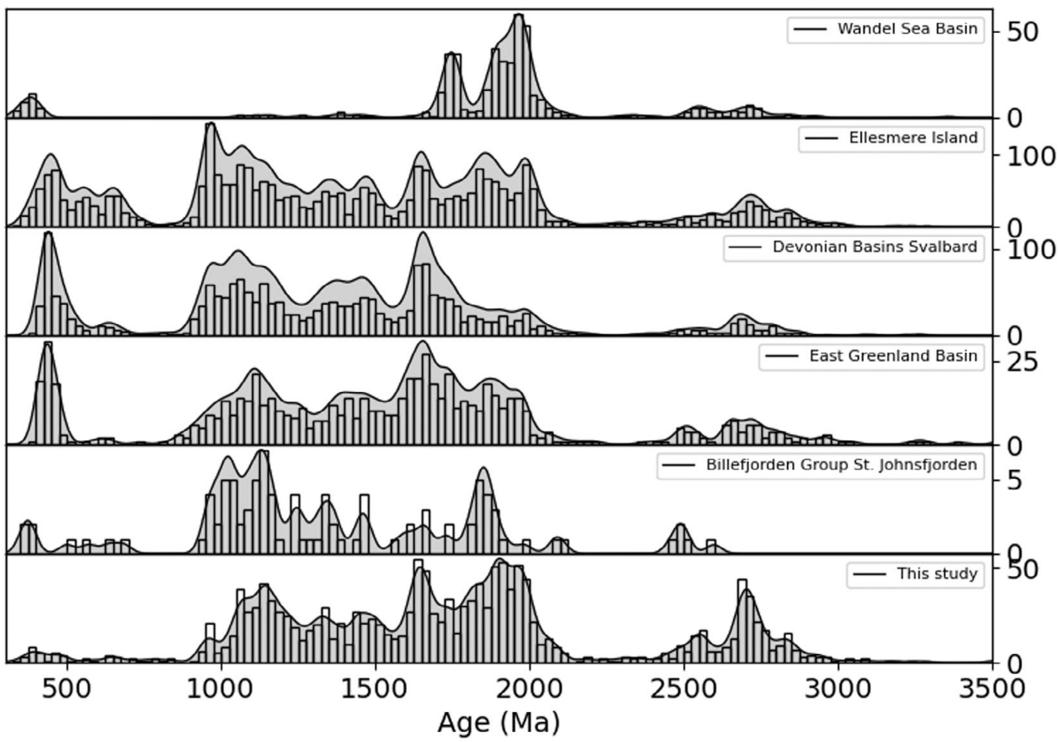

FIGURE 13 | KDE plots of selected Devonian and Carboniferous basins in the Arctic, including basins located on Svalbard (Pettersson, Pease, and Frei 2010; Gasser and Andresen 2013; Beranek, Gee, and Fisher 2020; Anfinson et al. 2022), Greenland (Slama et al. 2011; McClelland et al. 2016), and Ellesmere Island, Canada (Anfinson, Leier, Embry, et al. 2012; Anfinson, Leier, Gaschnig, 2012; Hadlari, Davis, and Dewing 2014; Malone et al. 2019).

Land at the very northern tip of Greenland during the early Carboniferous, consequently placing Bjørnøya further south near the north-eastern tip of Kron Prins Christian Land and the southern reaches of the Wandel Sea Basin (Harland 1997; Dalhoff and Stemmerik 2000; Brekke et al. 2001). The close resemblance of our detrital zircon age modes to those reported from the East Greenland Caledonides and the Northeast Greenland eclogite province, indicate a palaeogeographical proximity to these terrains, thus supporting these reconstructions (Figure 12).

Our data show that the detrital zircon age spectrum of the sediments that accumulated on Bjørnøya during the Late Devonian to early Carboniferous principally remained the same irrespective of the changes in fluvial style and drainage direction, or the inferred fault activity along the West Bjørnøya Fault. Possible scenarios are:

1. The fault activity was the main cause for the observed changes in drainage direction in the fluvial system supplying sediments to the basin as suggested by previous work (Gjelberg 1978, 1981; Gjelberg and Steel 1983); however, the activity was not of such extent that it changed the catchment area for the fluvial drainage systems. This may also indicate an exceptionally large, lithologically uniform (with respect to zircon-hosting rocks) and long-lived catchment, which despite faulting did not change or segment into smaller subcatchments of variable bedrock lithologies.
2. The observed changes in fluvial style and drainage direction have not been caused by the inferred West Bjørnøya Fault but reflect climatically driven changes in sediment supply combined with intrinsic factors which have caused random changes. However, given the systematic and coinciding changes, compatible with tectonic forcing, in combination with the regional tectonic framework, we find this less likely and favour the former scenario.

This contribution cannot answer to what extent the East Greenland Caledonides also controlled deposition of the Billefjorden Group and associated Palaeozoic strata elsewhere on Svalbard during the Late Devonian to early Carboniferous. Did the principal source area remain the same for the entire region throughout the period, contributing with sediments way into the Mesozoic? Or did onset of localised rifting in the middle Carboniferous intervene and eventually forcing a provenance change which affected the overlying syn-rift deposits of the Gipsdalen Group? Further investigations are clearly required to unravel the full extent and importance of the East Greenland Caledonides as a source terrain for sedimentary strata on the Barents Shelf and Svalbard, as well as to fully distinguish this provenance signal from other sources and understand the implications of being located at the border of a substantial, long-lived sedimentary source.

6 | Conclusion

This case study is the first attempt to show detrital zircon provenance of the Billefjorden Group along the western Barents Shelf margin focusing on exposed strata on Bjørnøya, the southernmost island of the Svalbard archipelago and the exposed crest of the Stappen High. Our most significant conclusions are summarised below:

- Broad detrital zircon age spectra indicate sourcing from a cratonic source terrane
- The data set reveals a series of distinct age modes spanning the Archean (oldest zircon ages of c. 2.9 Ga) to the Palaeozoic (zircons younger than < 500 Ma).
- Mesoproterozoic ages are most likely sourced from metasedimentary units exposed in Northeast Greenland, locally on Bjørnøya, or less likely in North Norway.
- Direct correlation of Caledonian metamorphic detrital zircons to the Northeastern Greenland eclogite province
- The proposed West Bjørnøya Fault has seemingly had little influence on the detrital zircon age distribution, albeit it appears to have controlled the drainage direction and depositional styles of the fluvial systems in the basin. This is evident by the stratigraphically repeated changes in palaeocurrent directions and the concurrent alternation of meandering and braided fluvial strata.
- Strong similarities to provenance data from Mesozoic strata in the Canadian Arctic Islands, Northeast Greenland, and Spitsbergen suggests that the Caledonian terranes of Northeast Greenland acted as a long-lived catchment providing sediments to adjacent Arctic basins onwards from the Devonian through the Mesozoic.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

All data presented in this contribution are available in the Supporting Information. In addition, we have uploaded them to the geochronology repository geochron.org.

Peer Review

The peer review history for this article is available at https://www.webofscience.com/api/gateway/wos/peer-review/10.1111/bre.70009.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.