

Article

Establishing a Provenance Framework for Sandstones in the Greenland–Norway Rift from the Composition of Moraine/Outwash Sediments

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Abstract: The crystalline basement and Caledonian orogenic belt of East Greenland between 70 and 78° N are divided into five source regions on the basis of heavy mineral assemblages, mineral geochemistry, and isotopic age data from 42 modern moraine/outwash samples. The sand types generated by the five source regions can be recognized in the Mesozoic sedimentary rocks of Mid-Norway, and are named, from south to north, MN7 (Gåseland), MN4i (Milne Land–Renland), MN2ii (Hinks Land–Suess Land), MN2iii (Payer Land–Dronning Louise Land), and MN6 (Germania Land). These provide a framework for interpreting the provenance of Greenland–Norway rift sedimentary deposits. The provenance characteristics of Liverpool Land have also been defined, but whether this relatively small region merits a separate provenance status is unclear. Provenance links can be made by comparing the source region sand types with the composition of onshore and offshore sediments from previous studies. Triassic sandstones of the Nordland Ridge and the far south of the Møre Basin, along with Jurassic sandstones of the Heidrun Field in the Haltenbanken area, were derived from the MN4i source region. The provenance of Cretaceous sandstones in East Greenland can be linked to the MN2ii source region. The source of Turonian sandstones on Traill Ø can be pinpointed by zircon U–Pb ages to the Neoproterozoic Lyell Land Group of the Franz Josef Allochthon. Cretaceous sandstones in the Vøring and Møre basins were derived from the MN2iii and MN4i source regions. In addition, some of the Cenomanian–Campanian sedimentary rocks of East Greenland and Mid-Norway contain Permian–Cretaceous-aged zircon grains that are absent from the moraine/outwash samples. The most likely source of these zircon grains is the circum-Arctic region, implying the existence of a long-lived axial drainage system that entered the Greenland–Norway rift from the north.

Keywords: provenance; heavy minerals; East Greenland



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1. Introduction

The crystalline basement and Caledonian rocks of East Greenland were the primary sediment sources for the adjacent Mesozoic rift basins of East Greenland, from Jameson Land in the south to Store Koldewey in the north (Figure 1). Previous provenance studies have shown that much of this sediment was transported offshore, where it contributed to the Vøring and Møre basins of the Mid-Norway hydrocarbon province [1–7]. These studies focused on Mesozoic detrital samples from onshore East Greenland and offshore Mid-Norway. However, the provenance characteristics of the basement source regions—a primary control on reservoir quality in Mid-Norway—have hitherto not been constrained.

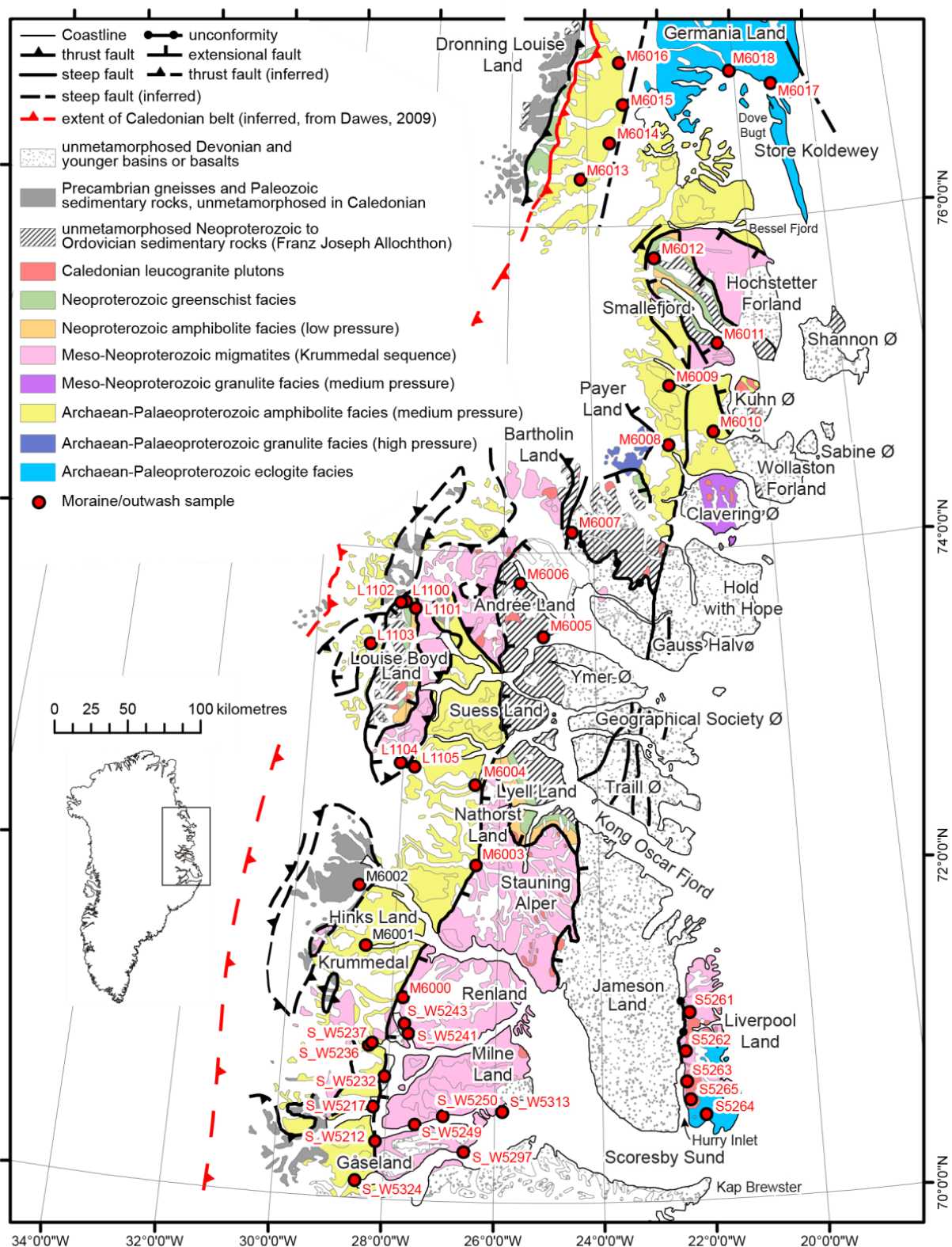


Figure 1. Regional metamorphic facies showing the peak metamorphic conditions [8] for the East Greenland Caledonides between 70 and 77° N, and the position of moraine/outwash samples examined in this study.

To provide a framework for the interpretation of provenance data from this region, modern moraine/outwash samples derived from glaciated catchments within the East Greenland basement were collected between 70 and 78° N (Table 1). Conventional (petro-

graphic) heavy mineral analysis and provenance-sensitive ratio determinations provided the basic analytical framework. Mineral chemical analysis was undertaken on amphibole, garnet, and rutile populations in a subset of the samples. Single-grain dating of zircon and amphibole populations was also carried out on selected samples. Combining these data helps to minimise the effects of regional mineral fertility variations during unroofing. The results were used to define five sand types that are associated with discrete source regions according to the spatial distribution of the samples. From south to north, these source regions are MN7 (Gåseland), MN4i (Milne Land–Renland), MN2ii (Hinks Land–Suess Land), MN2iii (Payer Land–Dronning Louise Land), and MN6 (Germania Land).

Table 1. Moraine/outwash sample list, with analytical techniques and sand type assignments. HM: heavy mineral analysis.

Sample	Lat.	Long.	HM	Gnt	Ru.	Amph.	Zr. U-Pb	Amph. Ar-Ar	Sand Type
M6018	76.9183	−20.1099	✓	✓		✓	✓	✓	MN6
M6017	76.8175	−19.0203	✓	✓					MN6
M6016	77.0029	−23.0862	✓	✓		✓	✓	✓	MN2iii
M6015	76.7440	−23.0189	✓						MN2iii
M6014	76.5101	−23.3978	✓				✓	✓	MN2iii
M6013	76.2923	−24.1747	✓	✓	✓	✓			MN2iii
M6012	75.7961	−22.3706	✓	✓		✓	✓	✓	MN2iii
M6011	75.2545	−20.9285	✓	✓		✓	✓	✓	MN2iii
M6009	75.0067	−22.1433	✓	✓					MN2iii
M6010	74.7124	−21.1639	✓						MN2iii
M6008	74.6458	−22.2178	✓						MN2iii
M6007	74.1225	−24.4744	✓	✓	✓	✓	✓		MN2ii
M6006	73.8077	−25.6163	✓	✓	✓	✓	✓	✓	MN2ii
M6005	73.4791	−25.1131	✓						MN2ii
L1100	73.6773	−28.1068	✓						MN2ii
L1102	73.6688	−28.2207	✓	✓		✓	✓	✓	MN2ii
L1101	73.6385	−27.8874	✓	✓	✓				MN2ii
L1103	73.4079	−28.8197	✓	✓					MN2ii
L1104	72.6852	−28.0488	✓		✓				MN2ii
L1105	72.6637	−27.7568	✓	✓		✓	✓	✓	MN2ii
M6004	72.5647	−26.4984	✓	✓					MN2ii
M6003	72.0691	−26.4412	✓	✓					MN2ii
M6002	71.9200	−28.7397	✓	✓		✓	✓	✓	MN2ii
M6001	71.5519	−28.5470	✓	✓					MN2ii
M6000	71.2446	−27.7829	✓	✓	✓	✓	✓	✓	MN4i
S_W5243	71.0840	−27.7303	✓	✓					MN4i
S_W5241	71.0226	−27.6507	✓	✓	✓		✓	✓	MN4i
S_W5237	70.9578	−28.3164	✓						MN4i
S_W5236	70.9396	−28.3787	✓	✓		✓			MN4i
S_W5232	70.7528	−28.0553	✓	✓	✓	✓			MN4i
S_W5217	70.5638	−28.2401	✓	✓					MN4i
S_W5249	70.4635	−27.4603	✓						MN4i
S_W5250	70.5239	−26.9465	✓	✓	✓	✓	✓	✓	MN4i
S_W5313	70.5581	−25.8609	✓	✓					MN4i
S_W5297	70.3036	−26.5550	✓	✓					MN4i
S_W5212	70.3508	−28.1637	✓	✓	✓	✓	✓	✓	MN7
S_W5324	70.1058	−28.4989	✓	✓	✓	✓			MN7
S5261	71.1542	−22.3197	✓	✓					?
S5262	70.9165	−22.4234	✓	✓	✓	✓	✓		?
S5263	70.7301	−22.4259	✓	✓					?
S5265	70.6194	−22.3670	✓	✓					?
S5264	70.5225	−22.0889	✓	✓	✓	✓	✓		?

2. Geological Background

The basement rocks forming the East Greenland margin consist of Archaean and early Proterozoic crystalline rocks together with Mesoproterozoic to Palaeozoic metasedimentary rocks of the Caledonian fold belt [9]. Isotopic studies of crystalline basement in thrust sheets and autochthonous windows indicate that Archaean rocks (c. 2700–2800 Ma) occur in the southern part of the area under discussion [10,11]. The Archaean basement shows evidence of variable metamorphic reworking during the Palaeoproterozoic. North of 72°50' N, the basement rocks are dated as c. 1900–2000 Ma, and belong to a Palaeoproterozoic block that extends as far north as 81° N [10].

The Krummedal and equivalent Smallefjord supracrustal sequences overlie the crystalline basement. These metasedimentary rocks are of Mesoproterozoic age, and were affected by early Neoproterozoic high-grade metamorphism at c. 900–950 Ma [12–14]. Subsequent high-grade metamorphism, crustal anatexis, and the formation of widespread leucogranites took place at c. 425–430 Ma [13,15,16].

The highest of the Caledonian allochthons comprises the Eleonore Bay Supergroup, which consists of unmetamorphosed to amphibolite-facies sediments of Neoproterozoic (c. 800–540 Ma) age [17–19]. The Eleonore Bay Supergroup comprises the Nathorst Land Group at the base, overlain by the Lyell Land Group and the Andree Land and Ymer Ø groups at the top.

The basement rocks exposed in the central and northern parts of Liverpool Land include metasedimentary rocks ascribed to the Krummedal sequence, spatially associated with granites, whereas the southern part of the area (south of the Gubbedalen Shear Zone) consists of the Liverpool Land Eclogite Terrane [20]. The Liverpool Land Eclogite Terrane consists of orthogneisses formed at 1640–1645 Ma, with eclogite-facies metamorphism at 400 Ma and subsequent migmatisation and granite intrusion at 385–388 Ma. These features are unlike any other part of East Greenland, but compare closely with the characteristics associated with the Western Gneiss Region of Norway. It has therefore been suggested that the Liverpool Land Eclogite Terrane is exotic with respect to Laurentia, and that a Baltican origin is more likely [20,21].

The sub-ice geology west of the field area has been inferred to comprise Palaeoproterozoic–Silurian units [22]. These rocks have likely been subjected to erosion beneath the ice sheet, particularly during deglacial phases [23]. It is likely that some of this sub-ice material has fed into the glaciers at the edge of the ice sheet. Provenance data from the moraine/outwash samples are therefore likely to provide insights into the sub-ice geology.

3. Materials and Methods

Moraine/outwash sample locations were chosen specifically to avoid drainage from post-Caledonide basins, and to sample a wide range of crystalline basement and supracrustal rocks, the latter ranging from weakly or unmetamorphosed to high-grade metamorphic.

Heavy mineral analysis and provenance-sensitive ratio determination were undertaken on all samples, with additional geochemical characterisation and radiometric dating on a variety of mineral populations from a subset. Garnet and amphibole geochemical data were acquired via electron microprobe analysis at the University of Aberdeen, UK, with rutile geochemistry carried out via laser ablation inductively coupled plasma mass spectrometry at the School of Earth, Ocean, and Planetary Sciences, Cardiff University, Aberdeen, UK. U–Pb geochronology of zircons by laser ablation multicollector inductively coupled plasma mass spectrometry (LA-MC-ICP-MS) was conducted at the LaserChron Center, University of Arizona, USA. Amphibole $^{40}\text{Ar}/^{39}\text{Ar}$ (Ar–Ar) geochronology was undertaken at the Lamont–Doherty Earth Observatory, Columbia University, Tucson, AZ, USA. Kernel density estimation (KDE) plots of the U–Pb and Ar–Ar data were generated using IsoplotR [24]. Detailed descriptions of all analytical methods, data tables, and additional plots are provided in the Supplementary Materials (Tables S1–S6).

4. Results

4.1. Conventional Heavy Mineral Data

A total of 21 non-opaque heavy minerals were identified, most of which are unstable during weathering and burial diagenesis. The most common phases were amphibole (mean abundance ~35%), garnet (~27%), and epidote (~12%), with common clinopyroxene (~8%), titanite (~3%), and kyanite (~2%). Rutile, tourmaline, and zircon were the only other minerals present, with mean abundances > 1%. The morphologies of the heavy mineral grains ranged from sub-angular to sub-rounded. The ultrastable mineral index (ZTR of [25]) was 3.3, testifying to the abundance of unstable minerals in the assemblages.

The samples from Liverpool Land all had amphibole- and pyroxene-rich assemblages, with subordinate garnet (Figure 2). Abundant titanite was most likely sourced from the early Palaeozoic granitoids on Liverpool Land [20].

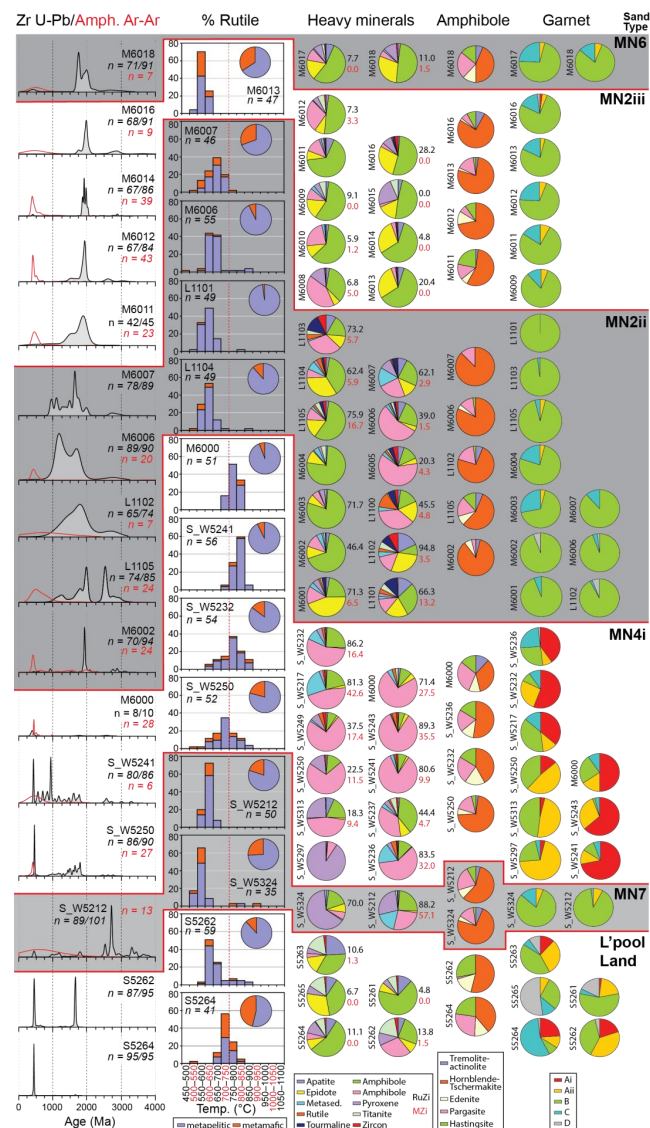


Figure 2. (overleaf) Heavy minerals, mineral chemistry, and isotopic age results. Zircon U–Pb and amphibole Ar–Ar ages are presented as KDE spectra. Note that only the 90% concordant zircon U–Pb ages are plotted, meaning that discordant Archaean–Palaeoproterozoic ages are underrepresented. The relative abundance of metapelitic and metamafic rutile (differentiated following [26]) is shown as bar and pie charts. The red line marks the division between amphibolite/eclogite and granulite-facies temperature conditions (determined following [27]). The heavy mineral components, amphibole assemblage, and garnet assemblage results are presented as pie charts.

In the Milne Land region there are garnet-dominated heavy mineral assemblages, some of which also have high abundances of metasedimentary minerals such as kyanite and staurolite. These assemblages were likely derived from the large region of migmatites in Milne Land and Renland. Clinopyroxene abundances are at their highest in the south, due to input from the Palaeocene–Eocene flood basalt succession.

Moving north into Hinks Land and Suess Land, the assemblages are dominated by amphibole and epidote, and correspond with a region dominated by amphibolite-facies metasedimentary rocks. The Andrée Land and Louise Boyd Land areas have complex assemblages with garnet, epidote, amphibole, pyroxene, tourmaline, and rutile all present in abundance. The increased garnet probably reflects the presence of migmatites in the region.

Two samples from the unmetamorphosed to weakly metamorphosed Neoproterozoic–Ordovician sedimentary rocks in the Franz Joseph Allochthon (samples M6005 and M6006) were garnet-dominated. This was interpreted as reflecting the detrital components of the source rocks, rather than mineral growth during metamorphism.

Sample M6007, which was taken from moraine associated with the Franz Joseph Glacier, has a complex assemblage that reflects the wide range of lithologies sampled by this glacier. Sample M6008, which originated from close to Payer Land, has a garnet-dominated assemblage, consistent with the widespread occurrence of migmatites in the area.

North of Wollaston Foreland, assemblages return to being amphibole- and epidote-rich, with subordinate garnet, coincident with the occurrence of lower grade (amphibolite-facies) metasedimentary rocks in the basement. The same type of assemblage occurs in Dronning Louise Land, where they are again associated with amphibolite-facies metasedimentary rocks. The two samples from the eclogite-facies terrane of Germania Land have heavy mineral suites that are indistinguishable from those of Dronning Louise Land and other amphibolite-facies belts.

4.2. Heavy Mineral Ratios

Provenance-sensitive heavy mineral ratios are not significantly influenced by differences in diagenetic modification or depositional environment, because they compare minerals that are both stable and hydrodynamically equivalent [28]. Suitable ratios are apatite:tourmaline (ATi), garnet:zircon (GZi), rutile:zircon (RuZi), monazite:zircon (MZi), and chrome spinel:zircon (CZi). These ratios have been used to characterise sediment types in East Greenland and Mid-Norway [3,4,7].

Of these ratios, ATi (mostly 60–100) and GZi (76–100) are consistently high across the study area (Table 1), and offer no obvious means to discriminate different basement regions. The only exception is that ATi values are distinctly lower (28–49) in two samples (L1102 and L1103) from the Andrée Land and Louise Boyd Land areas, reflecting an abundance of tourmaline. CZi values are uniformly low and, therefore, do not discriminate provenance. By contrast, the RuZi value shows marked regional variations (Figure 2).

RuZi values define two distinct regions—one from Hold with Hope southwards, and the other from Clavering Ø northwards. The bounding line defines the difference between the MN2iii source region to the north and the MN2ii/MN4i source regions to the south. This change essentially reflects the distribution of rutile-bearing lithologies (metapelites and metamafic rocks), which are evidently more widespread in the south. This reflects, at least in part, differences in the relative abundance of metasedimentary and crystalline basement rocks across the area. Liverpool Land appears to have consistently low RuZi, and is more akin to the MN2iii source region on this basis.

MZi values also show marked variations. In this case, high values are found in the south, in the area around Milne Land–Renland, and become much lower to the north. The high MZi values are associated with high-Ca, low-Mg garnet (type A as described by [29]), and granulite-facies rutile (see below), and appear to be a characteristic feature of the MN4i source region.

4.3. Mineral Geochemistry

4.3.1. Amphibole

Amphibole assemblages have been characterised in terms of the relative abundances of tremolite–actinolite, hornblende–tschermakite, edenite, pargasite, and hastingsite (Figure 2). The most common component is hornblende–tschermakite. Pargasite and hastingsite are the two other main components, with tremolite–actinolite and edenite being less common. There are distinct regional variations in the amphibole populations, with hornblende–tschermakite abundances at their lowest in the Milne Land–Renland area, Liverpool Land, and Germania Land, associated with increases in the abundance of pargasite and hastingsite.

4.3.2. Garnet

There are major regional variations in the composition of the garnet assemblages (Figure 2). The populations have been characterised in terms of the relative abundances of garnet types Ai, Aii, B, C and D [29–31]. Of particular note is the presence of garnet assemblages dominated by the Ai component in Renland and adjacent areas, since this feature is the defining characteristic of the MN4i sand type. Outside of this region, garnet assemblages are mostly dominated by the type B component, with variable amounts of type C (the latter reflecting input from high-grade metamafic rocks, including eclogites). However, two samples from Milne Land are distinctive in having assemblages dominated by the Aii component, and these are also common in some Liverpool Land samples. Type C garnet grains are especially common in one Germania Land sample and in the southern part of Liverpool Land, both being areas where eclogites are known to occur [8,20]. Liverpool Land is also distinctive in supplying type D (andradite–grossular) garnets, probably derived from the early Palaeozoic granites that are also inferred to supply the common titanite in this area.

4.3.3. Rutile

Rutile geochemistry provides further evidence for regional variations in source area lithology and metamorphic grade (Figure 2). The basement rocks over most of the area supply amphibolite-facies rutile, with rutile sourced from metapelitic rocks dominant over those provided by metamafic rocks. However, there are notable exceptions, particularly in the Milne Land–Renland area, where granulite-facies rutile is especially abundant. There is a direct correlation between the abundance of type Ai garnet and the abundance of granulite-facies rutile, confirming that type Ai garnet is supplied mainly from granulite-facies metasedimentary rocks. Another distinctive feature is the abundance of metamafic rutile with amphibolite/eclogite-facies temperatures in southern Liverpool Land, representing supply from the Liverpool Land Eclogite Terrane [20], as also indicated by the abundance of type C garnet. Rutile in the Dronning Louise Land sample (M6013) is also distinctive in having high relative abundances of metamafic types.

4.4. Single-Grain Dating

4.4.1. Zircon U–Pb

Zircon U–Pb age data were acquired from 14 samples, most of which yielded concordant or near-concordant (discordance < 10%) analyses. However, some samples contained relatively large numbers of grains with >10% discordance, with Caledonian-age (c. 450–500 Ma) discordia lower intercepts. These discordant ages were interpreted as being the result of lasing unseen Caledonian zircon rim overgrowths during downhole ablation. In addition, the Archaean zircon ages in some samples displayed Pb-loss discordia to the origin. Wetherill concordia diagrams are provided in the Supplementary Materials.

The zircon U–Pb age data reveal marked variations across East Greenland (Figure 2). The Liverpool Land samples are dominated by early Palaeozoic zircons, peaking at c. 430–440 Ma. This corresponds with ages from the Hurry Inlet Plutonic Terrane (c. 425–445 Ma, [20]). The c. 1600–1650 Ma zircons in sample S5262 are closely comparable to the main peak found in

the Krummedal sequence to the east [13]. Despite an eclogite signal from the garnet and rutile geochemistry data, sample S5264 shows little evidence for zircon provenance from the Liverpool Land Eclogite Terrane, which is therefore interpreted to be zircon-poor.

Sample S_W5212, from Gåseland, has a dominantly Archaean age spectrum, with a peak at c. 2700 Ma. This is consistent with the c. 2700–2800 Ma ages of the basement rocks of the area [11]. There is also a distinct peak at c. 2550 Ma. The most distinctive feature of the Archaean population, however, is the abundance of pre-3000 Ma grains, which comprise 19 of the 65 grains with concordant Archaean ages. The pre-3000 Ma grains form a peak at c. 3250–3350 Ma, and extend as far back as c. 3770 Ma. The zircon data therefore indicate that the basement rocks in the southernmost part of the study area have a prolonged pre-Neoproterozoic history, similar to the area further south around Kangerlussuaq [32].

Immediately to the north, in Milne Land, samples S_W5241 and S_W5250 have prominent early Palaeozoic peaks. These zircon grains were probably derived from the widespread migmatites of this age in the region [8,13]. Sample S_W5241 shows a distinct peak at c. 900–950 Ma, corresponding to the age of Neoproterozoic granites in the Stauning Alper region [13].

North of Renland, there is a common prominent age peak of c. 1900–2000 Ma, with variable proportions of Archaean ages. Most of the zircon grains were derived from the crystalline basement, which north of 72°50' N formed at c. 1900–2000 Ma, with variable reworking of Archaean crust [11,33,34]. Data from metasedimentary rocks such as the Mesoproterozoic–Neoproterozoic Krummedal sequence and Stauning Alper Migmatite Zone [13], the Neoproterozoic Smallefjord sequence [12], the Neoarchaeo–Mesoproterozoic Nathorst Land Group [13,15], and the Neoproterozoic Lyell Land Group [5] indicate that zircon dated at 1900–2000 Ma is scarce in the thrust sheets overlying the crystalline basement (Figure 3).

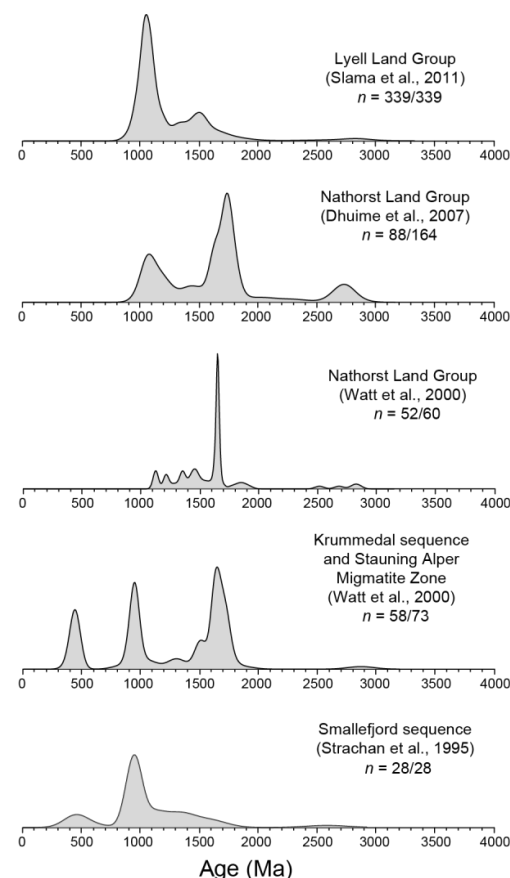


Figure 3. Kernel density estimation (KDE) plots of published zircon U–Pb ages from metasedimentary rocks in the Caledonides of East Greenland.

The abundance of younger Proterozoic ages (c. 1000–1900 Ma) is more variable. A diverse spectrum of Proterozoic ages coupled with a scarcity of > 1900 Ma ages (e.g., sample L1102) is consistent with the metasedimentary rocks of the Nathorst Land Group [15] (Figure 3). A peak at c. 950 Ma in samples M6006 and M6007 may reflect metasedimentary rocks affected by early Neoproterozoic crustal anatexis, similar to that recognised in the Krummedal sequence and Stauning Alper Migmatite Zone [13], and in the Smallefjord sequence [12]. The samples are located some distance from these regions, suggesting that crustal anatexis was relatively widespread. Sample M6006 has a uniquely prominent age peak of c. 1100 Ma and an age spectrum that is strikingly similar to that of the Lyell Land Group [5]. In the far north of the field area, sample M6018 contains a large Palaeoproterozoic age peak of c. 1700–1800 Ma, which matches ages from the local crystalline basement [33,34].

The zircon U–Pb age data support previous evidence for a significant change in provenance between the metasedimentary rocks of the Nathorst Land Group and those of the Lyell Land Group [5], with the Lyell Land Group apparently containing detritus that is exotic to East Greenland. Late Mesoproterozoic crustal growth has not been documented in this part of East Greenland [11], but is extensive in the Grenville Province of Laurentia [35,36] and on the western margin of Baltica [37]. Input from either of these areas is likely to have been responsible for the detritus comprising the Lyell Land Group.

4.4.2. Amphibole Ar–Ar

The vast majority of the 274 amphiboles analysed fall in the 380–600 Ma age range, with a single main peak at c. 410 Ma and little variation between samples (Figure 2). Compared to the zircon data, the younger and less variable amphibole ages reflect resetting during the Caledonian orogeny due to a lower resetting temperature (500 °C; [38]). This means that the amphibole Ar–Ar ages are less useful for provenance interpretations. Sample S_W5250 contains a significant number of amphiboles younger than 380 Ma, including a small number of Cenozoic age. The Cenozoic amphiboles are interpreted as having formed during the magmatic phase associated with the opening of the Northeast Atlantic, which also partially reset some of the older ages. It is not clear why the younger amphiboles are restricted to this sample.

5. Discussion

5.1. Sediment Source Regions

The combination of heavy mineral composition, mineral geochemistry, and isotopic age data permits five sand types with key provenance characteristics to be distinguished (Table 2). The same sand types can be recognised in the sedimentary rocks forming the Vøring and Møre Basin fill successions offshore of Mid-Norway, which are therefore named MN2ii, MN2iii, MN4i, MN6, and MN7. This renames, refines, and subdivides the previously defined sand types based on samples from Mid-Norway [3,4,7,39]. The other sand types found in the Vøring and Møre Basins (MN1, MN3, and MN5) were derived from areas of the conjugate Norwegian margin to the east [4]. Sand type MN2 [4] has similar characteristics to MN2iii, but is distinguished by the presence of Permian–Triassic and mid-Cretaceous zircons. The distribution of these sand types throughout the moraine/outwash samples reveals five source regions (Figure 4). These source regions include a mix of glacial environments that will generate sediment at variable rates both within and between individual drainage basins. Assessing the impact of this complexity on provenance was beyond the scope of the present study.

Table 2. The key distinguishing features of the identified sand types in the East Greenland moraine/outwash samples. Some zircon age ranges are not always present (indicated by $\pm$ in the table).

Sand Type	HM	RuZi	Garnet	Rutile Source	Rutile Grade	Zircon Ages (Ma)
MN2ii	Amphibole Epidote garnet	>40	B	metapelitic	amphibolite/eclogite	$\pm$ 2500–3000 1900–2000 900–2000 c. 1100
MN2iii	Amphibole epidote	<40	B	metapelitic	amphibolite/eclogite	$\pm$ 2500–3000 1900–2000 2500–3000
MN4i	garnet	>40	A	metapelitic	granulite	1800–2500 900–1800 400–500
MN6	Amphibole epidote	<40	C	metamafic	amphibolite/eclogite	1900–2000 $\pm$ 1700–1800
MN7	Amphibolite Epidote Garnet clinopyroxene	<40	B	–	–	>2500
Liverpool Land	Amphibolite Epidote Titanite $\pm$ garnet	<40	B C D	metapelitic metamafic	amphibolite/eclogite	1600–1700 400–500

5.1.1. MN7

This is a newly defined source region, based solely on the moraine/outwash data discussed herein. In the southernmost part of the study area, two samples (S_W5212 and S_W5324) contain garnet assemblages dominated by type B garnet, unlike the MN4i source region immediately to the north. Both samples are also dominated by amphibolite-facies rutile, in contrast to the MN4i region, and have comparatively high RuZi. These data therefore indicate the existence of a region with similar mineralogical characteristics to the MN2ii region further north. However, the zircon population in sample S_W5212 is dominated by Archaean ages, including abundant pre-3000 Ma grains. This is comparable to zircon assemblages in Cretaceous–Eocene sandstones from Kangerlussuaq to the south [32]. It is presently uncertain whether the Archaean basement that typifies the MN7 source region is directly related to that in Kangerlussuaq, or whether there are intervening regions with different mineralogical and isotopic characteristics. The detrital zircon data corroborate the discovery of Eo- and Mesoarchaean zircons in metamorphic basement rocks caught up in the Niggli Spids thrust sheet within the Krummedal sequence in the Hjørnedal area [40], which is located close to the MN7 source region.

5.1.2. MN4i

This region was previously termed MN4 [7], and coincides with part of a large area of migmatites in the East Greenland Caledonides [8]. Whether MN4i characterises the entire migmatite belt is uncertain, since samples have not been collected from the northern part of its extent. The MN4i region is characterised by high RuZi and abundant type A garnet, but there appear to be variations within the region based on rutile geochemistry and the abundance of type Ai garnet relative to type Aii. Most of the region supplies sand with type Ai garnet and granulite-facies metapelitic rutile, but in the southeastern part of Milne Land, type Aii garnet is prevalent in association with upper amphibolite facies rutile. These variations therefore appear to be related to metamorphic grade. MZi values are also distinctly higher in this region compared with elsewhere. Zircon U–Pb age populations contain a large early Palaeozoic component denoting supply from granites formed during the Caledonian orogeny, together with a wide range of Proterozoic grains. Palaeoproterozoic zircons older than 1800 Ma are scarce, and there is a small Archaean component. The zircon U–Pb age population associated with abundant type Ai garnet in

sample S_W5241 also has a peak at c. 900–950 Ma, indicating input from an area affected by early Neoproterozoic crustal melting.

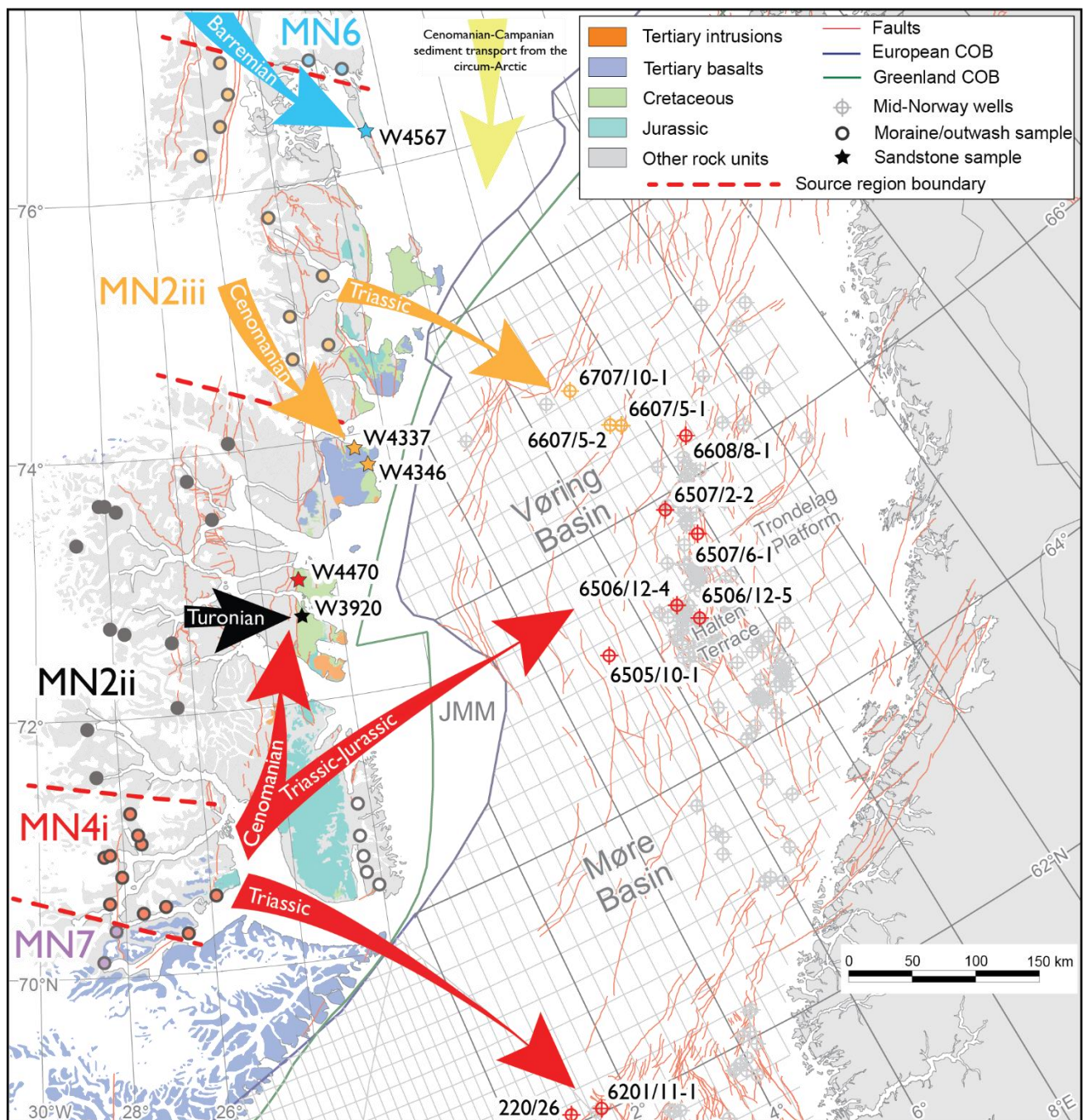


Figure 4. Map of the Greenland–Mid-Norway region prior to the onset of seafloor spreading in the Palaeogene, with present-day coordinates. The East Greenland crystalline basement and Caledonian orogenic belt are divided into five sediment source regions, as defined by moraine/outwash provenance signatures. Cretaceous sandstone samples [3] and offshore wells [1,3] are coloured according to the East Greenland source region. Provenance arrows indicate the approximate timing (note that the Cretaceous is divided into stages) and direction of source-to-sink transport, based on the published detrital data.

5.1.3. MN2ii

This region is characterised by high RuZi and type-B-dominated garnet assemblages. Rutile mainly comprises amphibolite-facies metapelitic types, with subordinate metamafic types. Zircon U–Pb age data indicate that most of the region supplies Palaeoproterozoic zircons—mostly in the 1900–2000 Ma range—with subordinate Archaean grains, and therefore comprises crystalline basement. Sample M6006, located in the Lyell Land Group catchment, is dominated by Mesoproterozoic zircon peaking at c. 1100 Ma, and has a spectrum that is closely comparable to that from a Lyell Land Group outcrop sample [5].

5.1.4. MN2iii

This region is characterised by low RuZi and type B garnet assemblages. Zircon U–Pb age data indicate that the region supplies Palaeoproterozoic zircons—mostly in the 1900–2000 Ma range—together with subordinate Archaean grains, representing input from crystalline basement. Rutile geochemistry indicates that the region mainly supplies amphibolite-facies metapelitic rutile, with subordinate metamafic types.

5.1.5. MN6

This region is limited to Germania Land, and is recognised on the basis of increased type C garnet abundances, which were sourced from local eclogites. The zircon U–Pb age spectrum from this region contains peaks at c. 1700–1800 Ma and c. 1900–2000 Ma.

Samples from this region and the adjacent MN2iii region yielded the highest number of zircon grains with discordant U–Pb ages. The dominant Caledonian amphibole Ar–Ar ages from these samples and the presence of eclogite- and amphibolite-facies Caledonian metamorphic terranes support the interpretation that the discordant ages are due to lasing Caledonian-age grain overgrowths.

5.1.6. Liverpool Land

Liverpool Land detritus is largely distinct from that of the rest of East Greenland, but the results are not considered definitive enough to designate this as a separate source region, because some of the sediment characteristics are not unique to Liverpool Land, there are differences in mineralogy between the north and south of Liverpool Land, and sandstones have not been identified that can be unequivocally tied back to a Liverpool Land provenance.

The consistently low RuZi of Liverpool Land samples contrasts with that associated with the source regions of MN4i and MN2ii sand types immediately to the west, and is more akin to values seen in the regions to the southwest and northwest, with MN7 and MN2iii sand types, respectively.

Type D (andradite–grossular) garnet is common, probably reflecting the widespread outcrop of early Palaeozoic granitoids in Liverpool Land. In the south, the Liverpool Land Eclogite Terrane supplies abundant type C garnet; this contrasts with the type-Aii- and B-garnet-dominated assemblages in the north. The abundance of type C garnet is a feature Liverpool Land shares with western Norway, including the Western Gneiss Region (source of the MN3 sand type; [3]). This is consistent with the interpretation of the Liverpool Land Eclogite Terrane as a fragment of Baltica that was once contiguous with the Western Gneiss Region [20].

Rutile geochemical data vary across Liverpool Land. The north supplies lower amphibolite-facies rutile, mostly of metapelitic origin, whereas the southerly Liverpool Land Eclogite Terrane supplies higher grade (upper amphibolite/eclogite–granulite-facies) rutile and a higher proportion of metamafic types.

Early Palaeozoic zircon, derived from the large Caledonian plutons (especially the Hurry Inlet Plutonic Terrane), forms c. 50% of the zircon population supplied from the northern part of the area. The remaining zircons (peaking at c. 1600–1650 Ma) are derived from metasediments of the Krummedal sequence. The southern part of the area

almost exclusively supplies early Palaeozoic zircons derived from the Hurry Inlet Plutonic Terrane [20].

5.2. Significance for the Fill of the Greenland–Norway Rift

Compositional data were collected from five Cretaceous sandstones from Traill Ø to Store Koldewey in East Greenland [3] (Figure 4). The signatures from Turonian sample W3920 from Traill Ø (RuZi > 40, type B garnet, zircon U–Pb ages: 950–1300 Ma dominant, 1500–2000 Ma, one concordant 297 Ma zircon) indicate an MN2ii source region provenance (Table 2). The Cenomanian sample W4470 from Geographical Society Ø (RuZi > 40, type A garnet, zircon U–Pb ages: 1500–2000 Ma, 400–500 Ma, 160–300 Ma) was largely derived from the MN4i sand type source region. Samples W4337 (Cenomanian) and W4346 (Santonian) from Hold with Hope yielded similar provenance signatures (RuZi < 40, type B garnet, 1600–2000 Ma, 900–1200 Ma), indicating a source from the MN2iii source region, and possibly a subordinate MN2ii source indicated by the younger zircons. The Barremian sample W4567 from Store Koldewey (RuZi < 40, type C garnet, zircon U–Pb ages: 1400–2000 Ma, with peaks at 1960 Ma and 1680 Ma) was derived from the MN6 source region.

Detrital zircon U–Pb ages have been presented from Carboniferous–Palaeogene sedimentary rocks on Wollaston Foreland [41]. The zircon age spectra reveal consistent 400 Ma, 1000–2000 Ma (with a main peak at c. 1900 Ma), and 2500–3000 Ma peaks. These zircon ages were most likely derived from the MN2ii and MN2iii source regions (Table 2), but in the absence of other heavy mineral data, it is not possible to distinguish which of the two areas was involved.

In the Jurassic–Palaeocene successions of the Møre and Vøring Basins of Mid-Norway, some of the reservoir sandstones have been assigned sources in East Greenland [1,3,7]. The moraine/outwash sample data can be used to test these previous assignments.

The MN4i source region of East Greenland has been proposed as the source of some of the Jurassic sandstones of Mid-Norway—in particular those in the Åre and Garn formations in Heidrun and adjacent parts of the Halten Terrace [1,7]. The moraine/outwash data demonstrate the existence of a source area with closely comparable heavy mineral and mineral chemical characteristics—notably abundant type Ai garnet, abundant granulite-facies rutile of metapelitic parentage, high MZi, and comparable zircon U–Pb ages. The Heidrun zircon spectra contain a large early Palaeozoic group in conjunction with a range of Proterozoic zircons that rarely predate 1800 Ma, together with a small Archaean component. These features also characterise the MN4i spectra in the moraine/outwash data, providing further support for the derivation of Åre and Garn sandstones from the migmatite belt of the East Greenland Caledonides. The presence of some additional zircon groups—notably at c. 1100–1200 Ma—in the Heidrun samples suggests that some detritus was fed from other parts of East Greenland. The composition of Triassic sandstones in the southern Møre Basin and northern Shetland Platform also points to an MN4i provenance [1].

Cretaceous sedimentary rocks in the Vøring Basin have compositional similarities to the East Greenland moraine/outwash samples [3,39]. These sandstones yielded RuZi < 40, type B garnet, and a wide range of zircon U–Pb ages (~100 Ma, ~250 Ma, 400–500 Ma, 1000–2000 Ma, 2500–3000 Ma), with the main peaks between 1700 and 1900 Ma. Combined, these signatures compare with the MN2iii sand type from the moraine/outwash data, apart from the Permian–Triassic and Cretaceous zircons. These characteristics support the interpretation that some of the Cretaceous sedimentary rocks in the Vøring Basin were sourced from the Hold with Hope region of East Greenland [3] (Figure 4). The addition of sand from Liverpool Land, and possibly the MN4i provenance region, could explain the presence of 400–500 Ma and 1600–1700 Ma zircon in the Vøring Basin sediments.

The youngest zircon grains in the moraine/outwash data are Devonian. The presence of Permian–Cretaceous zircons in Cenomanian–Campanian sedimentary rocks of East Greenland and offshore Mid-Norway (up to 25% of the zircon assemblages; [3])—along with the absence of zircon of this age in the moraine/outwash samples, or of similarly aged

volcanism in East Greenland—therefore requires a distal, extra-rift source from the circum-Arctic region. Permian–Triassic zircon is associated with subduction-related volcanism in the North Slope of Alaska [42] and Chukotka [43], as well as magmatism in Taimyr, Arctic Uralides [44]. These are source regions for Permian–Triassic sedimentary rocks [45,46], but are unlikely to have directly sourced the Greenland–Norway rift during the Jurassic–Cretaceous. The Permian–Triassic zircon grains in East Greenland and Mid-Norway were therefore probably recycled from Triassic sediments in the circum-Arctic. The Cretaceous zircon was most likely sourced from Canadian Arctic magmatism [47] or the Okhotsk–Chukotka volcanic belt [48].

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/geosciences12020073/s1>: File S1: Analytical methods; Table S1: Amphibole Ar–Ar data; Table S2: Zircon U–Pb data; Figure S1: Wetherill plots; Table S3: Heavy mineral data; Table S4: Amphibole chemistry data; Table S5: Garnet chemistry data; Table S6: Rutile chemistry data.

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