

Article

A Sediment Provenance Study of Middle Jurassic to Cretaceous Strata in the Eastern Sverdrup Basin: Implications for the Exhumation of the Northeastern Canadian-Greenlandic Shield

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Abstract

The Sverdrup Basin, Arctic Canada, is ideally situated to contain an archive of tectono-magmatic and climatic events that occurred within the wider Arctic region, including the exhumation of the adjacent (northeastern) part of the Canadian-Greenlandic Shield. To test this, a multi-analytical provenance study of Middle Jurassic to Cretaceous sandstones from the eastern Sverdrup Basin was undertaken. Most of the samples analysed were recycled from sedimentary rocks of the Franklinian Basin, with possible additional contributions from the Mesoproterozoic Bylot basins and metasedimentary shield rocks. The amount of high-grade metamorphic detritus in samples from central Ellesmere Island increased from Middle Jurassic times. This is interpreted to reflect exhumation of the area to the southeast/east of the Sverdrup Basin. Exhumation may have its origins in Middle Jurassic extension and uplift along the northwest Sverdrup Basin margin. Rift-flank uplift along the Canadian–West Greenland conjugate margin and lithospheric doming linked with the proximity of the Iceland hotspot and/or the emplacement of the Cretaceous High Arctic Large Igneous Province may have contributed to exhumation subsequently. The southeast-to-northwest thickening of Jurassic to Early Cretaceous strata across the Sverdrup Basin may be a distal effect of exhumation rather than rifting in the Sverdrup or Amerasia basins.

Keywords: Arctic; detrital zircon; heavy mineral analysis; Lu–Hf isotopes; Mesozoic; mineral chemistry; U–Pb geochronology



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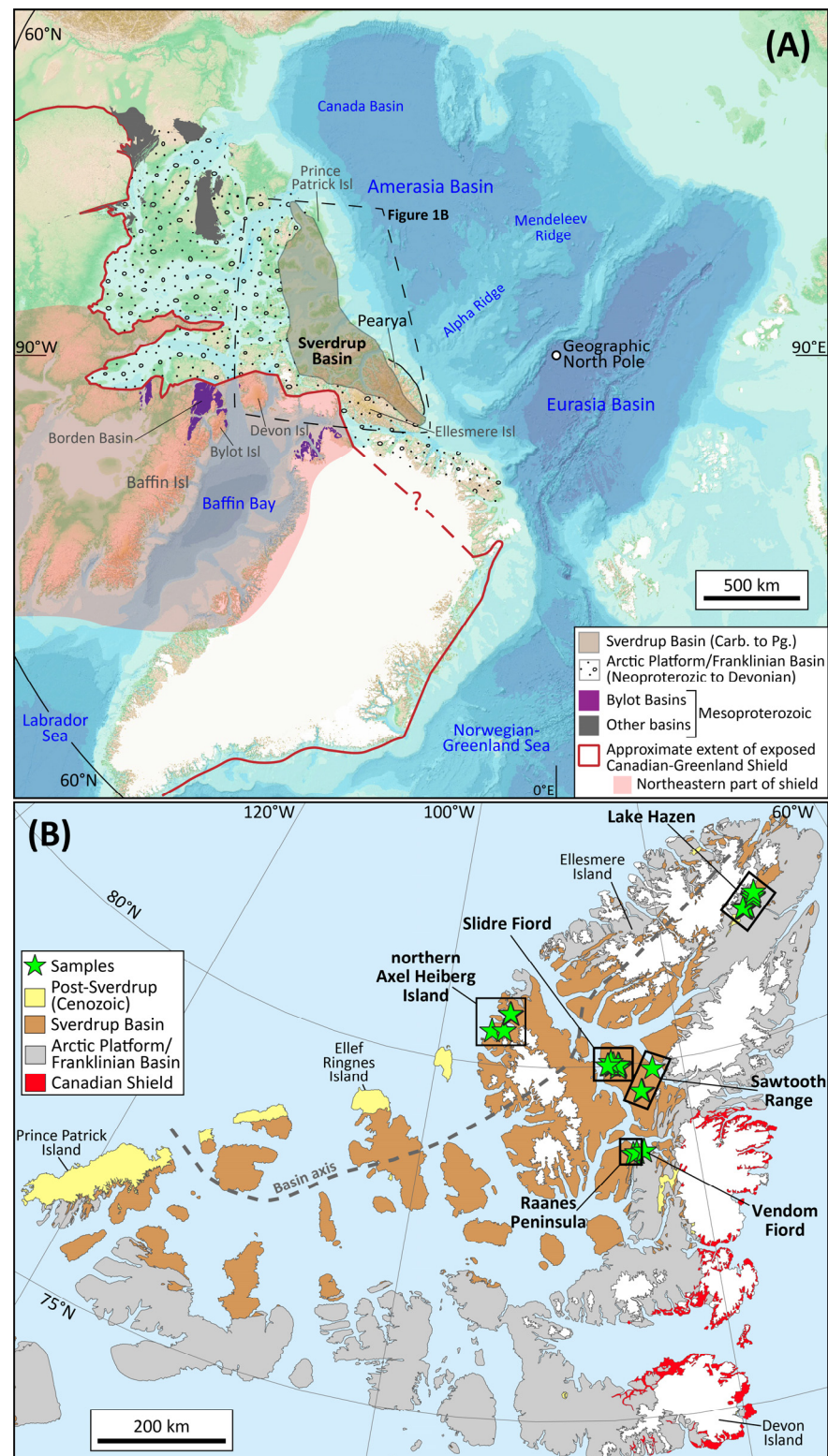
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1. Introduction

Today, large parts of the highly deformed and metamorphosed northeastern Canadian-Greenlandic Shield are exposed at surface level (Figure 1A). How and when these rocks were unearthed is poorly constrained. On Baffin Island and several small islands near

its southeastern coast, as well as on Bylot Island (Figure 1A), Aptian–Albian sedimentary rocks overlie the shield, demonstrating that it was exposed by this time [1–4]. Neoproterozoic to Silurian strata of the Arctic Platform/Franklinian Basin overlie shield rocks elsewhere on Baffin Island, as well as on southern Ellesmere Island, Devon Island, the Canadian mainland and West Greenland (e.g., [5]). The lack of intervening sedimentary cover makes reconstructing the exhumation history of the northeastern Canadian–Greenlandic Shield during a large part of Paleozoic and Mesozoic times extremely difficult. Detrital apatite and zircon (U–Th–Sm)/He ages from Devonian strata of the Franklinian Basin were tentatively interpreted to record protracted exhumation from Carboniferous to Cretaceous times [6]. Several thermochronology studies utilising apatite fission track analysis and (U–Th–Sm)/He geochronology have been undertaken on southern Ellesmere Island, Baffin Island and northwest Greenland to investigate exhumation (e.g., [7–11]). However, a difficulty of long-timescale thermal-history analysis is the non-uniqueness in modelled thermal histories that depend on diffusion-based observations [9], which compromises interpretations. Computed exhumation models vary from those that infer continuous protracted exhumation through Phanerozoic times (e.g., [10]) to more complex models involving recurrent burial and exhumation (e.g., [9,11]).

It is long established that the sedimentary fill of a basin provides an archive of tectonic, magmatic and climatic events within the surrounding sediment source areas (e.g., [12–14] and references therein). The Sverdrup Basin of the Canadian Arctic Islands (Figure 1) is well situated to have captured an expression of the exhumation history of the northeastern Canadian–Greenlandic Shield, as well as wider Arctic tectonic, magmatic and climatic events. The basin contains Early Carboniferous to Paleogene strata (e.g., [15]) and thus spans the missing time interval in the exhumation history of the adjacent shield area. Previous research based on facies trends and palaeocurrent vectors has shown that the Sverdrup Basin received sedimentary detritus from two main directions: (1) from the north/northeast and (2) from the southeast/east (present-day directions; e.g., [15,16]). Sediment was supplied from the southeast/east throughout much of the basin’s lifespan, whereas sediment from the north and/or northeast was delivered more intermittently, from Middle Permian times onwards [16,17]. A number of sediment provenance studies have been undertaken within the Sverdrup Basin to characterise both the northern/northeastern and southeastern/eastern sediment source areas. These have largely employed detrital zircon U–Pb geochronology (e.g., [17–25]) and whole-rock Nd isotopes [4]. Through the analysis of mostly fine-grained sediments on the southern limb of the Sverdrup Basin, Patchett et al. [4] inferred that, apart from during Carboniferous and Cretaceous times, sediment supplied from the southeast/east was derived from inverted Silurian and Devonian rocks of the Franklinian Basin (Figure 1A). Patchett et al. [4] thus inferred that the northeastern Canadian–Greenlandic Shield was likely covered by Paleozoic sediments until Cretaceous times, with cover units progressively removed during Mesozoic times. Detrital zircons analysed from southeast/east-derived sandstone units yield U–Pb age spectra consistent with the interpretations of Patchett et al. [4]. Carboniferous and Early Cretaceous strata have lower ϵNd_t values, which are inferred to reflect the reworking of shield-derived pre-Late Ordovician strata from the Franklinian Basin during the Carboniferous Period and a direct sediment input from shield rocks during the Cretaceous Period [4].



Whilst the analysis of shales and detrital zircons has yielded important inferences, a greater understanding of sediment provenance can be gained by employing additional analytical techniques. Pointon et al. [28] recently presented a multi-proxy sediment provenance study of Carboniferous to Middle Jurassic strata from the eastern Sverdrup Basin. As part of their study, they combined optical petrographic and conventional heavy mineral analysis, as well as single-grain geochemistry (apatite, garnet and rutile) and detrital zircon U–Pb geochronology to refine sediment provenance models. The aim of this study is to apply the same multi-analytical workflow to the Middle Jurassic to Cretaceous strata of the eastern Sverdrup Basin. New data are integrated with existing whole-rock Nd isotope [4] and detrital zircon U–Pb geochronology data [23,24] to refine sediment provenance interpretations. The new multi-analytical dataset is also combined with that of Pointon et al. [28] to explore for evidence of exhumation in the southeastern/eastern source area. Where exhumation is inferred, the possible underlying causes of exhumation are discussed.

2. Geological Background

The oldest rocks in the vicinity of the Sverdrup Basin are Archean to Paleoproterozoic, deformed and metamorphosed up to granulite facies, metasedimentary and metaigneous rocks of the Canadian-Greenlandic Shield (Figure 1; [29–32]). These are overlain by a series of intracratonic basins that span from the western Cordillera to East Greenland and contain unmetamorphosed Mesoproterozoic fluvial to shallow marine sedimentary strata [27,33,34]. The basins proximal to the southeast margin of the Sverdrup Basin are thought to be broadly coeval and to share similar geological histories. Therefore, they have been collectively termed the Bylot basins (Figure 1A; [34,35]).

From late Neoproterozoic to Late Devonian times, a thick succession of sedimentary rocks was deposited on the northern margin of Laurentia (Franklinian Basin/Margin succession; Figure 1; [36–41]). The lower part of the succession comprises passive margin Neoproterozoic to Ordovician mixed siliciclastic and carbonate shelfal to basinal sediments [38,40,42–44]. Siliciclastic strata within this stratigraphic package were derived primarily from the Canadian-Greenlandic Shield [38,42,45]. During Silurian times, the Franklinian Basin received substantial volumes of turbidites sourced from the Caledonian orogenic belt [38,45,46]. By Middle Devonian times, the Franklinian Basin had transitioned into a foreland basin and received fluvial to deltaic sediments, which are often termed the Devonian clastic wedge (e.g., [36,41,47–49]). The origin of the foreland basin has been linked to mid-Devonian collisional events that culminated in the Late Devonian to Early Carboniferous Ellesmerian Orogeny [38,39]. Initially, sediments of the Devonian clastic wedge were derived mostly from the East Greenland Caledonides, Pearya and the Ellesmerian orogenic belt; the last area ultimately dominated sediment supply [38,39,48]. Following orogenic collapse and rifting during the Early Carboniferous, sedimentation within the successor Sverdrup Basin commenced (e.g., [15]).

Sverdrup Basin

The Sverdrup Basin covers an area of ~300,000 km² and contains a Carboniferous to Eocene sedimentary succession of 13–15 km estimated thickness (Figure 1B; [15,29]). It is most widely viewed as an intracratonic basin that was dominated by passive thermal subsidence from Middle Permian until Late Jurassic or Early Cretaceous times and then experienced active rifting and extension until the end of the Albian [15,16,50,51]. Other workers have inferred a short episode of active rifting during Early Triassic times [52] and

that rifting started and ended earlier, lasting from Early Jurassic until Valanginian times [53]. Salt tectonics add further complexity: the basin experienced passive salt diapirism from at least Triassic times [52,54–56]. During Middle Jurassic times, the southwestern margin of the basin experienced rifting, manifested as normal faulting and the development of narrow rift sub-basins in the Prince Patrick Island area (Figure 1B; [15,57,58]). Following the cessation of Early Cretaceous rifting within the Sverdrup Basin, a passive thermal subsidence regime prevailed until the latest Cretaceous to the early Paleocene when compressional tectonics related to the Eurekan Orogeny began to affect sedimentation patterns [15,59]. Eurekan deformation climaxed during the Eocene and marked the end of sedimentation within the Sverdrup Basin [15,60].

The Sverdrup Basin drifted progressively northwards during Mesozoic times, from around 50–60° N at the start of the Early Jurassic, to 60–70° N by Middle Jurassic times, and then to >70° N by the Early Cretaceous [61–63]. As a consequence, the basin's climate evolved from a wet subtropical one during the Early Jurassic to a more temperate one by Middle Jurassic times [16]. The Late Jurassic to Early Cretaceous world was warm and largely ice-free (e.g., [64–66]). However, the presence of dropstones and glendonite-bearing horizons within the Awingak, Deer Bay and Christopher formations (Figure 2; [16,67–70]) indicates the intermittent presence of seasonal sea ice during climatic cold snaps, and attests to the high latitude of the Sverdrup Basin by this time. The analysis of fossil spore and pollen assemblages has provided additional insight into local Middle Jurassic and Cretaceous climate (Figure 2; [63,71–74]).

From Jurassic to Paleogene times, sedimentation within the basin was almost exclusively of siliciclastic composition (e.g., [15,16]). The basin margins are characterised by a series of fluvio-deltaic or marine shelfal sand-dominated units that prograded into the basin to varying extents (upper Heiberg Formation through to lower Expedition Formation; sandstone-dominated formations in Figure 2). Meanwhile sedimentation in the basin centre was mud-dominated (Jameson Bay to Kanguk formations; Figure 2).

Apart from several volcanic ash beds that occur interbedded within Triassic strata on northwest Axel Heiberg Island [19,20], records of Triassic to Jurassic magmatism within the Sverdrup Basin are sparse. The basin was more volcanically active from Hauterivian times onwards, as manifest by intermittent tholeiitic and alkaline magmatism, which forms part of the widespread High Arctic Large Igneous Province (HALIP; e.g., [75–83]). This includes mafic volcanic and volcanoclastic rocks in the Isachsen, Christopher and Hassel formations, continental flood basalts of the Strand Fiord Formation and numerous felsic altered volcanic ash layers (bentonites) within the Kanguk Formation (Figure 2; e.g., [29,75,77,78,80,84–91]). Several bentonites have also been reported from the Paleocene and younger Eureka Sound Group, which postdate HALIP magmatism and are possibly related to the opening of Baffin Bay, the North Atlantic and/or the Eurasian Basin [92].

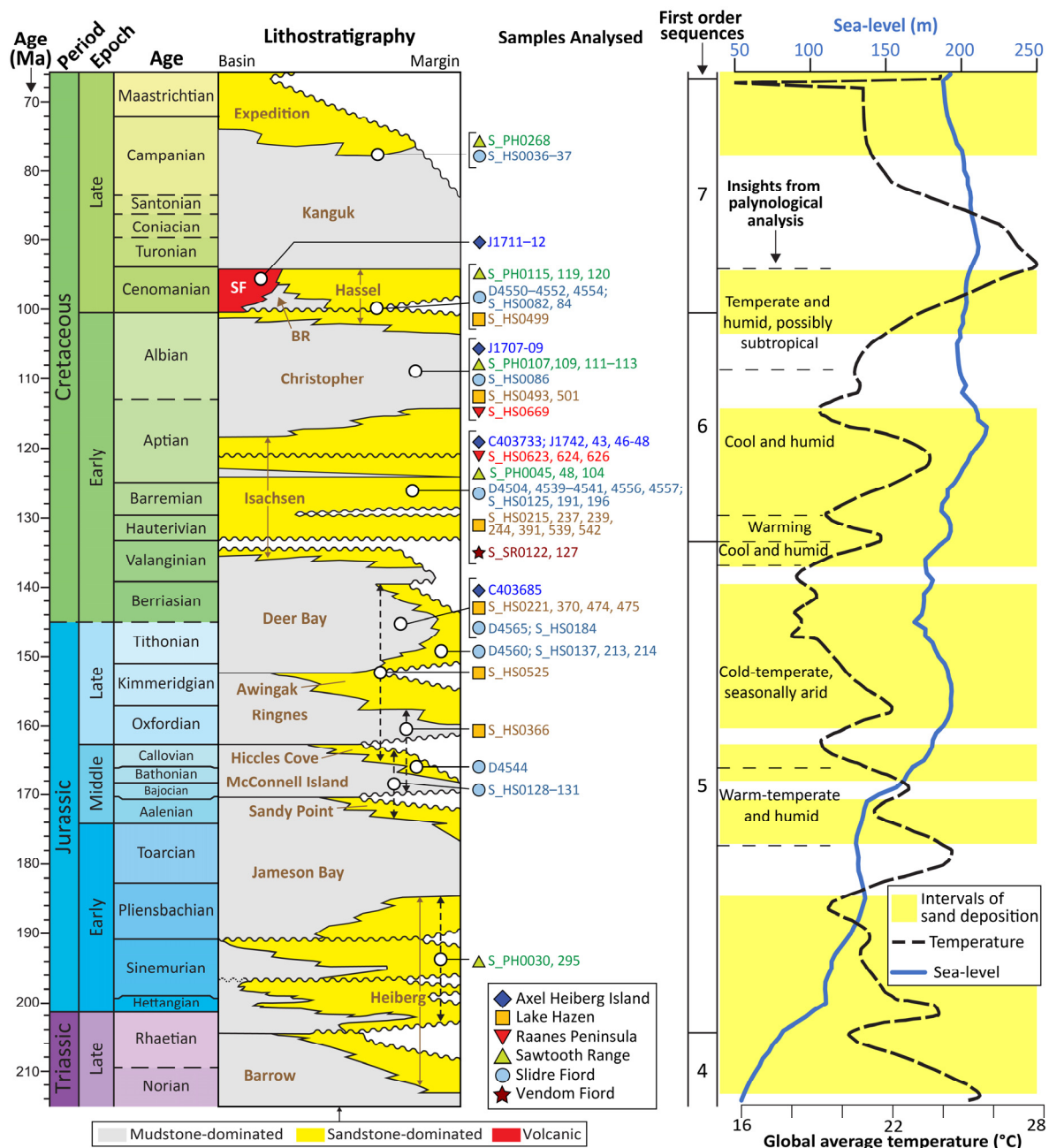


Figure 2. Late Triassic to Late Cretaceous lithostratigraphic framework of the eastern Sverdrup Basin shown against global average temperatures [93] and global sea level [94]. The lithostratigraphic framework is redrawn and modified from Hadlari [95] using information from Embry [16,96] and Embry and Beauchamp [15]. Numerical ages are from Cohen et al. [97]. First-order sequences are from Embry and Beauchamp [15]. Sample stratigraphic positions are known to formation level, apart from the following which have more uncertain lithostratigraphic assignments: S_HS0128–0131 (Wilkie Point Group), D4544 (probable Hiccles Cove Formation), S_HS0525 (Hiccles Cove or Awingak Formation) and S_HS0366 (McConnell Island or Ringnes Formation). Note that the boundary between the Kanguk and Expedition formations is transitional [59,98]; consequently, samples S_PH0268, S_HS0036 and S_HS0037 could be from the upper Kanguk or lower Expedition Formation. Climatic inferences derived from palynological analysis are drawn from Galloway et al. [63,72,99], Hopkins Jr and Balkwill [73], Nguyen et al. [71] and Sulphur [74]. BR = Bastion Ridge Formation; SF = Strand Fiord Formation.

3. Materials and Methods

3.1. Samples

Seventy-five Middle Jurassic to Cretaceous samples were analysed (Figure 2). The samples are predominantly sandstones, together with a few siltstones and conglomerates (Table S1). They were collected from six main areas of the basin: (1) northern Axel Heiberg Island, (2) the Lake Hazen area, (3) Slidre Fiord, (4) the Sawtooth Range, (5) the Raanes Peninsula and (6) Vandom Fiord (Figure 1B). Samples from Axel Heiberg Island are from the northern limb of the basin; all other samples are from the inferred axial region or the southern limb (Figure 1B). The samples were collected by CASP researchers across several field seasons between 2007 and 2013. This is apart from samples with C3740 prefixes, which were collected by Ashton Embry.

3.2. Methods

The samples were investigated using the same multi-analytical workflow as Pointon et al. [28], commencing with optical petrographic analysis and/or conventional heavy mineral analysis, followed by the chemical analysis of apatite, garnet and rutile grains, and then detrital zircon U–Pb geochronology. Detrital zircon Lu–Hf isotope analysis was subsequently undertaken on one sample (C403685). A breakdown of the analyses conducted on each sample is given in the supplementary materials (Table S1); this is also where the analytical data tables can be found (Tables S2–S8). The methods employed are identical to the ones used by Pointon et al. [28]. These are summarised below, much of which has been rephrased from Pointon et al. [28] at the insistence of the journal's editorial office, to comply with their anti-plagiarism software.

3.2.1. Optical Petrographic Analysis

Samples were thin-sectioned, vacuum-impregnated with blue-dyed epoxy resin, and then etched and stained with hydrofluoric acid and sodium cobaltinitrite to facilitate the identification of alkali feldspars. Samples from northern Axel Heiberg Island and Slidre Fiord were point-counted using the Gazzi–Dickinson method [100]. Conversely, samples from the Lake Hazen area and the Raanes Peninsula were counted using the traditional/Indiana method [101]. Comparing traditional/Indiana point-count data to Gazzi–Dickinson point-count data can be problematic where samples contain coarse-grained polymineralic grains. Such grains are, however, rare in the studied samples, meaning that comparing the two datasets herein does not introduce a significant bias. This is demonstrated quantitatively through the counting of samples from the Sawtooth Range using both methods. Sandstones were classified by reference to the scheme of Pettijohn et al. [102].

3.2.2. Conventional Heavy Mineral Analysis

Heavy minerals were separated, studied and analysed from the very fine sand (63–125 µm) grain size fraction. A narrow grain size range is commonly employed for several reasons, the most crucial of which is to help distinguish changes in provenance from potential grain-size-dependent compositional variations (see [103,104] for more details). The relative abundance of transparent heavy mineral species was estimated from, ideally, a count of 200 grains using the ribbon counting method [105]. Such a count was not always attainable, however, due to poor heavy mineral recovery. ATi (apatite:tourmaline index), GZi (garnet:zircon index), RuZi (rutile:zircon index), MZi (monazite:zircon index) and CZi (chrome spinel:zircon index) provenance-sensitive heavy mineral indices were determined based on Morton and Hallsworth [104]. These were also determined using the ribbon counting method and preferably from a count of 200 grains.

3.2.3. Mineral Grain Chemical Analysis

The trace element chemistry of apatite and rutile grains was determined by laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) at Cardiff University. Possible source rock lithology groups were assigned based on the work of O'Sullivan et al. [106]. Rutile grains were classified into metapelite and metamafic types following Meinhold et al. [107]. Rutile metamorphic temperatures were estimated using the Zr-in-rutile thermometer calibration of Watson et al. [108]. Electron microprobe analysis was used to ascertain the major element chemistry of garnet grains. Garnet grains were assigned possible host rock types and metamorphic facies from these data using the garnetRF program (version 1.1; [109]).

3.2.4. Detrital Zircon U–Pb Geochronology

The uranium–lead isotopic compositions of detrital zircon grains were determined using the LA-ICPMS and secondary ion mass spectrometry methods. This work was conducted at University College London (UK), Laurentian University (Ontario, Canada), Stellenbosch University (South Africa) and the NORDSIMS facility (Swedish Natural History Museum, Sweden). All analyses are spot analyses. The data collected at Stellenbosch University were corrected for common lead by employing the ^{204}Pb method and the Stacey and Kramers [110] terrestrial lead evolution model. All of the other U–Pb isotopic data are not corrected for common lead. Concordia ages (sensu [111]) were used in the interpretation to avoid arbitrary switching between the $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{206}\text{Pb}$ age systems. Concordia ages were calculated using Isoplot (version 4; [112]). Analyses that are more than 10% discordant (at the limit of the two-sigma confidence level uncertainty ellipse) or that have imprecise concordia ages (arbitrarily defined as greater than 10% uncertainty at the two-sigma confidence level) were omitted from the interpretation.

3.2.5. Detrital Zircon Lu–Hf Isotope Analysis

The Lu–Hf isotopic compositions of detrital zircon grains from sample C403685 were determined at the Geochronology and Tracers Facility, British Geological Survey, UK, using the multi-collector LA-ICPMS method. The methodology used closely followed that of Thomas et al. [113]. Thirty-five μm laser spots were positioned on top of previous U–Pb SIMS analyses reported by Omma et al. [23]. Initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios were calculated by employing a ^{176}Lu decay constant of $1.867 \times 10^{-11} \text{ a}^{-1}$ [114] and the U–Pb concordia ages of the corresponding SIMS spot analyses. Initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios were expressed as $\epsilon\text{Hf}(t)$ values using $^{176}\text{Hf}/^{177}\text{Hf} = 0.282785$ and $^{176}\text{Lu}/^{177}\text{Hf} = 0.0336$ for the present-day chondritic uniform reservoir (CHUR; [115]). Two analyses have corresponding U–Pb concordia ages that are more than 10% discordant; these analyses are consequently excluded from the interpretation.

4. Results

4.1. Optical Petrographic Analysis

Fifty-one samples were point counted: forty-eight arenites, one wacke (J1708) and two conglomerates (J1711 and J1742; Figure 3). Samples S_HS0525 (Hiccles Cove or Awingak Formation) and S_H0366 (McConnell Island or Ringnes Formation), together with the majority of samples analysed from the Awingak, Deer Bay and Isachsen formations, are very quartz-rich and are classified as quartz arenites or sublitharenites (Figure 3). Feldspar is almost entirely absent from the Lake Hazen sample set, whilst samples from elsewhere in the basin contain little to no plagioclase (Figure 3C). Rock fragments comprise mostly mudstone, chert and quartzite types, in varying proportions.

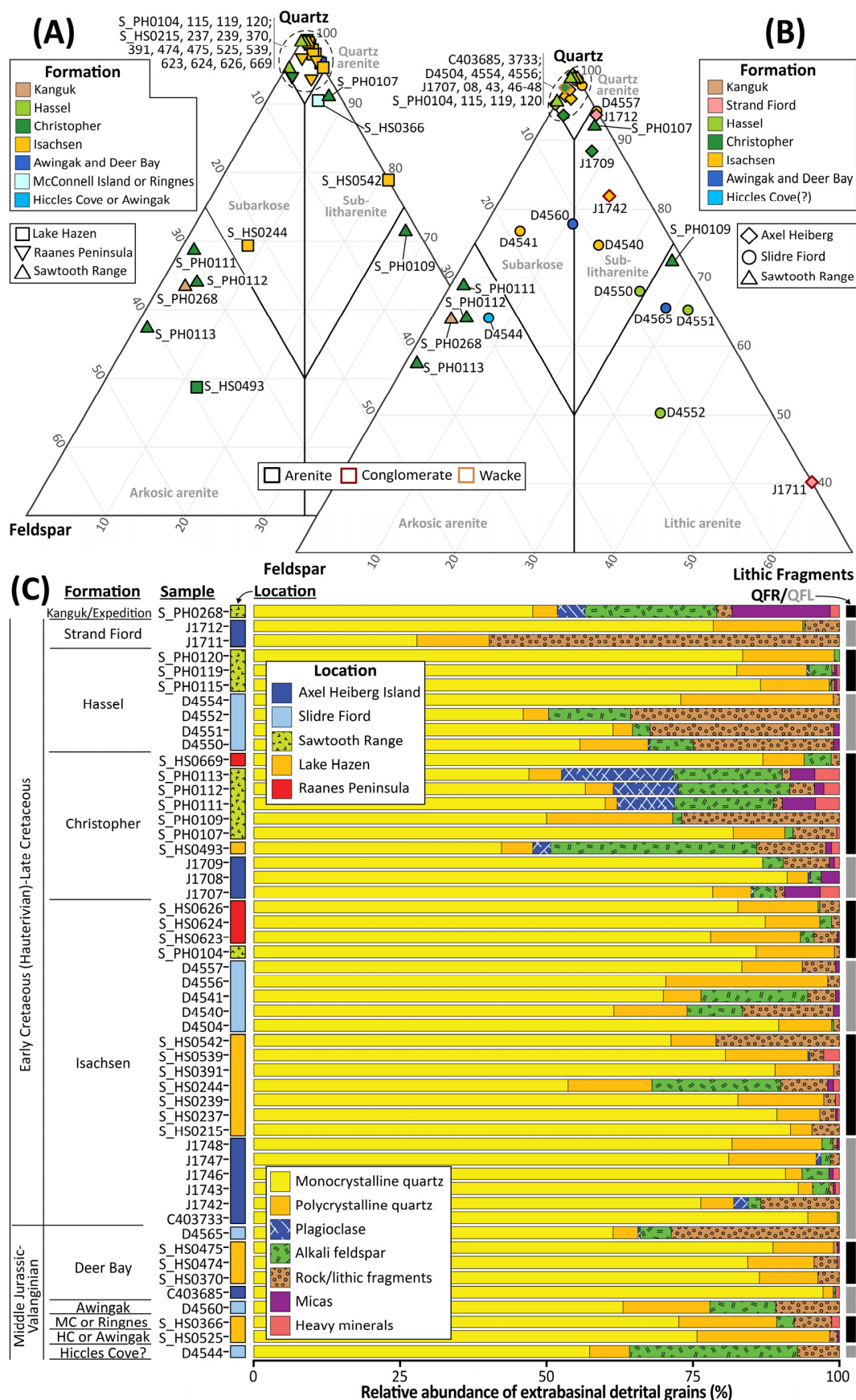


Figure 3. (A) Quartz–feldspar–rock fragment (QFR) ternary diagram showing point-count data collected using the traditional/Indiana counting method. (B) Quartz–feldspar–lithic fragment (QFL) ternary diagram showing point-count data collected using the Gazzi–Dickinson method. Samples from the

Sawtooth Range were counted using both methods and are consequently drawn in figures A and B; these samples plot in near identical locations in both plots, supporting that, in this instance, comparing data from the two methods does not introduce a significant bias. Compositional fields shown are from Pettijohn et al. [102]. Both ternary diagrams were drawn in R version 4.3 using the ggtern package [116] and are partially clipped, with the area comprising 0–30% quartz not shown because it contains no samples. (C) Bar charts showing the relative abundance of extrabasinal detrital grains as determined by point counting. QFR = quartz, feldspar and rock fragments (traditional/Indiana method data); QFL = quartz, feldspar and lithic fragments (Gazzi–Dickinson method data). HC = Hiccles Cove; MC = McConnell Island. The traditional/Indiana point-count data are drawn for the Sawtooth Range samples.

Samples from the Christopher Formation on Axel Heiberg Island (J1707–09), the Raanes Peninsula (S_HS0669) and from the lower part of the formation in the Sawtooth Range (S_PH0107) are also very quartz-rich (Figure 3). Sample S_PH0109, in contrast, contains abundant chert rock fragments. All of these samples contain only sparse feldspar. Rock fragments are sparse, apart from in sample S_PH0109, and include chert, mudstone and schistose metamorphic types. Samples S_PH0111 to S_PH0113 from the middle part of the Christopher Formation in the Sawtooth Range and sample S_HS0493 from the same formation near Lake Hazen are arkosic arenites (Figure 3A). Plagioclase is comparatively abundant in these samples, as is alkali feldspar (Figure 3C). Rock fragments comprise mainly mudstone and chert types.

Four Hassel Formation samples analysed from a section near Slidre Fiord show decreasing quartz content up-section (D4554, D4550, D4551 and D4552, from lowest to highest; Figure 3B,C). Feldspar comprises almost entirely alkali types (Figure 3C). Rock fragments are mostly chert, mudstone and semipelitic to psammitic types. Three samples from a section in the Sawtooth Range (S_PH0115, S_PH0119 and S_PH0120), in contrast, are all quartz arenites (Figure 3A,B). Sparse rock fragments in these include chert, siliciclastic sedimentary, felsic plutonic and schistose metamorphic types. Alkali feldspar and muscovite also occur sporadically.

From the Strand Fiord Formation, sample J1711 is a clast-supported conglomerate comprising mostly chert clasts in a poorly sorted, very-fine-grained quartz arenite matrix, whereas sample J1712 is a conglomeratic sublitharenite (Figure 3B). Feldspar is very rare to absent. Sample S_PH0268, from the upper Kanguk Formation or lower Expedition Formation, is a very-fine- to fine-grained arkosic arenite (Figure 3A,B). It contains both alkali feldspar and plagioclase, as well as abundant mica (mostly biotite; Figure 3C). Rock fragments are rare and comprise mudstone and chert types.

4.2. Conventional Heavy Mineral Analysis

The transparent heavy mineral assemblages from 54 samples were counted. RuZi values range from 6.5 to 35.7, whereas CZi values are low (0–8.3). Both show no clear geographic or stratigraphic trends (Figure 4) and are not discussed further. Samples from northern Axel Heiberg Island and Lake Hazen typically have lower MZi values (<2.4) compared to those from Slidre and Vandom Fiords, the Raanes Peninsula and the Sawtooth Range (0–14.5; Figure 4). MZi values are highest in samples from the Hassel Formation (Figure 4).

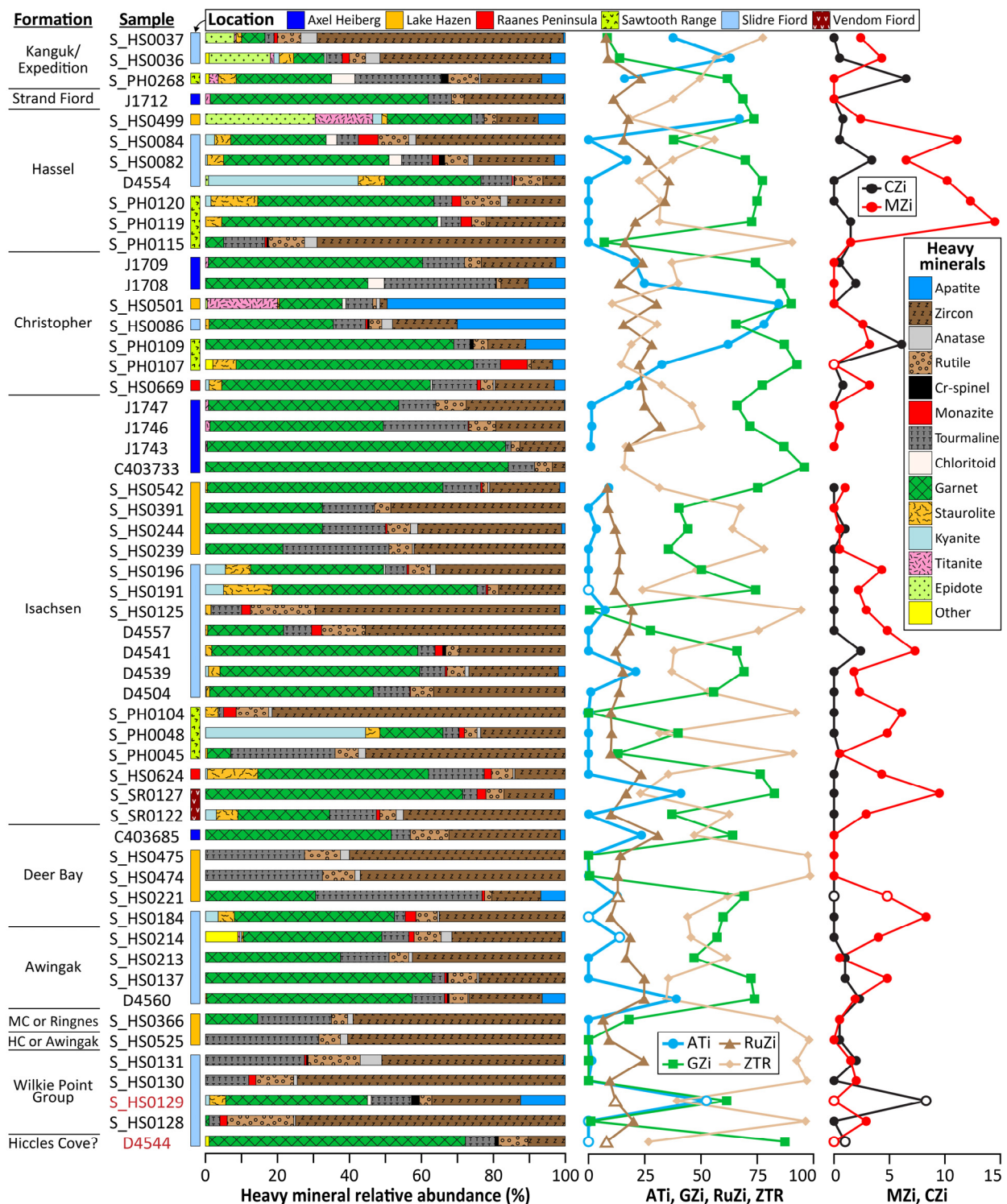


Figure 4. Conventional heavy mineral data. Sample numbers in red indicate assemblages based on <100 counts. Minerals plotted as “other” comprise calcic amphibole, clinopyroxene, garnite and orthopyroxene. ATi = apatite:tourmaline index, GZi = garnet:zircon index, RuZi = rutile:zircon index, MZi = monazite:zircon index and CZi = chrome spinel:zircon index (after [104]). ZTR index = sum of zircon, tourmaline and rutile as a percentage of total transparent heavy minerals. Open circles denote provenance-sensitive index values based on fewer than 30 counts. Data from sample C403685 are redrawn from Omma et al. [23]. Cr-spinel = chrome spinel; HC = Hiccles Cove; Isl = Island; MC = McConnell Island.

Samples from the Jurassic Wilkie Point Group (S_HS0128–131) plus samples S_HS0366 (McConnell Island or Ringnes Formation) and S_HS0525 (Hiccles Cove or Awingak Formation) mostly have stable heavy mineral assemblages dominated by zircon, tourmaline and rutile (ZTR values of >84%; Figure 4). Samples D4544, S_HS0129 and S_HS0366 also contain sizeable amounts of garnet (14.5–39.4%; Figure 4) and have correspondingly high GZi values. Sample S_HS0129 is the only one to contain significant amounts of apatite (12.4%) and chrome spinel (2.2%).

Garnet is very common in samples from Awingak, Deer Bay, Isachsen and younger formations (Figure 4). Staurolite and kyanite are present in several samples from the Isachsen and younger formations. Six samples, in contrast, contain little to no garnet and staurolite and are instead characterised by zircon-, tourmaline- and rutile-dominated assemblages (>90%; S_HS0474, S_HS0475, S_HS0125, S_PH0045, S_PH0104 and S_PH0115; Figure 4).

Apatite is generally poorly represented in the Awingak, Deer Bay and younger formations. This with the exception of samples investigated from the Christopher Formation, which all contain appreciable apatite (2.6–49.5%; Figure 4). ZTR values are generally low in this formation (<40). Samples S_HS0499, S_HS0036 and S_HS0037 (Hassel and Kanguk formations) contain sizeable amounts of epidote (Figure 4). Samples S_HS0036 and S_HS0037 are characterised by a high abundance of zircon but comparatively low amounts of rutile and tourmaline. They also have moderate to high ATi values (37.6–63; Figure 4).

4.3. Apatite Chemistry

Apatite grains were analysed from two samples of the Hassel (S_HS0499) and upper Kanguk to lower Expedition (S_HS0036) formations. Between 49 and 58 grains were analysed per sample. Both samples are characterised by a large proportion of grains from mafic/intermediate igneous rocks (53–55%), together with smaller proportions of metamorphic and ultramafic grains, as well as sparse grains potentially from felsic granitoids and alkaline rocks (Figure 5).

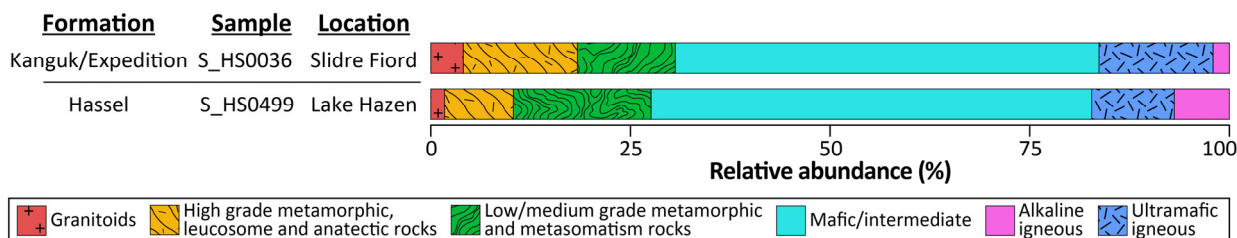


Figure 5. Bar chart summarising the likely source rocks from which the apatite grains were derived. Apatite grains were classified following O’Sullivan et al. [106].

4.4. Garnet Chemistry

Garnet grains from sixteen samples were analysed (50 to 59 grains per sample). Fourteen of these samples are Middle Jurassic or younger; two Late Triassic to Early Jurassic sandstone samples from the Sawtooth Range (S_PH0030 and S_PH0295) were analysed to redress a gap in the Pointon et al. [28] dataset. The vast majority of grains are of metamorphic origin (80–100%; Figure 6). These were derived from intermediate/felsic metaigneous rocks or metasedimentary rocks, although grains from metamafic rocks are present in many of the samples. The latter grains are classified predominantly as eclogite/ultra-high pressure and granulite-facies grade.

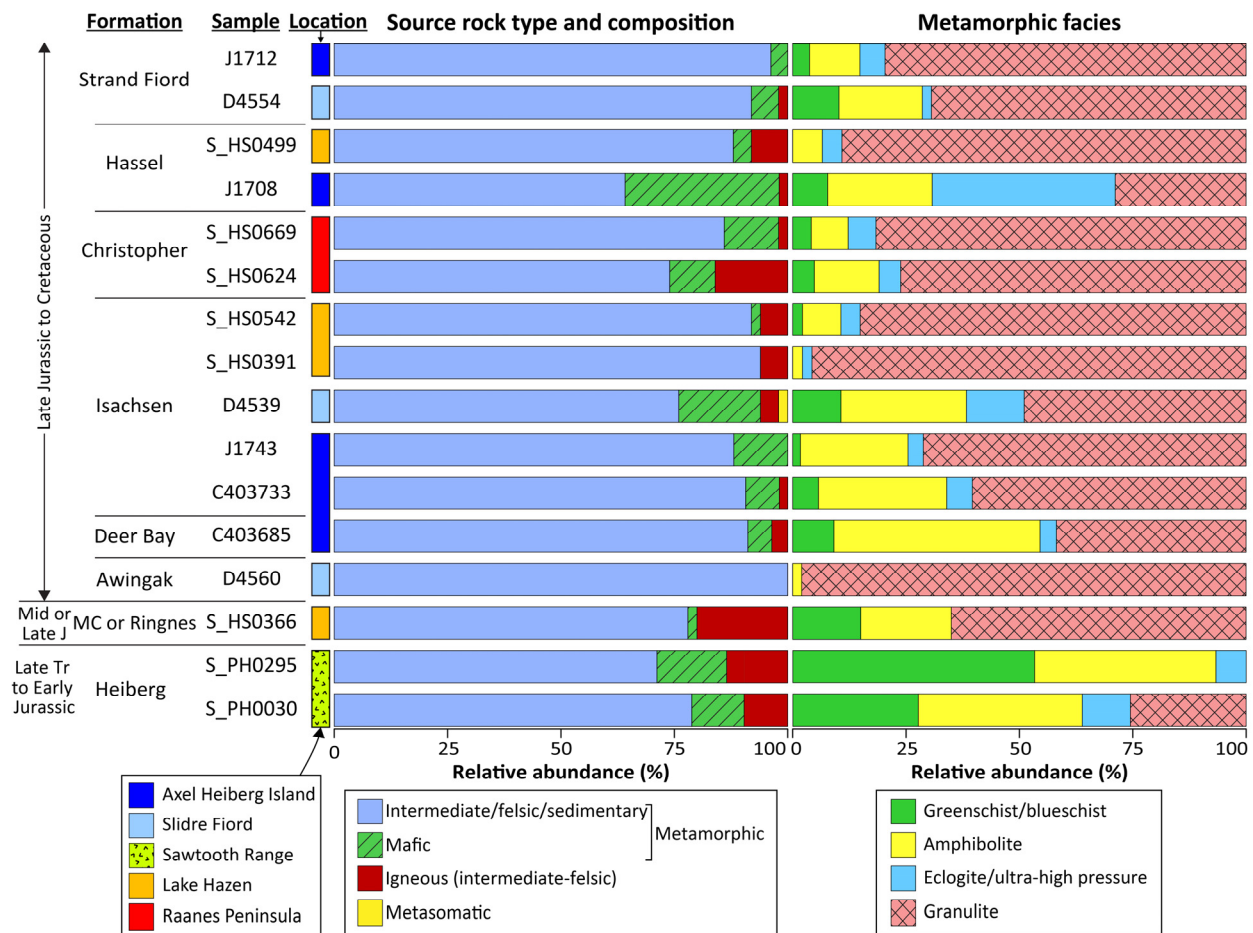


Figure 6. Bar chart summarising the likely source rocks from which the garnet grains were derived. Garnet grains were classified following Schönig et al. [109]. J = Jurassic; MC = McConnell Island; Tr = Triassic.

Garnet grains in samples S_PH0030 and S_PH0295 from the Late Triassic to Early Jurassic Heiberg Formation were predominantly sourced from greenschist- and amphibolite-facies rocks (Figure 6). Granulite-facies grains comprise the largest fraction in nearly all of the other samples analysed, followed by amphibolite-facies grains (Figure 6). Apart from J1712, samples analysed from northern Axel Heiberg generally have a lower proportion of granulite-facies grains than the rest of the Middle Jurassic and younger samples. Eclogite/ultra-high-pressure facies grains are particularly well represented in sample J1708; many of these are metamafic grains. Samples S_HS0624 and S_HS0366 contain 16–20% igneous grains; all other Late Jurassic and Cretaceous samples contain <9% igneous grains (Figure 6). The igneous grains are inferred to originate from rocks of intermediate to felsic composition.

4.5. Rutile Chemistry

Rutile grains from 13 samples were analysed for their trace element geochemistry (44 to 59 grains per sample). Metapelitic grains are more abundant than metamafic grains throughout (66–91% of grains; Figure 7). With the exception of samples from Lake Hazen, all samples are characterised by a high proportion of granulite-facies grains (48–68%), together with generally fewer amphibolite-facies grains (28–52%; Figure 7). In contrast, samples from Lake Hazen, from the Deer Bay (S_HS0474 and S_HS0475) and Isachsen (S_HS0542) formations, contain markedly fewer granulite-facies grains (32–33%) and a greater proportion of amphibolite grains (61–63%; Figure 7).

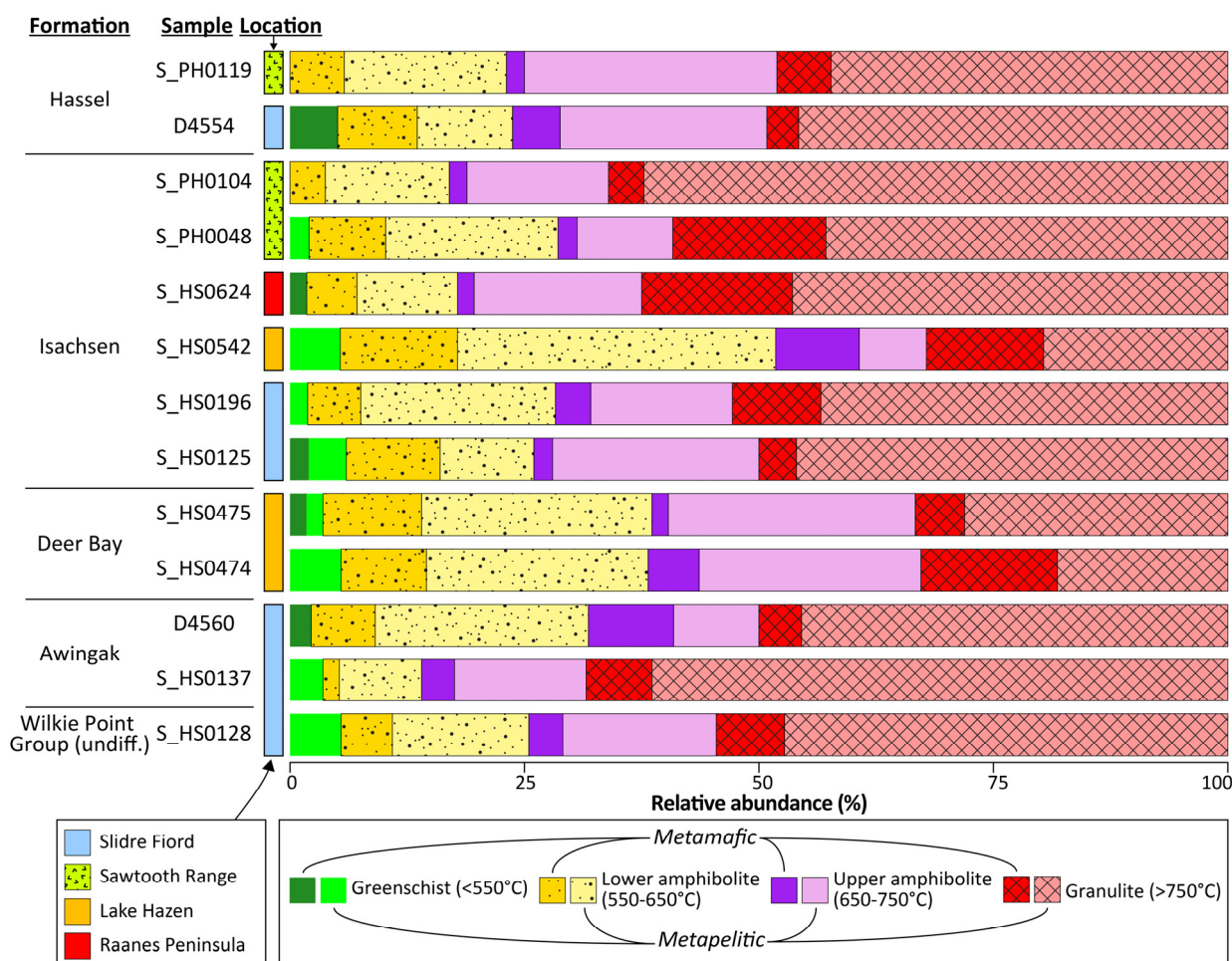


Figure 7. Bar chart summarising the likely source rocks from which the rutile grains were derived. The grains were classified into metapelite and metamafic types following Meinhold et al. [107]. Rutile temperatures were estimated using the Zr-in-rutile thermometer [108]. undiff = undifferentiated.

4.6. Detrital Zircon U–Pb Geochronology

Detrital zircon U–Pb age data have been obtained from 11 samples (Figure 8). Samples from the Hiccles Cove or Awingak Formation (S_HS0525), Deer Bay Formation (S_HS0475) and the Isachsen Formation (S_HS0391, S_HS0542) near Lake Hazen all have similar age spectra dominated by large *c.* 900–2100 Ma age groups, with fewer *c.* 380–490 Ma and sparse 2320–3000 Ma grains. Samples D4557, S_PH0104 and S_HS0624 contain a larger proportion of >2300 Ma grains than the other Isachsen Formation samples (Figure 8). Samples S_PH0113 and S_HS0669 (Christopher Formation) have contrasting age spectra (Figure 8); sample S_PH0113 contains a number of <600 Ma grains, including four Late Jurassic to Early Cretaceous grains (*c.* 105–161 Ma). Sample S_HS0669, instead, has a very similar age spectrum to S_HS0624 (nearby Isachsen Formation; Figure 8), although the spectrum from sample S_HS0669 is based on comparatively few analyses, in part because of a poor zircon yield. Sample S_HS0499 (Hassel Formation, Lake Hazen area) contains a high abundance of <600 Ma grains. In detail, these comprise numerous Carboniferous to Triassic (*c.* 229–341 Ma) grains, together with fewer older Paleozoic (*c.* 353–486 Ma) and Early Jurassic to Early Cretaceous ones (*c.* 121–196 Ma). In contrast, sample S_PH0119 (Hassel Formation, Sawtooth Range) is dominated by >1750 Ma ages; an age spectrum similar to sample S_PH0104 (nearby Isachsen Formation).

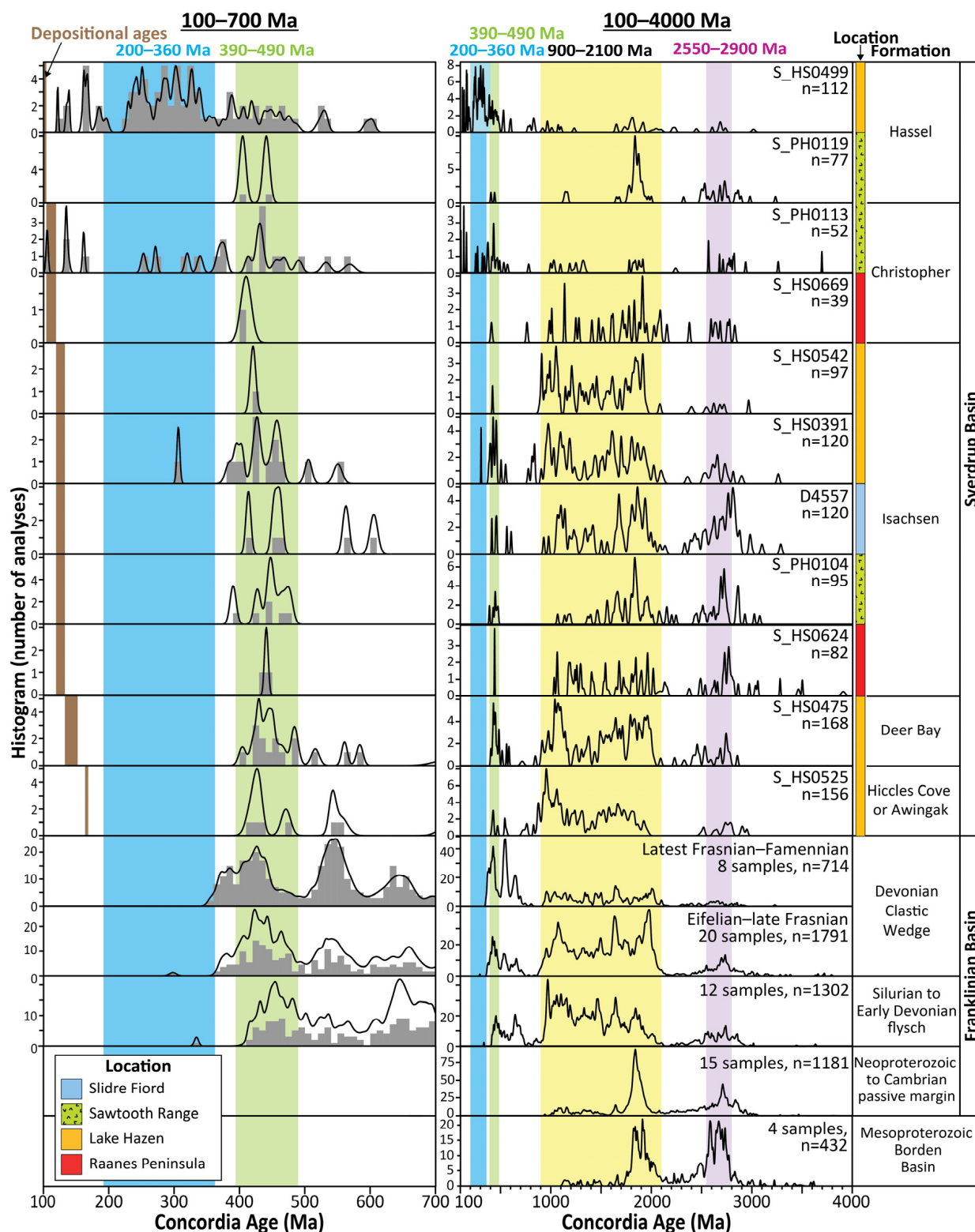


Figure 8. Probability density plots showing the detrital zircon U–Pb age data obtained from the Middle Jurassic to Cretaceous samples analysed. Data >10% discordant are not shown. Approximate depositional ages shown in the left-hand panel (brown bars) are from Figure 2. Histograms are also drawn in the left-hand plots (grey bars; 10 Ma bin width). The plots were drawn in R version 4.3 using the Detzrcr package [117]. Published data from the Franklinian Basin succession are from Anfinson et al. [38,39], Beranek et al. [42,46], Hadlari et al. [118], Malone et al. [119] and Spiegel et al. [11]. Data from the Borden Basin (one of the Bylot basins) are from Turner et al. [34]. *n* is the number of analyses used to construct each age spectrum.

4.7. Detrital Zircon Lu–Hf Isotopes

Forty-eight detrital zircons from Deer Bay Formation sample C403685 were analysed. Forty-six of these have corresponding U–Pb ages that meet the quality-control criteria defined in Section 3.2.4 and are considered robust; these are plotted in Figure 9A. Grains of 982–1721 Ma age yield -2.6 to $+7.5$ $\epsilon\text{Hf}_{(t)}$ values, whilst 1764–1860 Ma grains yield a wide range of $\epsilon\text{Hf}_{(t)}$ values from -20.7 to $+4.1$. Archean grains (2536–2839 Ma) yield -5.9 to $+2.6$ $\epsilon\text{Hf}_{(t)}$ values.

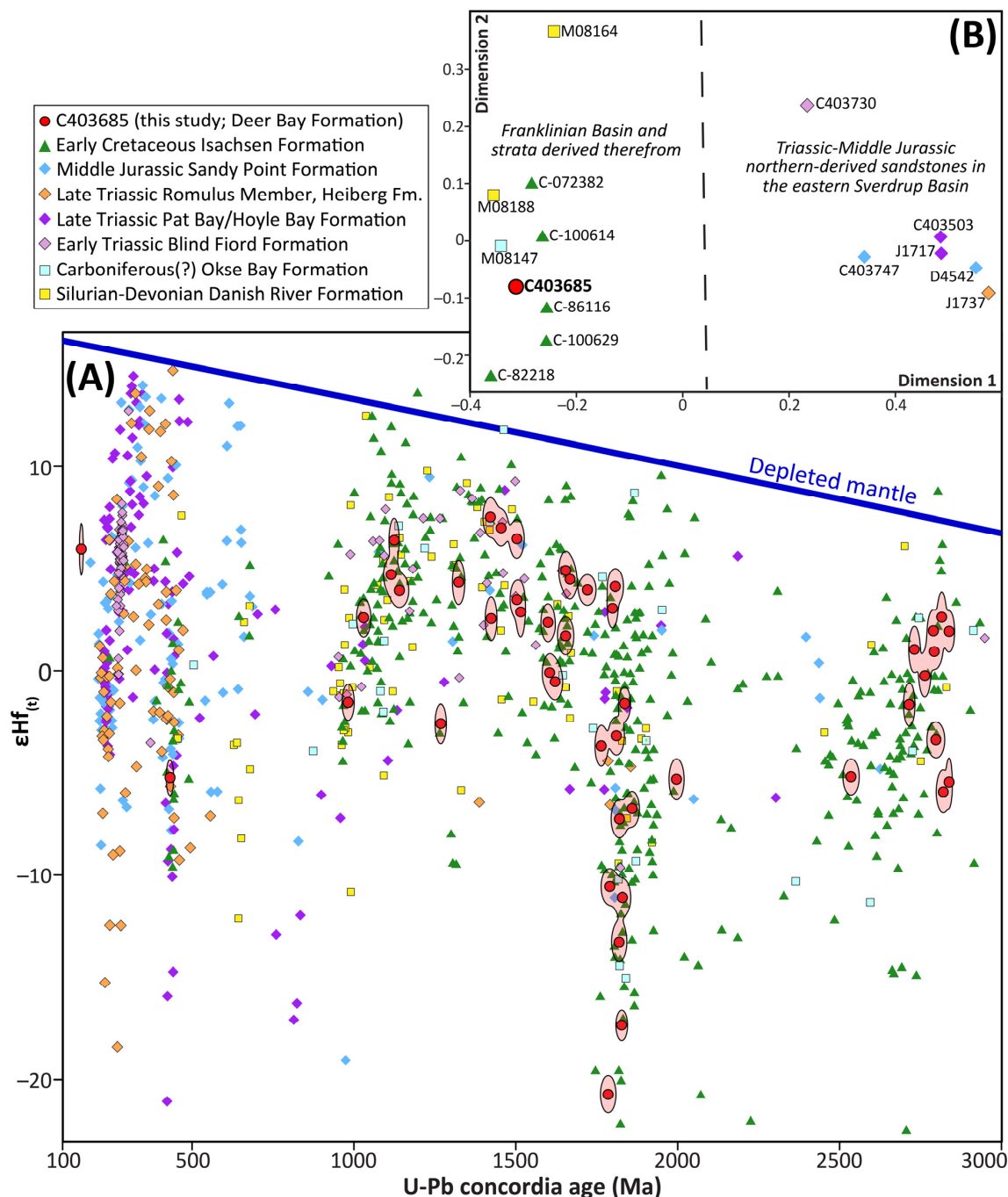


Figure 9. (A) U–Pb age versus $\epsilon\text{Hf}_{(t)}$ scatter plot showing data from sample C403685. Detrital zircon U–Pb age data from sample C403685 are from Omma et al. [23], whilst the combined U–Pb age and Lu–Hf isotope data from the Danish River, Okse Bay and Isachsen formations are from Malone et al. [119] and Røhr et al. [24]; all literature data were reprocessed using U–Pb concordia ages. Analyses with U–Pb ages >10% discordant are not shown. The red ellipses surrounding sample C403685 data points

are two-dimensional probability distributions drawn using analytical uncertainties in R version 4.3 using code modified from Sircombe [120]; they are drawn at the 2s confidence level. The depleted mantle trend is drawn assuming a present-day composition of $^{176}\text{Lu}/^{177}\text{Hf} = 0.0384$ and $^{176}\text{Hf}/^{177}\text{Hf} = 0.28325$ [121]. (B) Two-dimensional multidimensional scaling plot of U–Pb age and Lu–Hf isotope likeness. The analysis helps to visualise similarities and differences in detrital zircon U–Pb ages and $\epsilon\text{Hf}_{(t)}$ values for the data plotted in Figure 9A by reducing each sample dataset to a single point; samples that plot closer together have more similar U–Pb ages and $\epsilon\text{Hf}_{(t)}$ values than those that plot farther away. Dimension 1 primarily records the difference in zircon U–Pb ages and $\epsilon\text{Hf}_{(t)}$ values between: (1) northern-derived Triassic and Middle Jurassic sandstones of the eastern Sverdrup Basin, which are dominated by <600 Ma ages and include juvenile (positive) $\epsilon\text{Hf}_{(t)}$ values, and (2) samples of the Franklinian Basin or derived therefrom, which are characterised by older U–Pb ages and lack very juvenile $\epsilon\text{Hf}_{(t)}$ values. Dimension 2 reveals differences in U–Pb age and/or $\epsilon\text{Hf}_{(t)}$ values between samples within these two groups. Through this analysis, the dataset from sample C403685 is shown to be similar to the majority of samples from the Franklinian Basin or derived therefrom, supporting a Franklinian Basin provenance. This was indicated by the detrital zircon U–Pb age dataset and is corroborated by the new Hf isotope dataset. The plot was drawn using DZstats2D [122]. The data and symbology used are the same in both figures.

5. Discussion

5.1. Sediment Provenance

5.1.1. Middle Jurassic to Early Aptian (Wilkie Point Group to Isachsen Formation)

Samples from the Wilkie Point Group, as well as the Deer Bay, Awingak and Isachsen formations, are overwhelmingly quartz-rich, have restricted rock/lithic fragment assemblages dominated by mudstone, chert and quartzite types, and have stable heavy mineral assemblages dominated by zircon, tourmaline and rutile, with or without garnet. All of this is consistent with a predominantly sedimentary/metasedimentary provenance. The Awingak Formation is interpreted as being sourced from the southeast to east based on lateral thickness variations [16,123]. Facies trends and palaeocurrent vectors from the Isachsen Formation support the same sediment supply directions [16,124–127]. The Wilkie Point Group samples are compositionally similar to those from the Awingak, Deer Bay and Isachsen formations. They are also markedly different in composition from northern-derived samples of the Sandy Point Formation on northern Axel Heiberg Island, which contain abundant apatite, plagioclase and detrital zircons of Carboniferous to Triassic age [28]. Collectively, this supports a southeastern/eastern provenance for the Wilkie Point Group samples.

In detail, there are compositional differences between samples from: (1) northern Axel Heiberg, (2) the Lake Hazen area and (3) central Ellesmere Island (Raanes Peninsula, Slidre Fiord, Vendom Fiord and the Sawtooth Range). Samples from the Lake Hazen area generally contain less garnet, whilst kyanite and staurolite are almost entirely absent (Figure 4). They also contain a smaller proportion of granulite-facies rutile grains and more amphibolite-facies rutile grains compared to samples from central Ellesmere Island (Figure 7), although the garnet chemistry data indicates most of the garnet was sourced from granulite-facies rocks (Figure 6). Samples from the Hiccles Cove or Awingak (S_HS0525), Deer Bay (S_HS0475) and Isachsen formations (samples S_HS0391 and S_HS0542, and C-072382 from Røhr et al. [24]) from the Lake Hazen area have detrital zircon age spectra characterised by large c. 900–2100 Ma age populations (Figures 8 and 10). These are comparable to the Silurian to Middle Devonian strata of the Franklinian Basin succession. This is apparent through visual inspection of the respective probability density curves (Figure 8) and also through dissimilarity analysis (Figure 10). It follows that the Sverdrup Basin samples were likely reworked from this interval of the Franklinian Basin succession.

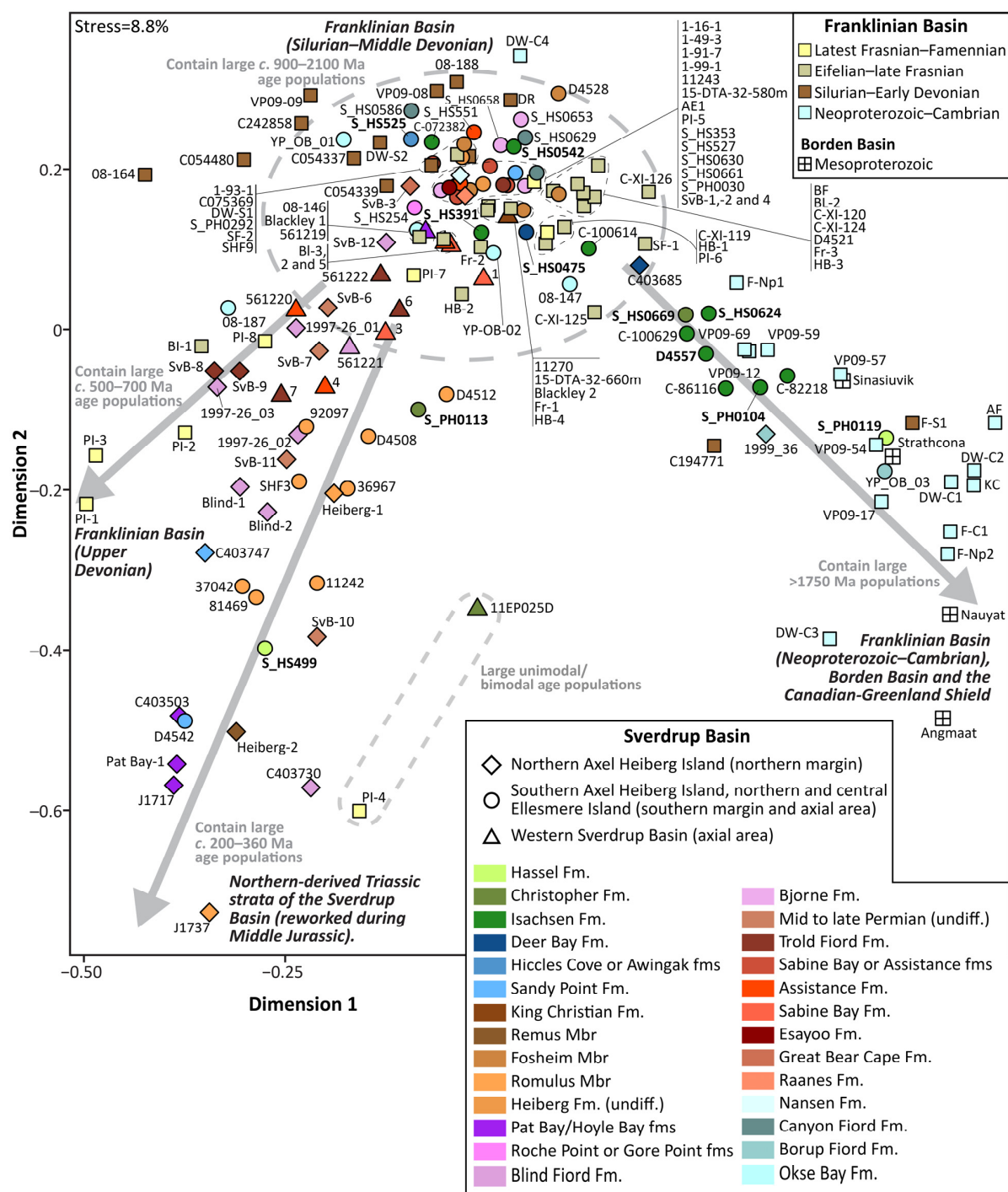


Figure 10. A two-dimensional multi-dimensional scaling plot showing the dissimilarity in U–Pb age spectra between samples from the Sverdrup, Franklinian and Borden basins. This analysis reveals that there are four distinct provenance-indicative age groups within the dataset, which, through inspection of the underlying data, are identified as c. 200–360, 500–700, 900–2100 and >1750 Ma. These lie towards the margins of the plot. Large c. 200–360 Ma age populations are prevalent in Triassic strata on the northern limb of the eastern Sverdrup Basin, whilst large c. 500–700 Ma age populations are common in the Upper Devonian levels of the Franklinian Basin. These two age groups are inferred as recording sediment input from the north of the Sverdrup and Franklinian basins, respectively; their sources are both enigmatic and contentious (e.g., see [18,20,28,38]). More importantly, however, by Middle Jurassic times, the enigmatic sediment transport systems supplying these zircons were no longer in operation. Consequently, where such detrital zircons are encountered

in the Middle Jurassic and younger samples of this study, they were likely reworked from local older strata (bold italic labels in the plot). Samples dominated by *c.* 900–2100 Ma ages are the most common within the available detrital zircon U–Pb age dataset. This group comprises samples from the Silurian to Middle Devonian strata of the Franklinian Basin and numerous Sverdrup Basin samples ranging from Carboniferous to Cretaceous age. Samples from the Borden Basin and Neoproterozoic–Cambrian levels of the Franklinian Basin are characterised by large >1750 Ma age groups (specifically *c.* 1750–2100 and 2250–2900 Ma age populations). As the Borden basins samples are inferred as being sourced from the Canadian–Greenlandic Shield [34], this age group likely also reflects direct shield sediment input. It is not possible to differentiate between a recycled (Franklinian/Bylot basins) and a direct shield input using detrital zircon U–Pb geochronology. Several samples form linear arrays between the end-member provenance-indicative age groups, which are picked out in the plot by the grey arrows. These samples possess more mixed age spectra; where they plot provides insight as to which sediment sources likely contributed detritus. Dissimilarity was estimated using the Kolmogorov–Smirnov statistic [128]. Samples analysed as part of this study have bold labels. All other samples are from the following literature sources: Sverdrup Basin = Alonso-Torres et al. [25], Anfinson et al. [18], Beauchamp et al. [129], Evenchick et al. [80], Galloway et al. [17], Hadlari et al. [19], Malone et al. [119], Midwinter et al. [20,21], Miller et al. [22], Omma et al. [23], Pointon et al. [28] and Røhr et al. [24]; Franklinian Basin = Anfinson et al. [38,39], Beranek et al. [42,46], Hadlari et al. [118], Malone et al. [119] and Spiegel et al. [11]; Borden Basin (one of the Bylot basins) = Turner et al. [34]. The figure was drawn in R version 4.3 using code from the Provenance package [130].

Samples analysed from central Ellesmere Island generally contain a higher proportion of garnet, staurolite, kyanite, monazite and granulite-facies rutile grains than coeval samples from the Lake Hazen area. Isachsen Formation samples from central Ellesmere Island are characterised by larger *c.* 2500–2800 Ma detrital zircon age populations than those from the Lake Hazen area (Figure 8; [24]) and are similar to Neoproterozoic to Cambrian strata within the Franklinian Basin succession (Figure 8). The high chemical stability of zircon and rutile excludes local diagenetic conditions as the root cause of these spatial compositional variations. In detail, the detrital zircon U–Pb age spectra from samples from central Ellesmere Island share age groups with both Neoproterozoic to Cambrian strata and Silurian to Middle Devonian strata of the Franklinian Basin, hence their intermediate position between these two stratigraphic packages in Figure 10. This mirrors whole-rock $\epsilon\text{Nd}_{(t)}$ values from the Isachsen Formation on central/southern Ellesmere Island and Axel Heiberg Island (−11 to −21), which lie between Silurian and Devonian strata (−5 to −14) and late Neoproterozoic to Ordovician strata of the Franklinian Basin (−17.8 to −25.5; all quoted $\epsilon\text{Nd}_{(t)}$ values are from Patchett et al. [4,45]). Taken together, the detrital zircon U–Pb age and whole-rock $\epsilon\text{Nd}_{(t)}$ datasets support the derivation of sediment on central Ellesmere Island from multiple levels within the Franklinian Basin succession. It has been argued that the Isachsen Formation was at least partially derived from the Canadian–Greenlandic Shield because it contains pebble- to cobble-sized clasts of vein quartz that are absent from the Franklinian Basin succession [4,16,126]. The available data from the Isachsen Formation overwhelmingly indicate a recycled (meta)sedimentary source; thus, whilst a direct contribution from metasedimentary units of the shield cannot be excluded, a detrital contribution from metaigneous rocks is unlikely. Pebbly sandstone and conglomeratic strata rich in quartz clasts are known from the Mesoproterozoic Bylot basins (e.g., [27,33,131]). Strata of the Borden Basin have yielded very similar detrital zircon U–Pb age spectra to Neoproterozoic–Cambrian strata of the Franklinian Basin succession (Figures 8 and 10). Erosion of Bylot basins' strata therefore offers a possible alternative source of quartz pebbles.

Samples from the Deer Bay and Isachsen formations on northern Axel Heiberg Island are also quartz-rich and have similar stable heavy mineral assemblages to coeval samples analysed from central Ellesmere Island. The detrital zircon U–Pb spectrum and Hf isotope

signature from sample C403685 are consistent with a reworked provenance from predominantly Silurian and younger strata of the Franklinian Basin. The northern Axel Heiberg Island samples lack sizeable amounts of apatite, feldspar and/or Permo-Triassic detrital zircon, which characterise northern-derived sediments [28], and were most likely derived from the southeast/east. This was suggested previously for sample C403685 by Omma et al. [23]. The Deer Bay (C403685) and Isachsen Formation samples (J1743 and C403733) generally contain fewer granulite-facies garnet grains than many of the coeval samples from Slidre Fiord, the Lake Hazen area and the Raanes Peninsula (D4560, S_HS0391, S_HS0542, S_HS0624; Figure 6). The reasons for this are unclear, but downstream mixing of sediment supplied from different systems that sampled different levels within the Franklinian Basin succession cannot be excluded.

In summary, the available data from the Lake Hazen area support a dominant detrital input from Silurian and younger levels within the Franklinian Basin succession to the southeast/east (Figure 11A,B). An additional, smaller detrital contribution from lower levels within the succession is still likely, however, to account for the granulite-facies garnet and rutile grains. Conversely, samples from central Ellesmere Island contain a much greater proportion of higher-grade, granulite-facies detritus. This suggests that these areas were likely fed from a distinct sediment supply system (Figure 11A,B). The higher-grade, granulite-facies detritus was likely supplied from the Neoproterozoic–Cambrian levels of the Franklinian Basin succession and/or the Bylot basins, although a direct input from metasedimentary units of the Canadian–Greenlandic Shield cannot be excluded. The data from the northern Axel Heiberg Island samples are also consistent with a southeast/eastern sediment source (Figure 11A,B).

5.1.2. Late Aptian to Albian (Christopher Formation)

Samples S_HS0669, J1707–J1709, S_PH0107 and S_PH0109 from the Christopher Formation on central Ellesmere and northern Axel Heiberg Islands are quartz-rich (Figure 3) and compositionally similar to local Isachsen Formation samples (Section 5.1.1). Consequently, they likely share predominantly the same sediment source area. These samples, however, contain slightly greater amounts of apatite than the underlying local Isachsen Formation, which may indicate a first-cycle input from the Canadian–Greenlandic Shield or alternatively an air-fall volcanic input from HALIP volcanic centres to the north of the basin. U–Pb isotope dates from the apatite grains are needed to differentiate between these possibilities.

Samples S_PH0111–0113 from the middle of the Christopher Formation in the Sawtooth Range have markedly more immature (arkosic) composition than samples S_PH0107 and S_PH0109 from lower in the formation (Figure 3). Sample S_PH0113 contains several <360 Ma detrital zircons, which are characteristic of northern-derived Late Triassic to Middle Jurassic strata [28] and strongly support sediment supply from the north/northeast at this time (Figure 11C). One of these grains (105.5 Ma) is indistinguishable in age to a hyalotuff at the top of the Invincible Point Member on Ellef Ringnes Island [80]. This, together with the immature composition of these samples, points to an influx of volcanic detritus at this time, which was likely supplied from HALIP volcanic centres to the north and/or northeast of the basin [16,75,80]. Volcanic-rich sandstones of the middle Christopher Formation are known from Ellef Ringnes Island and northern Axel Heiberg Island (Figure 1B; [16,75,80]); the data from samples S_PH0111–0113 support that volcanic detritus was transported at least as far south as the Sawtooth Range at this time (Figure 11C). Samples S_HS0086 and S_HS0501, from Slidre Fiord and Lake Hazen, respectively, are both very apatite-rich (Figure 4) and probably contain a first-cycle volcanic component, although further analysis is needed to confirm this.

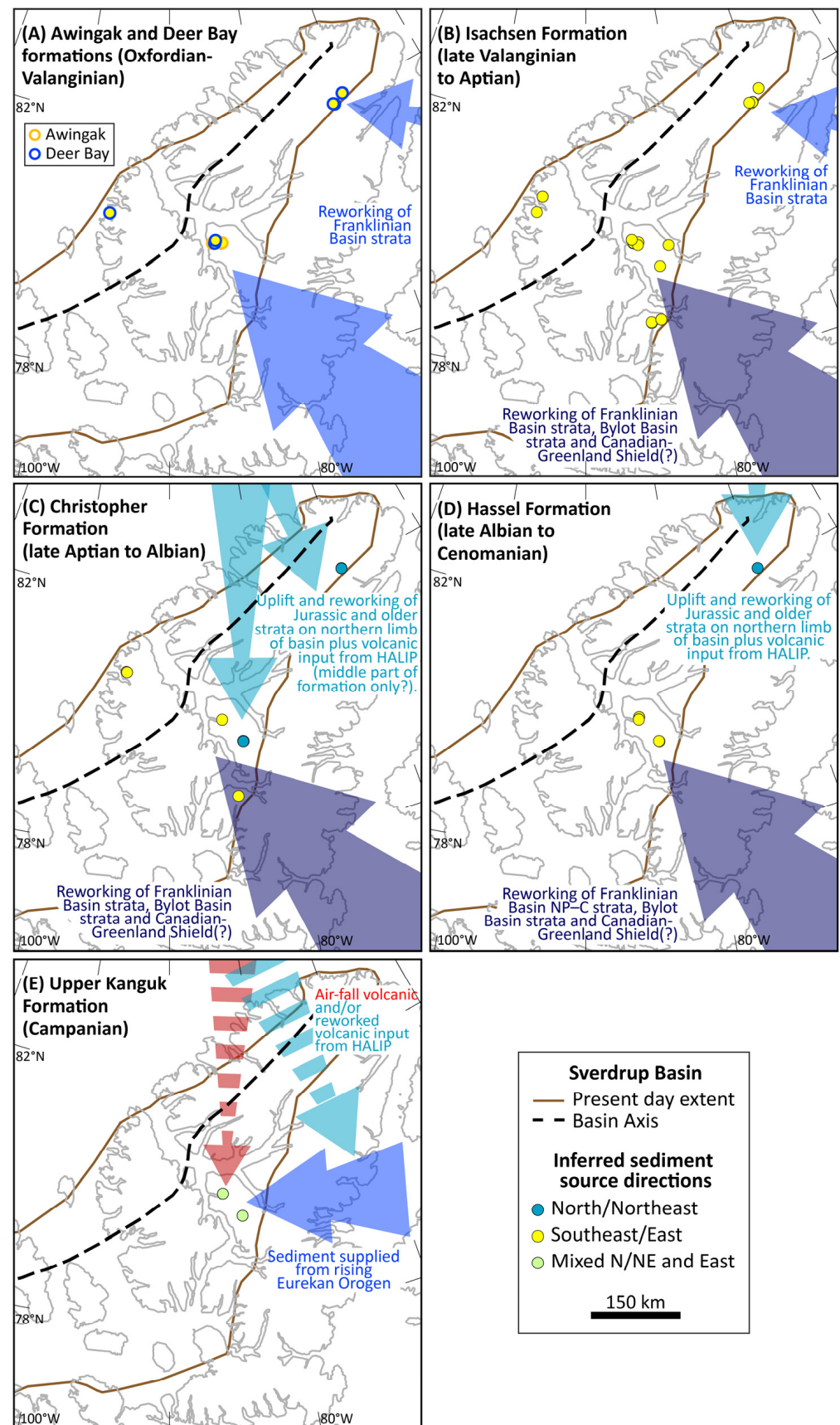


Figure 11. (A–E). Maps showing inferred sediment supply directions and sources for Late Jurassic to Cretaceous lithostratigraphic units of the Sverdrup Basin. The basin axis is redrawn from Embry and Beauchamp [15]. All plots are drawn at the same scale. NP–C = Neoproterozoic–Cambrian.

Sample S_PH0113 also contains some >600 Ma detrital zircons (Figure 8), which likely reflect a recycled detrital contribution from Franklinian Basin strata. The >600 Ma age populations are poorly resolved in the limited dataset from this sample; dissimilarity analysis tentatively supports the reworking of Silurian to Middle Devonian Franklinian Basin strata (Figure 10). Consequently, these grains were likely reworked from older, mixed (north/northeast and southeast/east)-provenance Sverdrup Basin rocks rather than sourced from Franklinian Basin strata to the southeast/east directly. This is because, by this time, sediment supplied to central Ellesmere Island from the southeast/east contained a greater proportion of >1750 Ma detrital zircons (e.g., samples S_H0669 and S_PH0104; Figures 8 and 10), which are indicative of detritus eroded from Neoproterozoic–Cambrian levels of the Franklinian Basin succession, the Bylot basins and the Canadian–Greenlandic Shield (Figure 11C).

5.1.3. Late Albian to Cenomanian (Hassel and Strand Fiord Formations)

Hassel Formation samples analysed from the Sawtooth Range and Slidre Fiord have dissimilar quartz abundance but similar rock/lithic fragment and heavy mineral assemblages (Figures 3 and 4). Rutile and garnet chemistry data indicate a high proportion of detritus from granulite-facies metasedimentary rocks (Figures 6 and 7). On balance, these samples were likely derived from sedimentary and metasedimentary rocks. Sample S_PH0119 has a detrital zircon age spectrum that is similar to Neoproterozoic–Cambrian strata of the Franklinian Basin succession (Figures 8 and 10). Consequently, sediment supplied from the southeast/east was now largely, or entirely, sourced from the Neoproterozoic–Cambrian part of the Franklinian Basin succession, the Bylot basins and/or the Canadian–Greenlandic Shield directly (Figure 11D).

Sample S_HS0499 (Lake Hazen area), in contrast to the other Hassel Formation samples analysed, has a more diverse heavy mineral assemblage and contains numerous Carboniferous to Triassic grains that are common in northern-derived Late Triassic and Middle Jurassic sandstones (Figure 10; [18–20,23,28]). The apatite grains in this sample were derived from predominantly mafic/intermediate igneous rocks (Figure 5). These data collectively support a dominant sediment input from the north and/or northeast at this time, from an area comprising Early Cretaceous volcanic rocks and Late Triassic and/or Middle Jurassic sandstones bearing Carboniferous–Triassic detrital zircons (Figure 11D).

Conglomeratic samples intercalated with basaltic lavas of the Strand Fiord Formation on northern Axel Heiberg Island (J1711 and J1712) are compositionally similar to nearby samples from the underlying Deer Bay and Isachsen formations. The overall coarse grain size of these samples unequivocally indicates local derivation. They were probably reworked from Late Jurassic to Early Cretaceous strata that were themselves derived from the southeast/east of the basin.

5.1.4. Campanian (Upper Kanguk Formation to Lower Expedition Formation)

Sandstone samples from the upper Kanguk Formation or the Lower Member of the Expedition Formation at Slidre Fiord and in the Sawtooth Range are compositionally immature (S_PH0268) and have diverse heavy mineral assemblages that include epidote and apatite (S_HS0036, S_HS0037 and S_PH0268). Sample S_HS0036 also contains trace amounts of arfvedsonite, which is common in peralkaline granites and syenites (e.g., [132]). Chemical analysis of apatite grains in sample S_HS0036 suggests that they were largely derived from mafic/intermediate igneous rocks (Figure 5). Diagenetically altered volcanic ash layers (bentonites) occur within the adjacent 30 m above and below sample S_PH0268, demonstrating an air-fall volcanic input to the basin during this time interval, from HALIP volcanic centres to the north of the basin [90,91]. Aside from the clear volcanic component,

the sedimentary rock fragments and probably also the garnet content suggest a recycled detrital contribution from sedimentary and metasedimentary rocks. The Lower Member of the Expedition Formation has been interpreted as the product of a west- or southwest-prograding wave-dominated delta system [59,133]. The data strongly indicate a mixed volcanic and reworked provenance for these samples, although it is unclear whether the volcanic component was air-fall or reworked (as reflected by the two dashed arrows shown in Figure 11E). It is likely that the rejuvenation in sediment supply represented by this member records an early expression of Eurekan deformation (e.g., [134]).

5.2. Regional Implications

Before Middle Jurassic times, detritus originating from the southeast to east of the Sverdrup Basin was sourced predominantly from the upper (Silurian and Devonian) levels of the Franklinian Basin [28]. From Middle Jurassic times, samples from central Ellesmere Island contain an increased proportion of high-grade metamorphic detritus, as indicated by an increased abundance of garnet, granulite-facies garnet and rutile grains, and Paleoproterozoic and older detrital zircon grains (Figure 12). This is interpreted to reflect provenance change driven by exhumation within the sediment source area. Exhumation is first apparent within the Wilkie Point Group and is marked by an increase in the proportion of granulite-facies rutile grains (S_HS0128; Figure 12). Samples D4544 and S_HS0129 (both Wilkie Point Group) contain much more garnet than all of the older samples analysed by Pointon et al. [28], although only a limited number of heavy minerals were recovered from these two samples. Furthermore, the other samples analysed from the same discontinuous section as sample S_HS0129 (i.e., S_HS0128, S_HS0130 and S_HS0131) lack significant garnet. This could reflect fluctuations in the intensity of acidic weathering or indicate that garnet-rich sediment was only supplied intermittently at this time. Garnet is generally abundant in samples from the Late Jurassic onwards (Awingak and Deer Bay formations, and younger; Figure 12). By at least Early Cretaceous times (Isachsen Formation) there was a shift in detrital zircon U–Pb ages, which is consistent with a greater proportion of detritus derived from the lower levels of the Franklinian Basin succession, the Mesoproterozoic Bylot basins and/or the Canadian–Greenlandic Shield (Figures 8 and 10). By Albian to Cenomanian times (Hassel Formation), the detrital contribution from the upper levels of the Franklinian Basin was greatly diminished, based on the reduction in number of <1750 Ma detrital zircons (Figure 8). Consequently, exhumation of the southeastern/eastern source area was underway from least Middle Jurassic times and continued into the Late Cretaceous, spanning at least 70 Myrs.

The increase in garnet abundance upwards through the stratigraphy, in isolation, could record burial diagenesis, with older, more deeply buried samples having lost garnet preferentially. However, the strong correlation between the increased abundance of garnet and granulite-facies rutile grains argues against this possibility. Moreover, several studies have shown that as burial depth increases, Ca-rich garnet is preferentially lost (e.g., [104,135,136]); however, in this instance, Ca concentrations are, on average, highest in the oldest samples analysed from the eastern Sverdrup Basin (Carboniferous; [28]), and there is no significant inverse correlation between Ca concentration and stratigraphic age. Therefore, the change in garnet grain chemistry up-stratigraphy, from Fe–Mn dominated types (greenschist- and amphibolite-facies types; Figure 12) to those containing more Mg (granulite-facies types; Figure 12), is probably not the result of diagenesis.

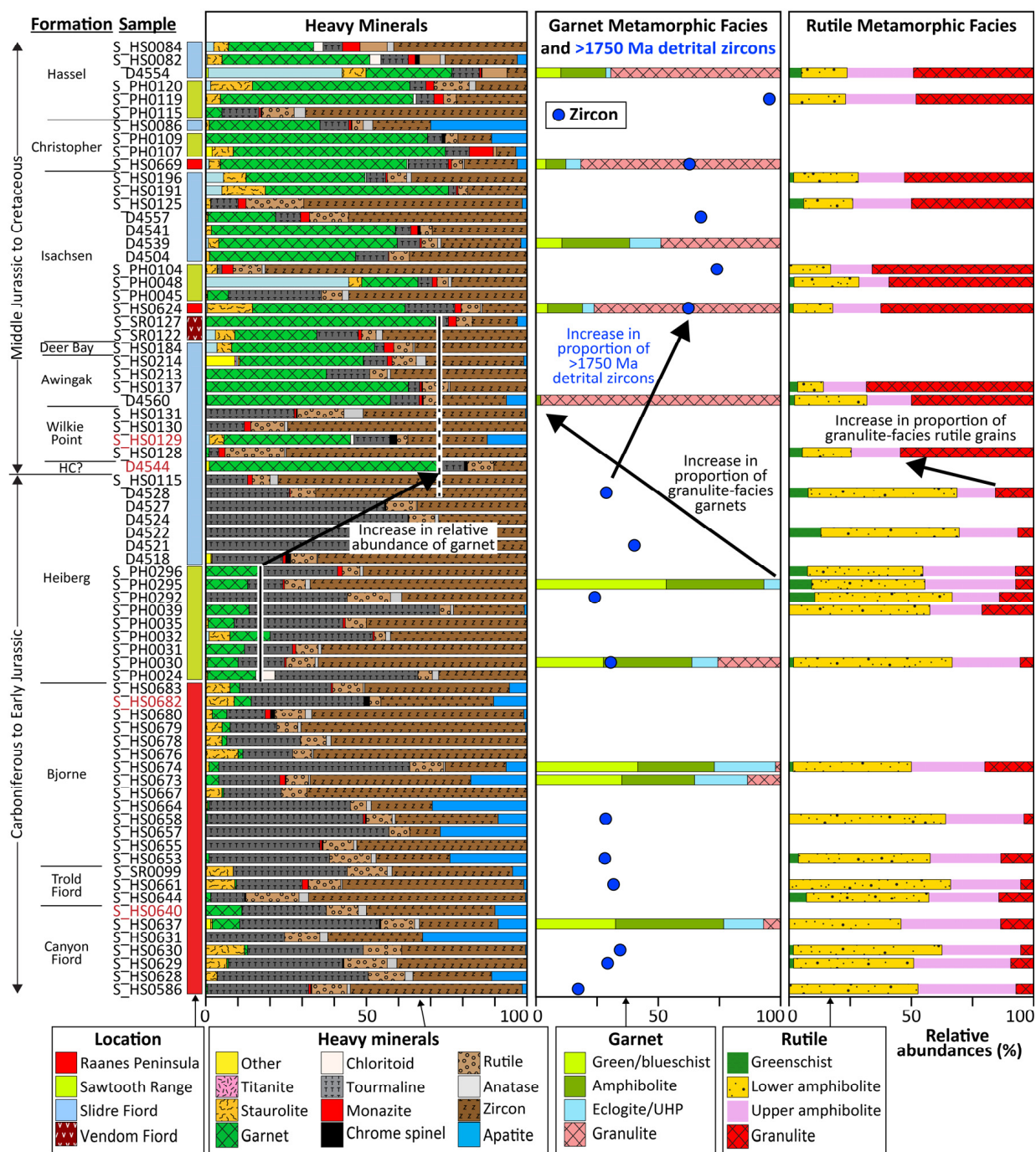


Figure 12. A summary diagram illustrating the main changes in sediment composition that are interpreted to indicate exhumation of the sediment source area. Only samples from central Ellesmere Island with an inferred southern/eastern provenance direction are included in the figure. The black arrows indicate the stratigraphic resolution of the changes in composition observed; a shift towards increasing metamorphic grade, through inferred exhumation, is first recorded in Middle Jurassic sandstones of the Wilkie Point Group, as an increase in abundance of garnet and granulite-facies rutile grains. The increase in abundance of >1750 Ma detrital zircons up-section marks a decreasing sediment contribution from Silurian–Middle Devonian strata of the Franklinian Basin and an increasing contribution from Neoproterozoic–Cambrian strata of the Franklinian Basin, strata of the Bylot basins and/or the Canadian–Greenlandic Shield. Sample numbers in red mark heavy mineral assemblages based on <100 counts. Data from the Heiberg and older formations are redrawn from Pointon et al. [28]. HC = Hiccles Cove; UHP = ultra-high pressure.

Whilst the case for exhumation is clear, the size of the southeastern/eastern source area and the mechanisms driving exhumation are not. The compositional data presented herein can be reconciled by a solely Franklinian Basin succession source, therefore necessitating only a relatively small catchment area. However, the presence of vein quartz pebbles and cobbles in the Isachsen Formation has been argued to indicate derivation from the Canadian-Greenlandic Shield [4,16,126], whilst isotopic data argue against sediment derivation from the closest exposed parts of the shield on Ellesmere Island [24]. Thus, a much larger catchment area is required from at least Early Cretaceous times. Based on the inferred sediment supply direction and the available compositional data, the source region for these Sverdrup Basin strata was likely the area now occupied by at least northwestern Greenland, northern Baffin Bay and Baffin Island, as envisaged by Balkwill [29]. The lack of Jurassic to Barremian strata in these areas lends weight to the idea that they may have been exposed and undergoing erosion at this time.

Complicating matters further, the Jurassic and Cretaceous were times of abundant tectonic and magmatic activity in the Arctic realm, including the opening of the Baffin Bay–Labrador Sea, the North Atlantic Ocean and the Amerasia Basin. Furthermore, the emplacement of the HALIP and, latterly, the onset of the Eurekan Orogeny also occurred. All of these processes could potentially have driven exhumation. Our understanding of Arctic geological history is fragmentary, with several points of contention existing. For example, it is generally accepted that the Amerasia Basin opened by Arctic Alaska and Chukotka rotating counter-clockwise away from Arctic Canada [137]. However, when rifting started is debated (*cf.* [21,57,137–139]), as is the timing and duration of sea floor spreading (*cf.* [95,137,140,141]).

The appearance of higher-grade metamorphic detritus in the samples from central Ellesmere Island broadly correlates with the deposition of northern-derived sandstones of the Sandy Point Formation on the northern limb of the basin (e.g., [16,28,142]). The composition of the latter sandstones is consistent with the reworking of local Triassic strata [28], suggesting uplift along at least part of the Sverdrup Basin margin at this time. Moreover, in the southwest corner of the Sverdrup Basin (Prince Patrick Island area; Figure 1B), there is evidence of extension and subbasin development at this time [58,143], which has been interpreted to mark the onset of rifting in the adjacent Amerasia Basin [15,57]. Uplift and exhumation in the Sverdrup Basin southeast/east source area could be a distal response to rifting. In which case, uplift elsewhere along the rifting margin would be expected. Both northern Svalbard and eastern North Greenland are interpreted to have experienced uplift during the Late Jurassic (Figure 13A; [144–146]), although only two of the Svalbardian samples analysed by Dörr et al. [144] yielded Jurassic fission track ages; the rest have Cretaceous and younger ages, several of which overlap with HALIP magmatism (*cf.* [76]). Sediment supplied to the Lake Hazen area of the Sverdrup Basin lacks an obvious exhumation trend. Consequently, if the Amerasia Basin started to open during the Middle Jurassic, then its effect on exhumation rates to the southeast/east of the Sverdrup Basin was limited.

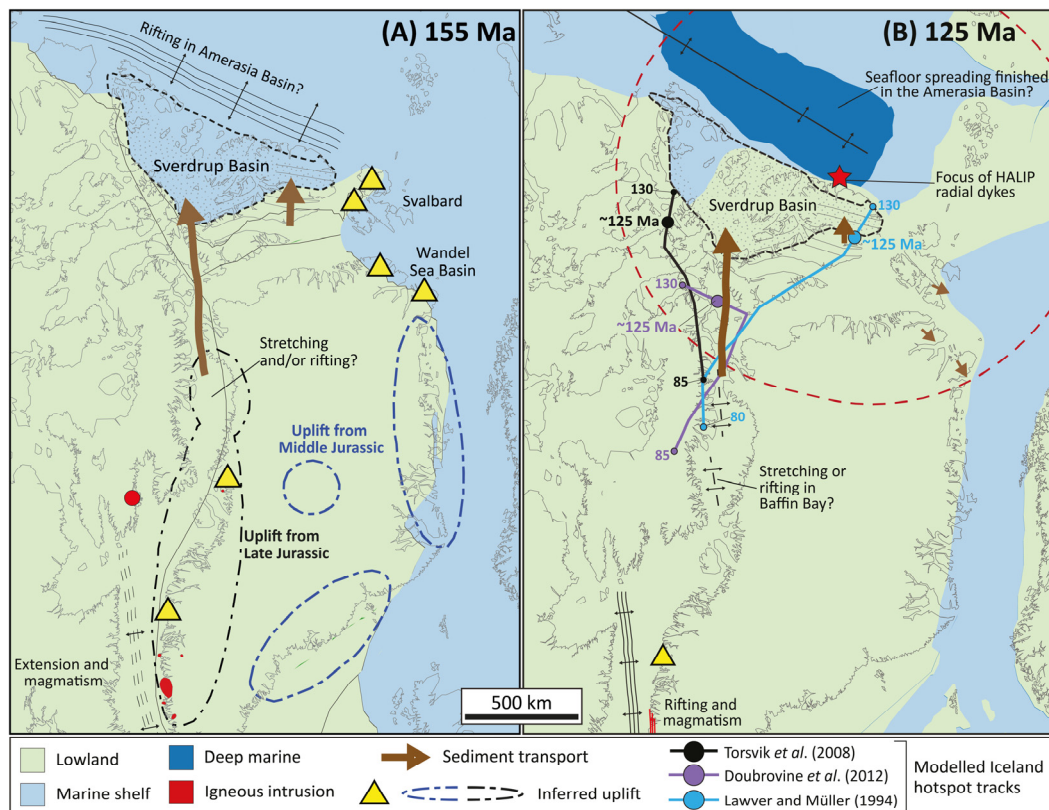


Figure 13. Schematic palaeogeographic reconstruction at (A) 155 Ma (Kimmeridgian) and (B) 125 Ma (Barremian–Aptian). The figures were drawn in GPlates v. 2.5 [147,148]. The palaeogeography is from Cao et al. [149]; the palaeogeography drawn in (B) was modified according to Embry [16], Ineson et al. [150] and Olausson et al. [145]. Instances of inferred uplift are drawn from the works of Danišík and Kirkland [151], Dörr et al. [144], Japsen et al. [152], Jess et al. [153] and Olausson et al. [145]. Igneous intrusions on Baffin Island and southwest Greenland are redrawn from Heaman et al. [154] and Larsen et al. [155], respectively. The focus of the HALIP radiating dyke swarm (red star) is redrawn from Buchan and Ernst [156]; the red dashed circle in (B) denotes the approximate radius of uplift from this focal point inferred from the work of Ineson et al. [150]. Inferred Iceland hotspot tracks [157–159] are also illustrated; note that the Doubrovine et al. [157] and Torsvik et al. [159] models are redrawn from Gaina et al. [160]. (A,B) are drawn at the same scale and use the same symbology.

The Canadian–West Greenland conjugate margin also experienced extension and uplift during Late Jurassic and Cretaceous times (e.g., [153,155]), although unravelling the pre-Cenozoic exhumation history of the section proximal to the Sverdrup Basin is complicated by subsequent Eurekan orogenesis. Farther south along the West Greenland margin, dyke emplacements and changes in dyke composition indicate extension from Late Triassic times, with increased intensity during the Late Jurassic (c. 150 Ma), followed by regional rifting and further dyke emplacement during Early Cretaceous times (c. 133–140 Ma; [155]). (U–Th–Sm)/He isotope data from central West Greenland point to Middle Jurassic to Early Cretaceous uplift, which is interpreted as rift-flank uplift [149]. Late Jurassic and Early Cretaceous exhumation of southern and central West Greenland has also been inferred from apatite fission track data [152,153,161,162]. Whether extension and associated uplift within the West Greenland incipient rift zone propagated sufficiently far north to affect the inferred source area for the Sverdrup Basin is uncertain, although the timing of these events correlates with the deposition of the Awingak Formation (Figure 13A) and the lower part of the Isachsen Formation in the Sverdrup Basin, suggesting that the two may be related.

The emplacement of the Cretaceous HALIP also caused regional-scale uplift. This is clear from the input of north/northeastern-derived volcanic-rich sediments into the Sverdrup Basin during the deposition of the Christopher and Hassel formations (Figure 11C,D). Moreover, regressive sedimentation patterns during Hauterivian and younger times in the Canadian Arctic Islands, northern Greenland and Svalbard have been correlated and attributed to HALIP-related regional thermal doming, centred to the north of present-day Ellesmere Island [81,150,163]. Radiating dykes of c. 120–138 Ma age converge at a similar location (Figure 13B; [156]), which has been interpreted to mark the location of a mantle plume head [75,81,156,163]. Ineson et al. [150] inferred that HALIP uplift reached at least as far as northeast Greenland. This distance, when extended as a radius from the HALIP dyke convergence point, is sufficient to have affected the area to the southeast and east of the Sverdrup Basin (Figure 13B). Numerical and fluid dynamic models predict domal uplift of up to 1–2 km as a mantle plume impinges on the base of the lithosphere (e.g., [164–166]). The amount of uplift is notoriously difficult to measure, however, as reflected by widely varying estimates from the same large igneous province; for example, uplift estimates for the Emeishan Traps range from 0 to more than 1000 m (*cf.* [167,168]). Consequently, whilst there is evidence to support some regional-scale uplift from the emplacement of the HALIP, its overall magnitude and how much of this reached the south to east periphery are unconstrained. Conversely, the Iceland plume, which may or may not be related to HALIP magmatism [158,160,169,170], has been modelled as passing underneath the area to the south and/or east of the Sverdrup Basin during the Cretaceous (Figure 13B), on the way to its present location. If this is broadly correct, then the Iceland plume is perhaps more likely to have promoted uplift and exhumation of the inferred sediment source area than the emplacement of the HALIP magmatism farther to the north, by virtue of its closer proximity.

There is also the possibility that more cryptic crustal and/or mantle processes contributed to exhumation. The Sverdrup Basin succession contains numerous widespread unconformities [15,171,172], which have been inferred to record the effects of epeirogenic uplift, possibly due to intermittent changes in the speed and direction of tectonic plates [172]. The formation of intraplate inversion structures is controversial, however (e.g., [173] and references therein). Whilst the action of such processes cannot be excluded, in this instance, unequivocal geological evidence for their existence is lacking.

The progradations of the Sandy Point, Hiccles Cove, Awingak, Isachsen and Hassel formations into the Sverdrup Basin record intervals of increased sediment supply (e.g., [7,16]). Forced eustatic regression can be excluded as a driving mechanism since these progradational episodes occurred during an interval of rising sea levels (Figure 2; [174–177]). They could reflect pulses of uplift in the sediment source area arising from one or more of the aforementioned tectono-magmatic events, although the possibility that they are partly climate-controlled merits consideration. The exhumation trend is first apparent in samples from the Wilkie Point Group, although these could be from the Sandy Point (late Toarcian to Aalenian; [16,96]) or Hiccles Cove (Bathonian to Callovian; [96]) formations. A comparison with global temperature records suggests that both formations were deposited during intervals of inferred climatic cooling (Figure 2; e.g., [71,93,178–181]). Several studies have documented an increase in erosion rates during late Cenozoic cooling (e.g., [182–186]). The underlying driving mechanisms are debated; however, there is general agreement that it is linked to the presence of glacial ice. There is a lack of physical evidence for ice in the proximity of the Sverdrup Basin during Middle Jurassic times. Based on estimated palaeotemperatures [93], significant ice likely only occurred if there was existing topography. Conversely, the initial deposition of the Awingak, Isachsen and Hassel formations occurred during warming intervals (Figure 2). The Awingak and

Isachsen formations were deposited under more variable temperatures (Figure 2); this is likely in part a reflection of the longer duration of deposition, although the possibility that a transitory, more variable climate facilitated enhanced denudation and sediment supply cannot be excluded. Precipitation trends are more difficult to assess. In broad terms, numerous reconstructions have inferred that sea level was relatively low during the Triassic Period, rose during Jurassic times and was high during the Cretaceous Period (e.g., [94,174–176,187–192]). In detail, estimates as to when the sea level started to rise range from Late Triassic (e.g., [94]) to Late Jurassic (e.g., [191]) times. Rising sea levels have been linked with the southward expansion of humid climate belts across North America during Late Jurassic to Cretaceous times [65,193]. It is possible that the deposition of sand-rich Middle Jurassic to Cretaceous units in the Sverdrup basin (Sandy Point to Hassel formations; Figure 2) is a reflection of this, with these units recording enhanced erosion of the sediment source area and/or sediment supply to the basin brought about by increased humidity, precipitation and ultimately sea level. The palynology dataset from the Sverdrup Basin also offers some support for this by indicating that humid conditions prevailed during at least the deposition of the Sandy Point, Isachsen and Hassel formations [63,71,73,74,99]. As climate exerts a fundamental control on physical erosion and chemical weathering rates, it is highly likely that it contributed to exhumation. Its significance relative to the other potential tectono-magmatic driving forces is, however, obfuscated by the resolution of the local climate record and sample ages. The effects of climate change would have been felt more severely in the sediment source area if significant topography existed. This would have increased the chance of alpine glacial ice formation and promoted orographic rainfall. Therefore, it may have been that climate modulated longer-term exhumation driven by tectono-magmatic processes.

Setting aside its uncertain origins, recognition of exhumation in the area to the south-east/east of the Sverdrup Basin from at least Middle Jurassic times offers a possible resolution as to whether the basin underwent rifting during Jurassic times. The Jurassic to Early Cretaceous sedimentary fill of the basin has been shown to thicken northwestwards and has been interpreted to record syn-rift sedimentation [53]. This has been used to argue in favour of Jurassic rifting in both the Sverdrup Basin and the adjacent Amerasia Basin [53,95]. Jurassic rifting in the Sverdrup Basin is contentious because, apart from in the southwest corner of the basin [58], there is no clear evidence of normal faulting within the basin at this time [15]. If exhumation and uplift affecting the southeastern Sverdrup Basin source area propagated northwards and impinged on the Sverdrup Basin, then it follows that its effects would have been felt more severely in the southeast of the basin compared to the northwest. Consequently, the asymmetric geometry of the Jurassic to Early Cretaceous sedimentary fill could reflect a reduced subsidence rate in the southeastern part of the basin rather than rifting in either the Sverdrup Basin or the adjacent Amerasia Basin.

6. Conclusions

Middle Jurassic to Cretaceous sandstones were analysed from the eastern Sverdrup Basin using a combination of optical petrography, conventional heavy mineral analysis, mineral grain chemistry, detrital zircon U–Pb geochronology and detrital zircon Hf isotope analysis. Samples from the Wilkie Point Group to the lower Christopher Formation and from the Hassel Formation are overwhelmingly quartz-rich and have restricted heavy mineral assemblages. They were predominantly to entirely reworked from strata of the Franklinian Basin and the Bylot basins to the southeast and/or east. Samples from central Ellesmere Island contain an increasing proportion of high-grade metamorphic detritus from Middle Jurassic times onwards. This is interpreted to reflect exhumation of the area

to the southeast of the Sverdrup Basin from Middle Jurassic to Late Cretaceous times. The mechanisms driving exhumation are less clear owing to there being several processes that could have contributed. Exhumation may have its origins in Middle Jurassic extension and uplift along the northwest Sverdrup Basin margin. Samples from northern Ellesmere Island show no such exhumation trend, however, possibly arguing against large-scale rifting at this time. Late Jurassic to Early Cretaceous rift-flank uplift along the Canadian–West Greenland conjugate margins likely augmented exhumation subsequently. Early Cretaceous lithospheric doming linked with the proximity of the Iceland hotspot and the emplacement of the Cretaceous HALIP may also have contributed. Climate change also likely played a role in driving the exhumation of the Sverdrup Basin sediment source area, possibly by modulating the effects of longer term tectono-magmatic processes. The asymmetric thickness of Jurassic to Early Cretaceous strata across the Sverdrup Basin, interpreted elsewhere to record rifting in the Sverdrup and Amerasia basins, may instead be a distal effect of exhumation.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/geosciences15080313/s1>: Table S1: A list of the samples studied, their locations and the analyses undertaken, Table S2: Optical petrography point-count data, Table S3: Conventional heavy mineral data, Table S4: Apatite trace element data, Table S5: Garnet major element data, Table S6: Rutile trace element data, Table S7: Detrital zircon U–Pb isotope data, Table S8: Detrital zircon Lu–Hf isotope data.

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