Silurian flysch successions of Ellesmere Island, Arctic Canada, and their significance to northern Caledonian palaeogeography and tectonics

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Abstract: Detrital zircon provenance studies of Silurian flysch units that underlie the Hazen and Clements Markham fold belts of Ellesmere Island, Arctic Canada, were conducted to evaluate models for northern Caledonian palaeogeography and tectonics. Llandovery flysch was deposited along an active plate margin and yields detrital zircons that require northern derivation from the adjacent Pearya terrane. If Pearya originated near Svalbard and NE Greenland, it was transported by strike-slip faults to Ellesmere Island by the Early Silurian. Wenlock to Ludlow turbidites yield Palaeozoic–Archaean detrital zircons with dominant age-groupings c. 650, 970, 1150, 1450 and 1650 Ma. These turbidite systems did not fill a flexural foreland basin in front of the East Greenland Caledonides, but rather an east–west-trending trough that was probably related to sinistral strike-slip faulting along the northern Laurentian margin. The data support provenance connections with the Svalbard Caledonides, especially Baltic–affinity rocks of SW Spitsbergen that were proximal to NE Greenland during the Baltica–Laurentia collision. Pridoli flysch has sources that include Pearya, the East Greenland Caledonides and the Canadian Shield. Devonian–Carboniferous molasse in Arctic Canada has analogous detrital zircon signatures, which implies recycling of Silurian flysch during mid-Palaeozoic (Ellesmerian) collisional tectonism or that some collisional blocks were of similar Baltic–Laurentian crustal affinities.

Supplementary material: Detrital zircon U–Pb age results, isotopic data and concordia diagrams of dated samples are available at http://www.geolsoc.org.uk/SUP18797.

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Siliciclastic rocks deposited in sedimentary basins adjacent to mountain belts have provenance signatures that are dominantly controlled by plate-tectonic setting (Dickinson & Suczak 1979; Garzanti et al. 2007; Cawood et al. 2012) and scale of the depositional system (Ingersoll et al. 1993; DeGraaff-Surpless et al. 2003; Link et al. 2005). In particular, collision-related sedimentary basins are typically filled with synorogenic, deep-water flysch or shallow-water molasse deposits and have mixed provenance from igneous, metamorphic and sedimentary rock assemblages that are reworked during continent–continent or arc–passive margin convergence (e.g. Allen et al. 1991). Petrographic studies have traditionally used the detrital compositions of flysch and molasse sandstones to determine an orogenic provenance (Dickinson et al. 1983), but this approach is generally limited to describing the lithological composition of source areas. In the past few decades, single-mineral-based provenance studies centred around detrital zircon U–Pb geochronology have emerged as powerful techniques for deciphering the precise crustal sources of synorogenic strata and other sedimentary units (e.g. Fedo et al. 2003; DeCelles et al. 2004; Ross et al. 2005; Cawood et al. 2007; Dickinson & Gehrels 2008; Park et al. 2010; Hietpas et al. 2011; Thomas 2011; Gehrels 2012).

The tectonic evolution of the Arctic Ocean region continues to be the subject of debate (Lawver et al. 2010; Pease et al. 2011, 2014; Shephard et al. 2013). Controversy largely stems from the uncertain geographical extent of Palaeozoic mountain belts and collision-related basins that formed along the margins of the circum-Arctic continents prior to Cretaceous sea-floor spreading and opening of the Amerasia Basin (Pease 2011). The Appalachian–Caledonian mountain belt of eastern North America, Greenland, Scandinavia and the British Isles (Fig. 1) is a key element for Arctic plate-tectonic reconstructions and there is significant interest in the northern parts of the orogen that grew during the closure of the Iapetus Ocean, Scandian collision between greater Baltica (Baltica + Ganderia–Avalonia) and Laurentia, and Silurian assembly of the supercontinent Laurussia (Gee 1975; van Staal et al. 1998, 2009; McKerrow et al. 2000; Roberts 2003; van Staal & Hatcher 2010; Gee et al. 2013; Gasser 2014). The northern Caledonides might have included a sinistral transcurrent fault system that was related to lateral escape during Silurian continent–continent collision, analogous to Cenozoic orogens of Eurasia (e.g. Gee & Page 1994). In this model, large-scale faulting during lateral escape contributed to the amalgamation of Svalbard’s (SV in Fig. 1) basement terranes (Soper et al. 2002; Dewey & Strachan 2003; Mazur et al. 2009; Gasser & Andresen 2013). Various Silurian plate reconstructions further predict that circum-Arctic terranes of uncertain crustal affinity, including the Pearya and Arctic Alaska–Chukotka terranes, were integral components of the northern Caledonides and were juxtaposed against the Canadian Arctic margin by sinistral transpression during the Scandian collision (e.g. Sweeney 1982; McClelland et al. 2012; von Gosen et al. 2012). Contrasting scenarios consider the Arctic Alaska–Chukotka terrane to have been located to the east of the Caledonides and positioned along the continental margin of NE Baltica (Miller et al. 2006, 2010, 2011).

In this paper, we report detrital zircon U–Pb data for three Silurian flysch successions on northern Ellesmere Island (Fire Bay, Danish River, Lands Lokk formations), Arctic Canada, that...
Fig. 1. Circum-Arctic cratons, orogens and geographical locations modified from base map of Colpron & Nelson (2011). The grey box in northern Canada indicates the location of Figure 2. AA, Arctic Alaska; AX, Alexander terrane; CH, Chukotka; SV, Svalbard. The Caledonides are shown by the diagonal lined pattern that underlies East Greenland, the British Isles, Scandinavia and Svalbard.

FIG. 2

Fig. 2. Location map showing the distribution of rock units, Silurian sediment transport directions, and Silurian detrital zircon sample locations in northern Ellesmere and Axel Heiberg islands, Canada. CMFB, Clements Markham fold belt; HFB, Hazen fold belt; NHFB, Northern Heiberg fold belt; palaeo., palaeocurrents.

were deposited along the NE margin of Laurentia during the Caledonian orogeny. The new data are consistent with the Silurian flysch being sourced from local magmatic systems, the Pearya terrane, and various Baltic and Laurentian rock assemblages of the Caledonian realm that were involved in the Scandian collision. These results provide new constraints on published models for northern Caledonian palaeogeography and tectonics, the locations of circum-Arctic terranes during the assembly of Laurussia, and the recycling of Silurian flysch successions into Devonian and younger rock units of the Canadian Arctic.

Stratigraphic and tectonic framework

Hazen fold belt

Silurian and older rocks of the northern Ellesmere Island region are assigned to four stratigraphic–tectonic zones that from south to north comprise the Hazen fold belt, Clements Markham fold belt, Northern Heiberg fold belt and Pearya terrane (Trettin 1994, 1998; Hadlari et al. 2014). The Hazen fold belt (HFB in Fig. 2) is primarily underlain by early Palaeozoic strata of the Grant Land and Hazen formations (Fig. 3) that were sourced from the Laurentian craton to the south and deposited along the north-facing (present coordinates) Franklinian passive margin (Dewing et al. 2008; Beranek et al. 2013a). Lower Silurian (late Llandovery) to Lower Devonian flysch of the Danish River Formation (Fig. 3) gradationally overlies the passive margin rocks and includes up to 2800 m of turbiditic shale, sandstone and conglomerate. Palaeocurrent measurements \( (n=2619) \) indicate that the turbidity currents were sourced from the north and east (Fig. 2; Trettin 1994). Correlative rocks in northern Greenland were deposited in an east–west-trending trough that received sediment from the Caledonides (Surlyk & Hurst 1984; Higgins et al. 1991). Sandstone compositions (50% quartz, 25% calcite or dolomite, 15% feldspar, <10% metamorphic or volcanic rock fragments) and conglomerate clast lithologies (limestone, quartzose to feldspathic sandstone) indicate provenance from multiple source regions (Trettin 1994). Recent studies have shown that the upper Danish River Formation has variable detrital zircon signatures; Hadlari et al. (2014) reported an Upper Silurian sandstone to yield clusters of 1020–1183, 1749–1983 and 2541–2915 Ma ages, whereas Anfinson et al. (2012a) reported a
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Lower Devonian sandstone to mostly contain a broad distribution of 900–2150 Ma ages.

**Clements Markham fold belt**

The Clements Markham fold belt (CMFB in Fig. 2) lies between the Hazen fold belt to the SE and Pearya terrane to the NW. The exposed base consists of theelitic basalt and marine strata that resemble the Grant Land and Hazen formations of the Hazen fold belt. Along the northern boundary of the Clements Markham fold belt, Upper Ordovician rocks of the Kulutingwak Formation and Mount Rawlinson complex (Fig. 3) comprise >100 m of mafic to intermediate volcanic rocks with arc-type geochemical signatures, volcaniclastic rocks and carbonatic rocks and minor chert and metamorphic rock fragments (Trettin 1998). Hadlari et al. (2014) reported Danish River Formation sandstones of the Clements Markham fold belt to yield Ordovician to Cryogenian detrital zircon populations that are not recognized in underlying strata of the Franklinian passive margin.

The Lands Lokk Formation (Fig. 3) consists mostly of turbiditic shale, sandstone and conglomerate in faulted or concealed contact with the underlying Danish River Formation. The Lands Lokk Formation is poorly dated, but deep- and shallow-water facies are known to contain Wenlock to Ludlow strata (Trettin 1998). In contrast to other Silurian formations, palaeocurrent measurements (n = 178) indicate that Lands Lokk Formation strata were in part derived from sources to the south and east of the Clements Markham fold belt (Trettin 1998).

**Northern Heiberg fold belt**

The Northern Heiberg fold belt (NHFB in Fig. 2) is located in northern Axel Heiberg Island, immediately west of NW Ellesmere Island. The exposed base of the Northern Heiberg fold belt consists of theelitic basalt and marine strata that are correlative with the Grant Land and Hazen formations (Fig. 3). The Svartevaag Formation (Fig. 3) lies in faulted or concealed contact with the underlying Hazen Formation and comprises >1600 m of Llandovery to Wenlock strata that form two informal members: a northeastern facies of mafic to intermediate volcanic rocks with arc-type geochemical signatures, volcaniclastic rocks and carbonatic rocks and minor chert and metamorphic rock fragments; and a southwestern facies of turbiditic volcaniclastic rocks and minor limestone conglomerate. Trettin (1998) interpreted the Svartevaag Formation to comprise part of a north-facing continental arc system.

**Pearya terrane**

The Pearya terrane or Pearya underlies northernmost Ellesmere Island (Fig. 2) and has long been an enigmatic feature of the Arctic (e.g. Churkin & Trexler 1980). Trettin (1998) divided rocks of Pearya into five tectonostratigraphic successions (Fig. 3). The exposed basement of Pearya (Succession 1) consists of metasedimentary rocks, amphibolite and Tonian orthogneiss units that yield zircon U–Pb ages of 962–974 Ma (Malone 2012). Succession 1 metasedimentary rocks mostly contain Tonian detrital zircons of margin collision analogous to Cenozoic events in Papua New Guinea, Timor and Taiwan (Dewey & Bird 1970).

Late Llandovery units of the Fire Bay Formation comprise >500 m of volcanic flows and volcaniclastic rocks that lie between the Hazen and Danish River formations (Fig. 3). The Fire Bay Formation is divided into three informal members: a lower unit of shale, sandstone, conglomerate, and carbonate olistoliths deposited by gravity flows; a middle unit of mafic to felsic volcanic rocks; and an upper unit of shale. The northwestern facies of the formation is coarser and has a greater volcanic content than the southeastern facies, and Trettin (1998) considered gravity flows of the lower member to be derived from volcanic sources to the NW. Fire Bay Formation sandstone is typically composed of quartz (45%), chert (27%), volcanic rock fragments (23%), and minor chlorite, feldspar, mica, chromite, and metamorphic and carbonate rock fragments (Trettin 1998).

Late Llandovery to Wenlock strata of the Danish River Formation record the main phase of Silurian flysch sedimentation in the Clements Markham fold belt (Fig. 3). The Danish River Formation is represented by turbidite successions of shale, sandstone and conglomerate that are >500 m thick. Palaeocurrent measurements (n = 97) indicate that the turbidity currents were sourced from areas to the NE (Trettin 1998). Danish River Formation sandstone in this region is typically composed of quartz (60%), calcite or dolomite (23%), mica (6%), chlorite (6%), feldspar (5%), and minor chert and metamorphic and volcanic rock fragments (Trettin 1998). Hadlari et al. (2014) reported Danish River Formation sandstones of the Clements Markham fold belt to yield Ordovician to Cryogenian detrital zircon populations that are not recognized in underlying strata of the Franklinian passive margin.

The Lands Lokk Formation (Fig. 3) consists mostly of turbiditic shale, sandstone and conglomerate in faulted or concealed contact with the underlying Danish River Formation. The Lands Lokk Formation is poorly dated, but deep- and shallow-water facies are known to contain Wenlock to Ludlow strata (Trettin 1998). In contrast to other Silurian formations, palaeocurrent measurements (n = 178) indicate that Lands Lokk Formation strata were in part derived from sources to the south and east of the Clements Markham fold belt (Trettin 1998).

![Fig. 3. Ordovician to Silurian stratigraphic correlation chart for northern Ellesmere and Axel Heiberg islands, Canada. Silurian detrital zircon samples are shown by black dots and sample numbers. Depositional ages are constrained by fossils (Trettin 1998) and the youngest detrital zircons in the samples. Clem. Mark., Clements Markham; Disc., Discovery; E., Early; Lland., Llandovery; Mt., Mount; N., North. Geological time scale of Gradstein et al. (2012).](image-url)

Lower Ordovician arc-type rocks and variably serpentinitized ultramafic–mafic assemblages of Succession 3 were juxtaposed with the Pearyan passive margin sequence during the M’Clintock orogeny (Fig. 3; Trettin 1987). The timing of the M’Clintock orogeny is constrained by 475 Ma syntectonic and 462 Ma post-tectonic intrusive rocks (Trettin 1998). The M’Clintock orogeny is perhaps analogous to Ordovician tectonic events of Atlantic Canada (Taconic orogeny), Scotland and Ireland (Grampian orogeny), and Svalbard (formation of Vestgötabreen and Richardalen complexes), which similarly involved the collision of a Palaeozoic arc against a passive margin floored by Grenvillian-aged crust (Gee & Teben’kov 2004; Dewey 2005; van Staal et al. 2009; McClelland et al. 2012; Gasser 2014). Middle to Upper Ordovician units of Succession 4 (Fig. 3) unconformably overlie the M’Clintock belt and include alkaline to calc-alkaline volcanic rocks and volcanostratigraphic strata from 450–500 Ma detrital zircons (Hadlari et al. 2014).

Angular unconformities separate the basal units of Succession 5 from both underlying Succession 4 strata and overlying Silurian flysch (Fig. 3). Above the lower angular unconformity, Upper Ordovician sandstone mainly yields Tonian detrital zircons, with additional age intervals of 450, 1002–1174, 1450 and 1588–1647 Ma (Hadlari et al. 2014). The Danish River Formation is assigned to the upper part of Succession 5 and consists of Llandovery to Wenlock turbiditic rocks (Fig. 3) that were sourced from the east and NE (Trettin 1998).

The Late Ordovician to Silurian evolution of Pearya is disputed. Trettin (1998) concluded that Pearya accreted against the Canadian Arctic margin via Late Ordovician sinistral strike-slip faulting prior to the deposition of the Danish River Formation. Based on inferences for Late Ordovician arc–passive margin collision involving rocks in the Clements Markham fold belt, Klaper (1992) instead considered the Llandovery to Wenlock onset of Danish River Formation deposition to be syntectonic with respect to the accretion of Pearya. Hadlari et al. (2014) offered a third option whereby Pearya represents a pericratonic block that has been proximal to the Canadian Arctic margin at Ellesmere Island since the Neoproterozoic. Danish River Formation flysch in this model was generated by a Late Ordovician–Silurian collision that resulted from the attempted subduction of an unidentified continental block beneath Pearya. Hadlari et al. (2014) inferred that Llandovery sandstones of Pearya, which contain 440–471, 628–663 and 908–1174 Ma detrital zircons characteristic of both Succession 4 strata and Silurian rocks of the Clements Markham fold belt, were deposited in a foreland basin setting.

**Materials and methods**

Ten rock samples from the Fire Bay, Danish River and Lands Lokk formations were analysed for detrital zircon U–Pb geochronology (see locations in Figs 2 and 3). Zircon crystals were separated from rock samples, handpicked onto double-sided tape, and mounted in epoxy. After polishing to expose the interior of the crystals, cathodoluminescence imaging of the mounts using a Hitachi S4300 scanning electron microscope was completed at the Swedish Museum of Natural History, Stockholm. The images were used to locate homogeneous regions of the zircons and to avoid complex internal structures, cracks and zones of potential Pb loss.

**SIMS**

Six samples (C-054339, C-075369, C-242770, C-242744, C-242858, VP09-09) were analysed by secondary ion mass spectrometry (SIMS) at the NordSIM facility, Swedish Museum of Natural History. The analyses were made using a CAMECA IMS 1280 ion-microprobe following the standardized procedures of Whitehouse et al. (1999) and Whitehouse & Kamber (2005). A 20 µm spot size was used. U–Pb ages were calibrated to the 1065 Ma zircon standard 91500 (Wiedenbeck et al. 1995).

**LA-ICP-MS**

Four samples (C-054337, C-054480, C-194771, VP09-08) were analysed by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) at the Department of Geological Sciences, Stockholm University. The analyses involved the ablation of zircon with a New Wave Research 193UC excimer laser using a spot diameter of 25–40 µm, laser fluence of 7.5 J cm⁻² and a pulse rate of 10 Hz. The ablated material was transported by helium carrier gas into the plasma source of a Thermo Scientific XSeries-2 quadrupole ICP-MS system following procedures similar to those of Beranek et al. (2013a). Time-integrated signals were analysed offline using loltie software (Paton et al. 2010) and age calculations were made using the VizualAge reduction routine of Petrus & Kamber (2012). U–Pb ages were calibrated to the 337 Ma zircon standard Plešovice (Slåma et al. 2008).

**Data presentation and evaluation**

Detrital zircon U–Pb age results are presented in relative probability plots with stacked histograms (Figs 4–6) made with the Isoplot Excel macro of Ludwig (2003). Unless stated otherwise, all single-grain ages in the text are given with 2σ uncertainties. Analyses with excessive discordance (>10% discordance or >5% reverse discordance) or high error (>10% uncertainty in 206Pb/238U or 207Pb/206Pb age) were rejected. 206Pb/206Pb ages were selected for analyses older than 1200 Ma, whereas 206Pb/238U ages were selected for analyses younger than 1200 Ma. The total number of analyses evaluated for each sample is presented with the results; for example, n = 100/120 indicates that a total of 120 analyses yielded 100 ages that were suitable for interpretation.

**Results**

**Fire Bay Formation**

Results from two samples of the Fire Bay Formation are shown in Figure 4a and b. Sample C-272744 (n = 27/38) is a granule to pebble, matrix-supported, polymictic (vein quartz, chert) conglomerate collected 65 m above the base of the type section at Fire Bay. The main detrital zircon populations form three groups with ages of 1044–1207 Ma (24%), 1735–2036 Ma (33%) and 2490–2979 Ma (33%); three Palaeozoic zircons give single-grain ages of 474±5, 492±5 and 536±5 Ma (1σ). Sample C-272700 (n = 43/56) is a granite to pebble, matrix-supported, volcanic lithic conglomerate collected from a turbidite succession in the lower member of the type section. Palaeozoic age populations of 429–449 Ma (51%), 459–465 Ma (3%) and 470–482 Ma (14%) dominate this sample; the youngest zircon gives an age of 429±5 Ma (1σ) and the only Proterozoic zircon is 1178±12 Ma (1σ).

**Danish River Formation**

Results from two samples of Wenlock sandstone from the Clements Markham fold belt are shown in Figure 5a and b. Sample C-242858 (n = 132/143) overlies the Fire Bay Formation and consists of 623–693 Ma (8%), 961–991 Ma (12%) and 1014–1690 Ma (62%) age
Lands Lokk Formation

Results from two samples of the Lands Lokk Formation are displayed in Figure 6a and b. Sample C-054480 (n = 164/180) is a coarse-grained, chert lithic sandstone with main age groupings of 523–715 Ma (26%) and 1002–1683 Ma (51%) and minor age groupings of 834–869, 953–987 and 1750–1799 Ma. The youngest zircons in this sample are 471 ± 21, 523 ± 19 and 528 ± 15 Ma. Sample C-194771 (n = 112/124) is a granule to pebble, matrix-supported, chert lithic conglomerate with three principal age groupings of 420–492 Ma (20%), 1772–2095 Ma (32%) and 2265–2884 Ma (39%). The youngest zircons in this sample are 413 ± 6, 416 ± 11 and 418 ± 29 Ma.

Silurian palaeogeography and tectonics

Silurian flysch successions of the present study have detrital compositions and palaeocurrent characteristics that indicate provenance from various igneous, metamorphic and sedimentary source rocks. The zircon U–Pb age signatures of the Fire Bay, Danish River and Lands Lokk formations therefore contribute valuable information on the identities of source rocks and test existing models for northern Caledonian palaeogeography (Fig. 7a–f). At a broader scale, the new provenance data constrain Silurian sedimentation trends adjacent to the Caledonian mountain belt that are otherwise unobtainable through field observations.

Early Silurian stratigraphic ties between Pearya and Canadian Arctic margin

The two Llandovery samples from the Fire Bay Formation have contrasting provenance with a lower, sedimentary lithic conglomerate that yields mainly Precambrian zircon populations (Fig. 4a) and an upper, volcanic lithic conglomerate dominated by Early Ordovician to Early Silurian zircon populations (Fig. 4b). Whereas the lower conglomerate sample has provenance signatures that are characteristic of NE Laurentian and Pearyan passive margin strata (Anfinson et al. 2012a; Hadlari et al. 2012, 2014; Beranek et al. 2013a), the upper conglomerate sample implies derivation from early Palaeozoic rocks that likewise sourced Ordovician–Silurian units of Pearya (Hadlari et al. 2014). Therefore, a significant outcome of this study is that the Fire Bay Formation preserves Llandovery stratigraphic ties with Pearya, including provenance connections with igneous and volcaniclastic rock units of Successions 3, 4 and 5 (Fig. 3). These new data broadly support the palaeogeographical scenarios of Trettin (1998) and Hadlari et al. (2014) that argue for Pearya to be proximal to the Canadian Arctic margin at Ellesmere Island during the Early Silurian (Fig. 7b).

An active margin environment with rapid erosion and sedimentation is implied for the Fire Bay Formation based on the evidence of Early Silurian detrital zircons in the Llandovery samples (see Cawood et al. 2012). These zircons were most probably sourced from adjacent volcanic rocks of the Fire Bay Formation or Llandovery lavas of the Svartevaeg Formation on Axel Heiberg Island. Detailed bedrock mapping and modern geochemical and geochronological studies of volcanic rocks in the Clements Markham and Northern Heiberg fold belts are required to test the Late Ordovician arc–passive margin collision model of Klapar (1992) and the Early Silurian continental arc model of Trettin (1998).

Middle Silurian connections with the Svalbard Caledonides

Wenlock and Ludlow flysch of the Danish River and Lands Lokk formations (Fig. 8a) displays repeatable detrital zircon age populations that are expected for well-mixed turbidite systems (e.g. Ingersoll et al. 1993; DeGraaff-Surpless et al. 2003). The dominant 970–2000 Ma age signature of the samples is accompanied by variable Ediacaran–Cryogenian contributions that together are consistent with proximity to rocks of the northern Caledonides. For example, the c. 650, 970, 1150, 1450 and 1650 Ma age peaks that characterize the Wenlock and Ludlow flysch compare favourably with the following: (1) clastic strata of similar age in Pearya and Svalbard (Fig. 8c–e); (2) Neoproterozoic supracrustal units of Svalbard, East Greenland and Scandinavia that were involved in the Scandian collision and Caledonian folding and thrusting (Fig. 8f–h); (3) the age of late Neoproterozoic tectono-thermal activity in Svalbard (e.g. Majka et al. 2008, 2010, 2012); (4) the ages of early Neoproterozoic and older magmatic rocks in Svalbard, Greenland and Scandinavia (e.g. Bingen & Solli...
Based on the available evidence, our preferred model is that Wenlock and Ludlow flysch was mainly derived from Svalbard rock assemblages, especially parts of Wedel Jarlsberg Land (SW Spitsbergen; WJL and VC in Fig. 7c) with Silurian and older source rocks of comparable provenance. Sediment contributions from rock units of Baltoscandian margin, which occupied the lower plate position in the Scandinavian collision, are also possible but require transverse river systems to cut across the Caledonian mountains in a manner similar to some modern Himalayan drainages.

The east–west trend of the Silurian trough along northern Greenland and Ellesmere Island was nearly perpendicular to the trend of the East Greenland Caledonian front, which suggests that Wenlock and Ludlow turbidites were not deposited in a simple flexural foreland basin, unless the associated orogen was oriented parallel to the Franklinian margin (Fig. 7b) as proposed by Hadlari et al. (2014). It is possible that these turbidite systems were transported westward within a sinistral strike-slip fault zone at the northern end of the Caledonides during the Scandinavian collision and assembly of Svalbard (see Fig. 7c; Harland 1971; Surlyk & Hurst 1984; Soper et al. 1992; Mazur et al. 2009; McClelland et al. 2012; von Gosen et al. 2012). Gasser & Andresen (2013) proposed a two-stage model to explain the Ordovician–Devonian amalgamation of Svalbard: (1) Baltic (Timanian margin) affinity rocks of SW Spitsbergen (WJL and VC in Fig. 7c) were sinistrally transported to a location north of Greenland after widespread Ordovician tectonism that is recorded in the Taconic, Grampian, M’Clintock, and Vestgåtubreken and Richardson belts; (2) Laurentian affinity rocks of NW Spitsbergen and Nordaustlandet (NWS in Fig. 7c) were sinistrally detached from NE Greenland and subsequently amalgamated to the eastern side of the SW Spitsbergen block near Pearya and the Canadian Arctic margin. The scenario of Gasser & Andresen (2013) permits late Neoproterozoic and older detrital zircons within Wenlock and Ludlow flysch successions to have provenance from Baltic-affinity rocks that at present underlie SW Spitsbergen.

**Late Silurian connections with the Greenland Caledonides and local orogenic uplifts**

Pridoli flysch of the Danish River and Lands Lokk formations (Fig. 8b) has detrital zircon signatures that differ from those of Wenlock and Ludlow flysch, which imply a change in regional sedimentation sometime between the Middle and Late Silurian. This change is marked by (1) the addition of Ordovician–Silurian (c. 420–460 Ma) components, including Pridoli to Wenlock detrital zircons that suggest deposition in an active tectonic environment, (2) the general absence of Ediacaran–Cryogenian ages that are prevalent in Wenlock and Ludlow strata, (3) the addition of Palaeoproterozoic and Archaean detrital zircons, and (4) south- and east-directed sediment transport directions. The early Palaeozoic ages, especially for the Lands Lokk sample in the Clements Markham fold belt, are consistent with a northern or eastern source from magmatic rocks or their sedimentary derivatives of Pearya (e.g. Succession 5 strata; Hadlari et al. 2014), the Canadian Arctic margin (Fire Bay and Svarveaev formations) and Svalbard (e.g. Johansson et al. 2005), whereas a southern provenance may best fit the Danish River Formation strata in the Hazen fold belt. In this scenario, the 420–460 Ma detrital zircons in the Hazen fold belt samples indicate derivation from

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**Fig. 5.** Probability density distribution-stacked histogram plots of detrital zircons from the Danish River Formation. (a) Wenlock sandstone (C-242858); (b) Wenlock sandstone (C-075369); (c) Ludlow sandstone (VP09-08); (d) Ludlow sandstone (VP09-09); (e) Pridoli sandstone (C-054337); (f) Pridoli sandstone (C-054339).
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Ordovician–Silurian granitoids of the East Greenland Caledonides (e.g. Rehnström 2010). Neoproterozoic supracrustal units of East Greenland (Fig. 8g) yield c. 1050 Ma age populations that are recognized within the Danish River Formation. Palaeoproterozoic (c. 1800 Ma) and Archaean (c. 2700 Ma) detrital zircon components provide strong evidence for NE Laurentian craton provenance and are probably sourced from (1) well-characterized Mesoproterozoic to Cambrian clastic strata of northern Greenland and Ellesmere Island (Fig. 8i) or (2) Late Silurian cratonic uplifts of the Canadian Shield (e.g. Inglefield, Boothia, Rens Fiord uplifts) that were generated during the Caledonian orogeny (Ökulitch et al. 1991).

Silurian palaeogeographical models for the circum-Arctic

Palaeocurrent and regional stratigraphic data permit some of the Silurian flysch successions of Ellesmere Island to be partially derived from source areas other than Greenland, Svalbard or Scandinavia. Although the identities of these sources remain a matter of debate, some palaeogeographical models for the northern Caledonian orogen have predicted that arc and microcontinental terranes currently in the North American Cordillera, Arctic Alaska and Arctic Russia were adjacent to Silurian flysch basins during the assembly of Laurussia, as follows.

Fig. 6. Probability density distribution-stacked histogram plots of detrital zircons from the Lands Lokk Formation. (a) Ludlow sandstone (C-054480); (b) Pridoli sandstone (C-194771).

Fig. 7. Contrasting palaeogeographical models for the northern Caledonian orogen. (a) Middle Silurian reconstruction of the supercontinent Laurussia (e.g. Cocks & Torsvik 2005). Rectangle in the centre of the figure indicates the location of (b)–(f). (b) Model of Hadlari et al. (2014): Silurian flysch successions occupy the foreland of a continent–continent collision between Pearya–Canadian Arctic margin and an unknown continental block. (c) Model of Gasser & Andresen (2013): Silurian flysch successions are flanked to the north by Pearya (PT) and SW Svalbard terranes (VC, Vestgøya breen complex; WJL, Wedel Jarlsberg Land) and east by Greenland (GL), NW Svalbard (NWS; Nordaustlandet and NW Spitsbergen), and the Baltoscandian margin (BSM) of the Scandinavian Caledonides. (d) Models of Colpron & Nelson (2009, 2011), Miller et al. (2011) and Nelson et al. (2013): Silurian flysch successions are located SSW of a westward-propagating arc complex and Caledonian-affinity rocks of Arctic Alaska–Chukotka and Alexander terranes that overlie Timanian basement. AA, Arctic Alaska; AX, Alexander; CH, Chukotka; GL, Greenland; NT, northern Taimyr; NZ, Novaya Zemlya; SZ, Severnaya Zemlya; YR, Yreka. (e) Model of Kuznetsov et al. (2010): Silurian flysch successions are broadly related to the Silurian collision between palaeeocontinent Arctica and Laurussia. NSI, New Siberian Islands; SV, Svalbard. (f) Model of Cocks & Torsvik (2011): several of the stratigraphic–structural domains of present-day Ellesmere Island fringe the Laurentian craton to the south and are flanked east by the Barents Shelf and NW Russia (NT, NZ and SZ) to the east.
modulated the transport of the Alexander terrane and other NE Baltic (Timanian) margin fragments into the palaeo-Pacific Ocean realm after a period of Silurian–Devonian orogenesis and sedimentation (see also Beranek et al. 2012, 2013b,c). In this model, at least part of the composite Arctic Alaska–Chukotka terrane was positioned along the NE Baltic margin during the Scandian collision (see also Miller et al. 2006, 2010, 2011). The southern boundary of the westward propagating arc system was a sinistral transform fault and was perhaps kinematically linked to the assembly of Svalbard (Mazur et al. 2009; McClelland et al. 2012; von Gosen et al. 2012) and transcurrent displacements within the Caledonides (Dewey & Strachan 2003). Flysch successions of Ellesmere Island have some detrital zircon characteristics (Fig. 9a and b) that are compatible with derivation from basement or early Palaeozoic supracrustal cover assemblages of Arctic-affinity terranes, including 420–490, 565–750 and 970–2000 Ma age populations of the Alexander and Arctic Alaska–Chukotka terranes (Fig. 9c and d). We recommend that additional provenance information, such as the Hf isotopic compositions of dated zircons, is required to further evaluate Silurian provenance ties between these terranes and the Canadian Arctic margin (see Beranek et al. 2013c).

Fig. 8. Detrital zircon reference frames for the northern Caledonian orogen and surrounding regions. (a) Wenlock to Ludlow flysch of the Danish River and Lands Lokk formations, Ellesmere Island (this study). (b) Pridoli flysch of the Danish River and Lands Lokk formations, Ellesmere Island (this study). (c) Pearya terrane: Silurian Danish River Fm. 1 sample, n = 65. (d) Svalbard (SW terrane) Silurian strata: 2 samples, n = 227. (e) Svalbard (NW terrane) Silurian–Devonian strata: 3 samples, n = 307. (f) Svalbard (SW terrane) Neoproterozoic strata: 3 samples, n = 412. (g) East Greenland Neoproterozoic strata: 4 samples, n = 340. (h) Baltoscandian margin Neoproterozoic strata: 22 samples, n = 1788. (i) N. Greenland and Ellesmere Is: Proterozoic-Cambrian strata: 16 samples, n = 973.

1 Colpron & Nelson (2009, 2011) and Nelson et al. (2013) proposed that a westward propagating arc system was active at the northern end of the Caledonides (Fig. 7d) and accom-

Potential recycling of Silurian flysch along Canadian Arctic margin

Silurian flysch successions were superseded by synorogenic molasse that filled the foreland of the Ellesmerian orogen, an extensive fold and thrust belt that developed along the length of the Canadian Arctic margin (Fig. 1). Although the Ellesmerian orog-

Fig. 10. Detrital zircon reference frames for northern Canadian rocks that may be partially composed of recycled Silurian flysch. (a) Canadian Arctic margin: Fire Bay, Danish River and Lands Lokk formations, Ellesmere Island (this study). (b) Ellesmerian foreland strata: Blackley and Parry Islands formations, Canadian Arctic Islands (Anfinson et al. 2012b). (c) Devonian and Mississippian strata: Imperial, Tuttle and Tsichu formations and Keno Hill Quartzite, Yukon and Northwest Territories (NWT) (Beranek et al. 2010a). (d) Cordilleran margin: Triassic strata of Alaska, Yukon and British Columbia (Beranek et al. 2010b; Beranek & Mortensen 2011). (e) Sverdrup Basin: Triassic and Jurassic strata, Axel Heiberg Island (Omma et al. 2011). (f) Sverdrup Basin: Cretaceous strata, Ellesmere and Axel Heiberg islands (Rohr et al. 2010).

Fig. 9. Detrital zircon reference frames for known or inferred Caledonian- and Timanian-affinity rocks. (a) Wenlock-Ludlow flysch of the Danish River and Lands Lokk formations, Ellesmere Island (this study). (b) Pridoli flysch of the Danish River and Lands Lokk formations, Ellesmere Island (this study). (c) Alexander terrane: Donjek and Icefield assemblages, NW Canada (Beranek et al. 2013b, 2013c). (d) Arctic Alaska–Chukotka terrane: Palaeozoic rocks, Seward Peninsula, western Alaska (Amato et al. 2009). (e) Novaya Zemlya: Baltic margin strata, NW Russia (Pease & Scott 2009). (f) Northern Taimyr: Baltic margin strata (Pease & Scott 2009). (g) Ladoga (St. Petersburg area) and Polar Urals: Baltic margin and cratonal strata (Miller et al. 2011). (h) Severnaya Zemlya: Baltic margin strata (Lorenz et al. 2008).

An outstanding question relevant to Canadian Arctic basin development is what percentage of Ellesmerian foreland strata were cannibalized from Silurian flysch successions during Devonian-Carboniferous mountain building. Answering such questions may provide clarity on the precise crustal sources of northern Canada. For example, Anfinson et al. (2012b) demonstrated that Middle to Upper Devonian strata preserving Ellesmerian foreland sedimentation in the Canadian Arctic Islands are in part characterized by 420–750, 900–2100 and 2550–3000 Ma detrital zircon populations. Upper Devonian to Mississippian Ellesmerian clastic rocks of NW Canada yield similar age signatures, as described by Beranek et al. (2010a) and Lemieux et al. (2011). Based on the available detrital zircon reference frames for the circum-Arctic continents, those researchers all suggested that the colliding block(s) in the Ellesmerian orogeny were of Caledonian (c. 430 Ma) and Timanian (c. 550–750 Ma) crustal affinity. The results of the present study compare favourably with these Ellesmerian detrital zircon databases (Fig. 10a–c), and importantly show that occurrences of c. 420–750 Ma detrital zircons along the Canadian Arctic margin can be traced back to at least the Late Silurian, prior to the Ellesmerian orogeny.

The cause of the Ellesmerian orogeny remains uncertain, but it is generally ascribed to the collision between northern North America and another continental block (e.g. Embry 2009).
involved in the Ellesmerian orogeny. For example, recent palaeo-geographical scenarios for the Ellesmerian orogeny (e.g. Beranek et al. 2010a; Anfinson et al. 2012b) would need modification if foreland basin detrital zircons were recycled through Silurian flysch instead of being sourced directly from Caledonian- or Timanian-affinity blocks within the Ellesmerian mountain belt. Using a combination of U–Pb and (U–Th)/He dating techniques, Anfinson et al. (2013) recently reported c. 425–430 Ma peak exhumation ages for detrital zircons contained within some Ellesmerian foreland strata. Because several Llandovery to Pridoli samples of the present study yield c. 425–430 Ma detrital zircon U–Pb signatures consistent with synsedimentary magmatic activity and Silurian uplift and erosion (see Cawood et al. 2012), it follows that Silurian flysch of the Canadian Arctic margin was a suitable source for at least some Ellesmerian foreland basin rocks. Garzoni et al. (1997) and Patchett et al. (1999, 2004) further proposed that widespread recycling of Silurian–Devonian sources is evident by the Nd isotopic compositions of shales in the Sverdrup Basin of northern Canada and the Cordilleran margin of western North America. Mesozoic strata of both the Sverdrup Basin and NW Cordilleran margin have detrital zircon provenance signatures that correspondingly imply significant contributions from recycled Silurian–Devonian sources (Fig. 10d–f). Future studies in the Canadian Arctic may solve these problems by combining zircon U–Pb data with complementary provenance techniques that include detrital zircon Hf isotope geochemistry, detrital feldspar Ar–Ar geochronology and Pb–Pb isotopic geochemistry, and detrital monazite U–Pb geochronology and Nd isotopic geochemistry.

Conclusions

Silurian flysch successions of Ellesmere Island were deposited by turbidite systems in proximity to the northern Caledonian orogen. Lower Silurian conglomerates of the Fire Bay Formation were generated along an active plate margin and one sample yields early Palaeozoic detrital zircons that require provenance from igneous rock units of the Pearya terrane. Detrital zircons and other geological evidence suggest that Pearya was located near its current position at Ellesmere Island by the Early Silurian. Wenlock and Ludlow turbiditic rocks of the Danish River and Lands Lokk formations contain a range of early Palaeozoic to Proterozoic detrital zircons that are most consistent with SW Svalbard provenance, but sediment contributions from Pearya and other regions are possible. Because the east–west-trending trough of northern Ellesmere Island and Greenland was nearly perpendicular to the trend of the East Greenland Caledonian front, the Wenlock and Ludlow turbidites were not deposited in a flexural foreland basin fed from that orogen, but rather a sinistral strike-slip fault zone at the northern end of the Caledonides. It is possible for some of the flysch to have additional source areas, including rock assemblages of the Arctic Alaska–Chukotka and Alexander terranes, which were proximal to Ellesmere Island during the Scandinavian orogeny. Some Pridoli flysch units of the Danish River Formation were sourced from early Palaeozoic granites of the East Greenland Caledonides and local cratonic uplifts. Foreland basin strata of the Ellesmerian orogen in northern Canada display detrital zircon ages that closely resemble those for Silurian formations of the present study, which may indicate the recycling of flysch during Devonian–Carboniferous mountain building along the Canadian Arctic margin. The precise sources of Ellesmerian foreland basin strata are uncertain, but it is possible that collisional blocks of the Ellesmerian orogeny were of similar crustal affinity to those involved in Scandinavian collision.

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