JGS
Research article
Journal of the Geological Society
Published online December 23, 2014
doi:10.1144/jgs2014-027 | Vol. 172 | 2015 | pp. 201–212

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

Luke P. Beranek[1*], Victoria Pease[2], Thomas Hadlari[3] & Keith Dewing[3]

[1] Department of Earth Sciences, Memorial University of Newfoundland, 300 Prince Philip Drive, St. John's, NL A1B 3X5, Canada
[2] Department of Geological Sciences, Stockholm University, Svante Arrhenius väg 8, 106 91 Stockholm, Sweden
[3] Geological Survey of Canada, 3303–33 Street North West, Calgary, AB T2L 2A7, Canada
* Correspondence: lberanek@mun.ca

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 Baltican-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 Baltican–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.

Received 7 March 2014; **revised** 10 October 2014; **accepted** 10 October 2014

Siliciclastic rocks deposited in sedimentary basins adjacent to mountain belts have provenance signatures that are dominantly controlled by plate-tectonic setting (Dickinson & Suczek 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*. 1992; 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

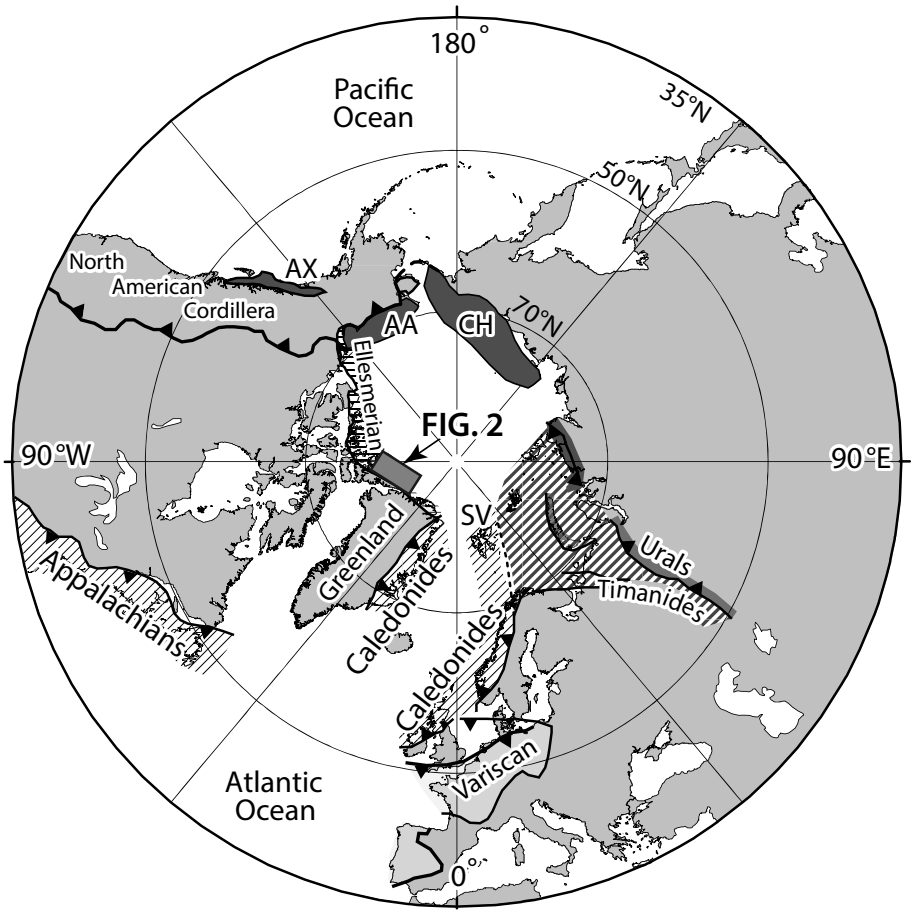

Fig. 1. Circum-Arctic cratons, orogens and geographical locations modified from base map of Colpron & Nelson (2011). The grey box in northern Canada indicates the location of Figure 2. AA, Arctic Alaska; AX, Alexander terrane; CH, Chukotka; SV, Svalbard. The Caledonides are shown by the diagonal lined pattern that underlies East Greenland, the British Isles, Scandinavia and Svalbard.

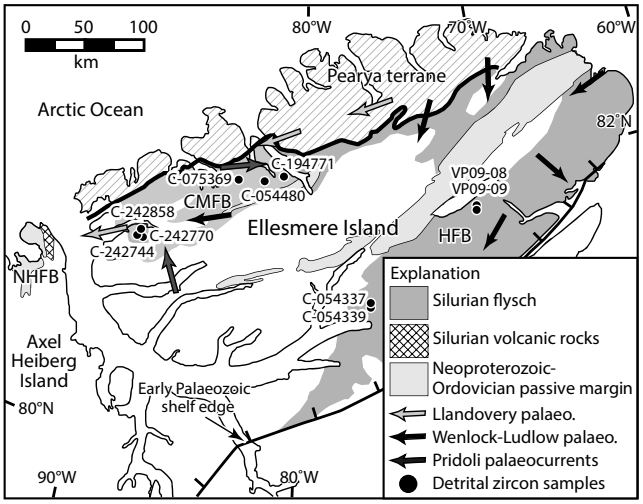

Fig. 2. Location map showing the distribution of rock units, Silurian sediment transport directions, and Silurian detrital zircon sample locations in northern Ellesmere and Axel Heiberg islands, Canada. CMFB, Clements Markham fold belt; HFB, Hazen fold belt; NHFB, Northern Heiberg fold belt; palaeo.,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

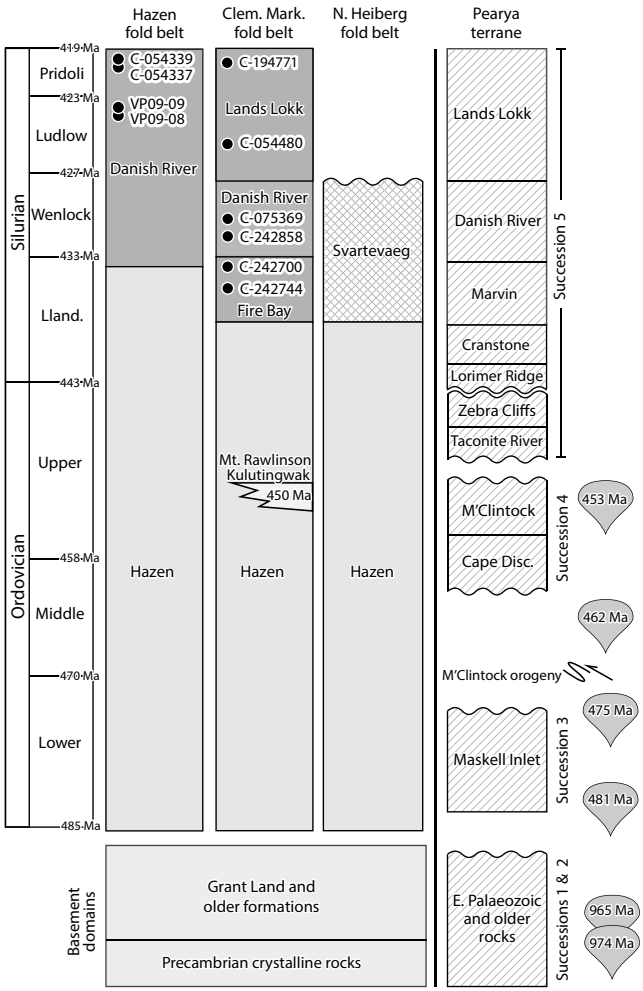

Fig. 3. Ordovician to Silurian stratigraphic correlation chart for northern Ellesmere and Axel Heiberg islands, Canada. Silurian detrital zircon samples are shown by black dots and sample numbers. Depositional ages are constrained by fossils (Trettin 1998) and the youngest detrital zircons in the samples.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

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 tholeiitic 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 felsic volcanic flows, volcaniclastic strata and marble. Andesitic to dacitic lavas of these two units yield arc-type geochemical signatures and zircon U–Pb crystallization ages *c*. 450 Ma (Trettin *et al*. 1987; Trettin 1998). Fault slivers within the Kulutingwak Formation consist of fragmental serpentinite and serpentinitic sandstone units >300 m thick (Trettin 1998). Klaper (1992) interpreted Ordovician rocks of the Clements Markham fold belt to represent the vestiges of an island arc complex and accretionary prism that formed above a north-dipping subduction zone. In this scenario, Kulutingwak Formation arc-type lavas were generated by the consumption of an ocean basin prior to the entry of the buoyant Laurentian passive margin into the Ordovician subduction zone, leading to arc–passive 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).

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 tholeiitic basalt and marine strata that are correlative with the Grant Land and Hazen formations (Fig. 3). The Svartevaeg 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 carbonate olistoliths; and a southwestern facies of turbiditic volcaniclastic rocks and minor limestone conglomerate. Trettin (1998) interpreted the Svartevaeg 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

local basement provenance (Hadlari *et al*. 2014). Neoproterozoic to early Palaeozoic shallow-marine rocks of Succession 2 overlie the exposed basement and represent a passive margin sequence (Trettin 1998). A Marinoan diamictite of Succession 2 yields 909–997 Ma detrital zircons derived from Pearya basement units and 1001–1511, 1572–1702, 1754–1997 and 2774–2949 Ma detrital zircons that broadly suggest NE Laurentian crustal affinities (Hadlari *et al*. 2014).

Lower Ordovician arc-type rocks and variably serpentinized 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 Richarddalen 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 volcaniclastic strata with 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 908–990 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 Iolite 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 (Sláma *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 $^{206}Pb/^{238}U$ or $^{207}Pb/^{206}Pb$ age) were rejected. $^{207}Pb/^{206}Pb$ ages were selected for analyses older than 1200 Ma, whereas $^{206}Pb/^{238}U$ 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 (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 granule 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 (33%) 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

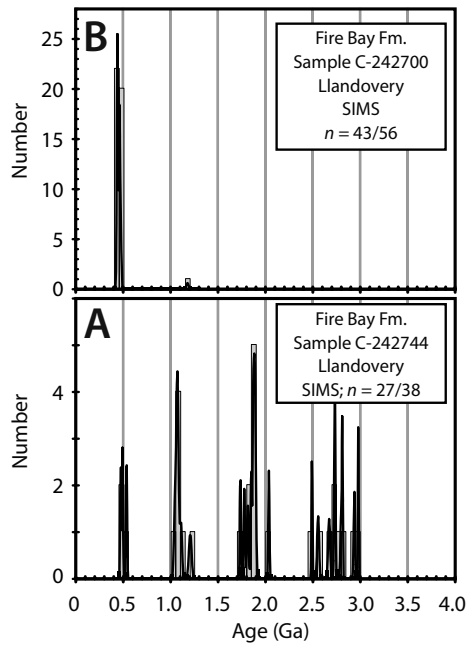

Fig. 4. Probability density distribution-stacked histogram plots of detrital zircons from the Fire Bay Formation. (**a**) Llandovery sedimentary lithic conglomerate (C-242744); (**b**) Llandovery volcanic lithic conglomerate (C-242700).

groupings with probability age peaks of 644, 971, 1451 and 1651 Ma. The youngest zircons analysed in this sample are 465 ± 4, 523 ± 5 and 553 ± 5 Ma (1σ). Sample C-075369 (*n* = 73/79) yields 638–709 Ma (9%), 956–984 Ma (6%), 1022–1650 Ma (53%), 1798–1880 Ma (8%) and 2520–2872 Ma (11%) age groupings with probability peaks of 644, 970 and 1638 Ma. The youngest zircons give ages of 459 ± 4, 565 ± 5 and 603 ± 6 Ma (1σ).

The results of four samples from the Hazen fold belt are shown in Figure 5c–f. South of Lake Hazen, samples VP09-08 (*n* = 136/165) and VP09-09 (*n* = 62/84) consist of medium-grained sandstones that overlie Franklinian passive margin strata. Mesoproterozoic ages of 1000–1690 Ma are provided by 77% of the zircons in both samples. The youngest zircons in sample VP09-08 are 538 ± 17, 607 ± 18 and 694 ± 13 Ma, whereas the youngest zircons in sample VP09-09 are 938 ± 13, 966 ± 12 and 968 ± 11 Ma (1σ). Samples C-054337 (*n* = 159/165) and C-054339 (*n* = 40/60) are medium-grained sandstones collected 125 km SW of Lake Hazen. Although Mesoproterozoic zircons also characterize these rocks, samples C-054337 and C-054339 contain Palaeozoic (420–428, 431–448, 459–467 Ma) and Archaean zircons that are uncommon in samples VP09-08 and VP09-09. The youngest zircons in sample C-054337 are 421 ± 13, 428 ± 8 and 431 ± 7 Ma, and the youngest concordant zircons in C-054339 are 421 ± 4, 421 ± 5 and 421 ± 5 Ma (1σ).

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 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 Klaper (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 tectonothermal activity in Svalbard (e.g. Majka *et al*. 2008, 2010, 2012); (4) the ages of early Neoproterozoic and older magmatic rocks in Svalbard, East Greenland and Scandinavia (e.g. Bingen & Solli

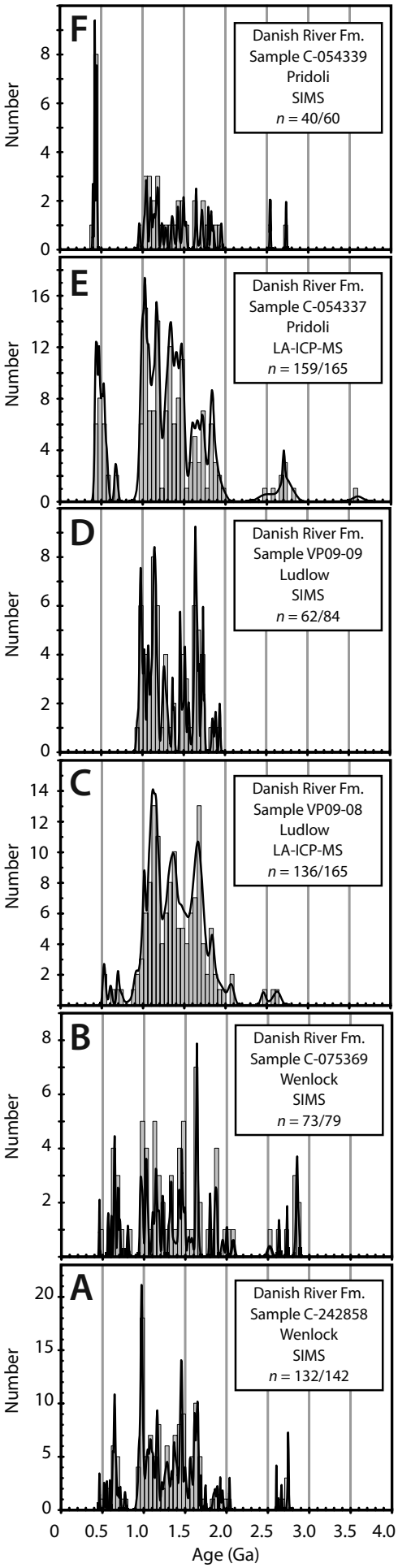

Fig. 5. Probability density distribution-stacked histogram plots of detrital zircons from the Danish River Formation. (**a**) Wenlock sandstone (C-242858); (**b**) Wenlock sandstone (C-075369); (**c**) Ludlow sandstone (VP09-08); (**d**) Ludlow sandstone (VP09-09); (**e**) Pridoli sandstone (C-054337); (**f**) Pridoli sandstone (C-054339).

2009). 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 Scandian 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 Scandian 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) Baltican (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 Vestgötabreen and Richarddalen 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 Baltican-affinity rocks that at present underlie SW Spitsbergen.

Late Silurian connections with the Greenland Caledonides and local cratonic 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 Svartevaeg 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

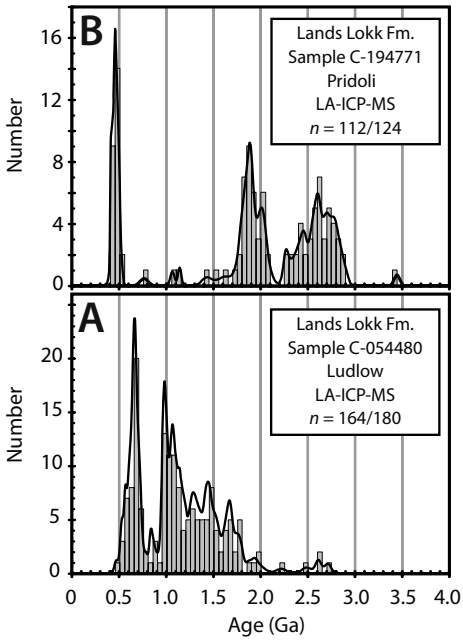

Fig. 6. Probability density distribution-stacked histogram plots of detrital zircons from the Lands Lokk Formation. (**a**) Ludlow sandstone (C-054480); (**b**) Pridoli sandstone (C-194771).

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 (Okulitch *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.

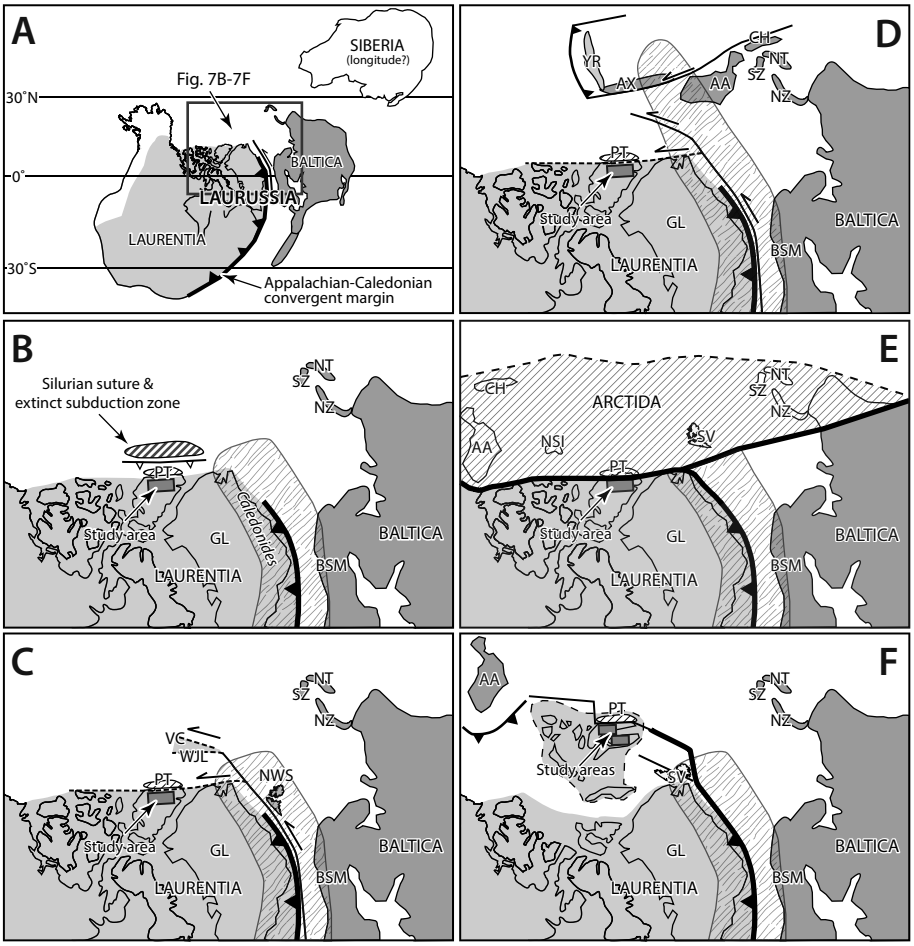

Fig. 7. Contrasting palaeogeographical models for the northern Caledonian orogen. (**a**) Middle Silurian reconstruction of the supercontinent Laurussia (e.g. Cocks & Torsvik 2005). Rectangle in the centre of the figure indicates the location of (**b**)–(**f**). (**b**) Model of Hadlari *et al*. (2014): 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, Vestgötabreen 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 palaeocontinent Arctida 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.

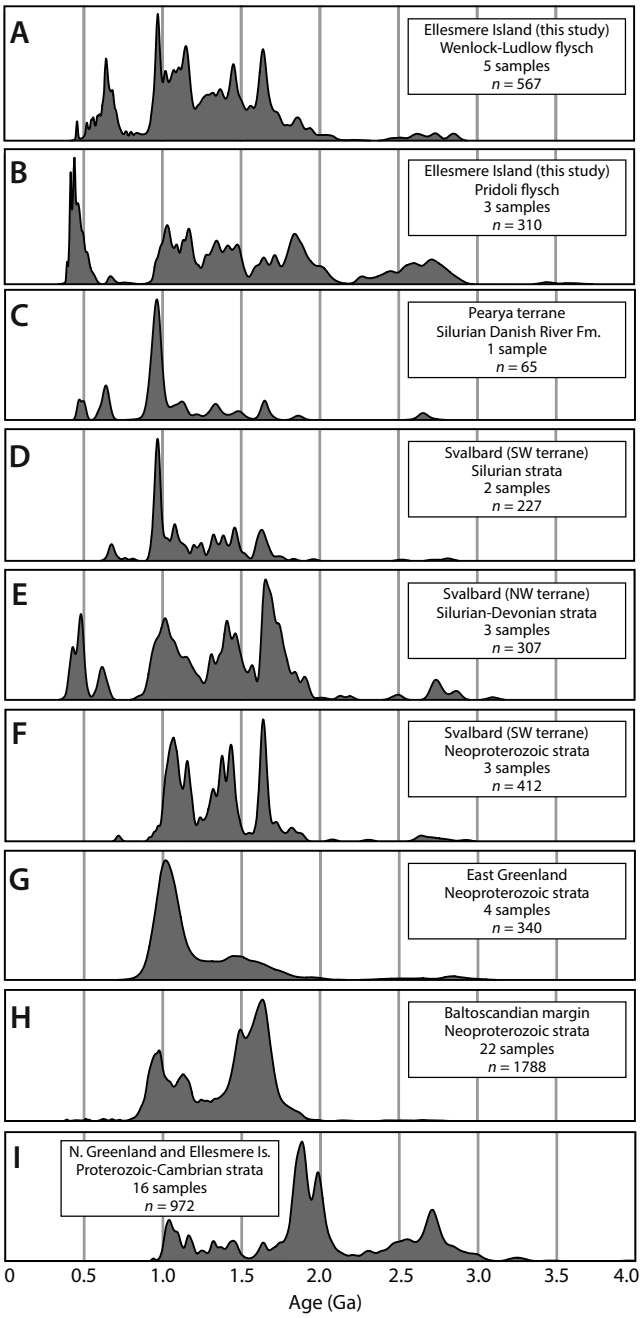

Fig. 8. Detrital zircon reference frames for the northern Caledonian orogen and surrounding regions. (**a**) Wenlock to Ludlow flysch of the Danish River and Lands Lokk formations, Ellesmere Island (this study). (**b**) Pridoli flysch of the Danish River and Lands Lokk formations, Ellesmere Island (this study). (**c**) Pearya terrane: Danish River Formation, Ellesmere Island (Hadlari *et al*. 2014). (**d**) SW Svalbard: Holmesletfjella and Bulltinden formations (Gasser & Andresen 2013). (**e**) NW Svalbard: Siktefjellet and Red Bay groups, Spitsbergen (Pettersson *et al*. 2010). (**f**) SW Svalbard: St. Jonsfjorden, Daudmannsodden and West Coast units (Gasser & Andresen 2013). (**g**) East Greenland: Eleonore Bay Supergroup, Kong Oscar Fjord (Sláma *et al*. 2011). (**h**) Scandinavian Caledonides: Baltoscandian margin, Norway and Sweden (Be'eri-Shlevin *et al*. 2011; Bingen *et al*. 2011; Kirkland *et al*. 2011). (**i**) NE Laurentia: Nesmith beds and Grant Land Formation of Ellesmere Island (Beranek *et al*. 2013a) and Inuiteq Sø Group, Morænso Formation, and Portfjeld Formation, Greenland (Kirkland *et al*. 2009).

(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 accommodated the transport of the Alexander terrane and other NE Baltican (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 Baltican 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).

(2) Zonenshain & Natapov (1987), Zonenshain *et al*. (1990) and Kuznetsov *et al*. (2010) argued for the so-called Arctida palaeocontinent, a large and independent continental mass that existed between Laurentia, Baltica and Siberia after the breakup of Rodinia, to have collided with Baltica in the late Neoproterozoic and subsequently northern Canada in the Late Silurian (Fig. 7e). In this model, Arctida comprises the basement successions that underlie Arctic Alaska, Chukotka, Novaya Zemlya, Severnaya Zemlya, northern Taimyr, New Siberian Islands, Pearya, Svalbard and the submerged Lomonosov Ridge. Silurian provenance signatures of the present study are not incompatible with the Arctida collisional scenario, but there is currently an absence of supporting structural, stratigraphic and other geological data for a widespread Late Silurian collisional event along the Canadian Arctic margin. Known and inferred Laurentian connections for parts of Pearya (Malone 2012; Hadlari *et al*. 2014), Svalbard (Gee *et al*. 2008) and the Arctic Alaska–Chukotka terrane (Strauss *et al*. 2013) imply that the Arctida concept is oversimplified.

(3) Cocks & Torsvik (2011) proposed that the closure of the Iapetus Ocean led to NE Laurentia being adjacent to the Baltican margin that underlies the Barents Shelf and the Novaya Zemlya, northern Taimyr and Severnaya Zemlya regions of NW Russia (Fig. 7f). The Silurian fossil record of northern Laurentia correspondingly shows an influx of benthic species that are characteristic of the Ural Mountains region (Pojeta & Norford 1987; Jin & Chatterton 1997). In the Cocks & Torsvik (2011) model, the Ellesmere Island fold belts underlie some of the crustal blocks that fringe the Laurentian craton (Fig. 7f). Silurian flysch successions lack most of the age peaks and age distributions that are characteristic of NW Russia (Fig. 9e–h), and therefore do not support provenance connections with that region of NE Baltica.

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-

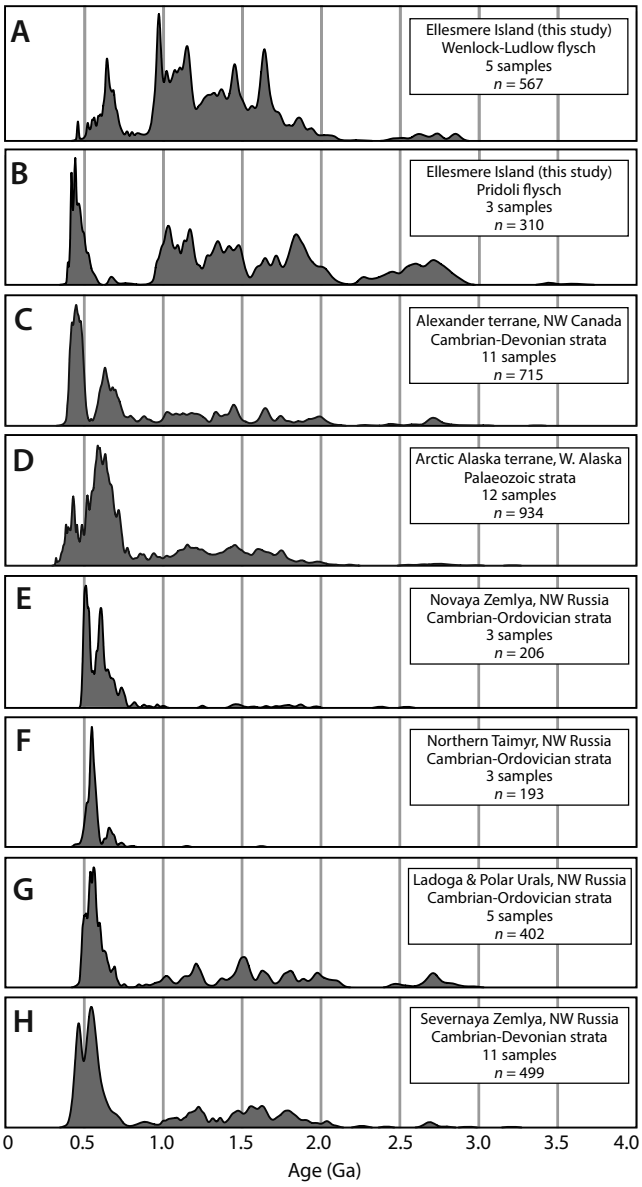

Fig. 9. Detrital zircon reference frames for known or inferred Caledonian- and Timanian-affinity rocks. (**a**) Wenlock to Ludlow flysch of the Danish River and Lands Lokk formations, Ellesmere Island (this study). (**b**) Pridoli flysch of the Danish River and Lands Lokk formations, Ellesmere Island (this study). (**c**) 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: Baltican margin strata, NW Russia (Pease & Scott 2009). (**f**) Northern Taimyr: Baltican margin strata (Pease & Scott 2009). (**g**) Ladoga (St. Petersburg area) and Polar Urals: Baltican margin and cratonal strata (Miller *et al*. 2011). (**h**) Severnaya Zemlya: Baltican margin strata (Lorenz *et al*. 2008).

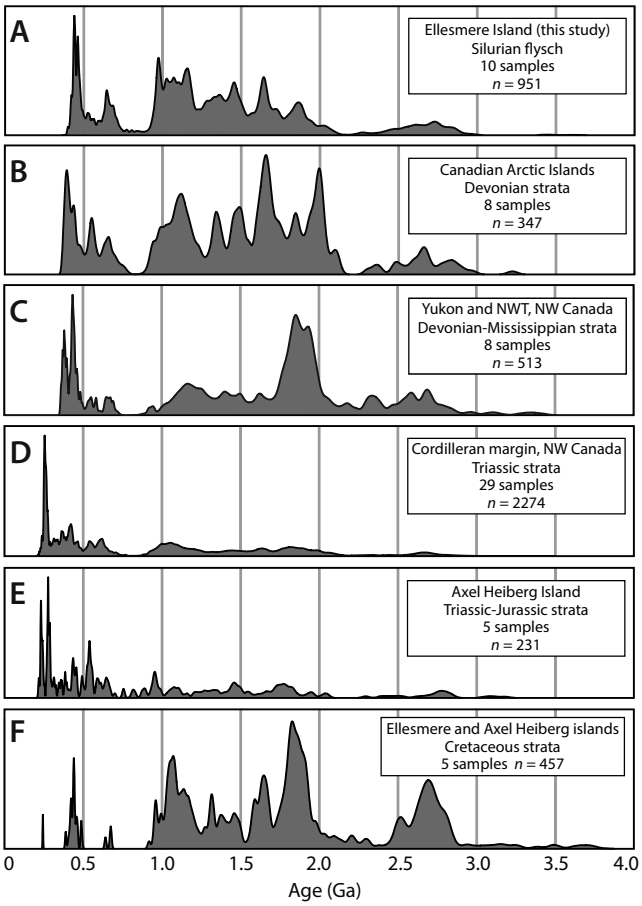

Fig. 10. Detrital zircon reference frames for northern Canadian rocks that may be partially composed of recycled Silurian flysch. (**a**) Canadian Arctic margin: Fire Bay, Danish River and Lands Lokk formations, Ellesmere Island (this study). (**b**) Ellesmerian foreland strata: Blackley and Parry Islands 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 (Røhr *et al*. 2010).

eny was originally defined as a Late Devonian to Early Mississippian regional event in the Canadian Arctic Islands and northern Greenland (Thorsteinsson & Tozer 1970), this definition was further expanded to include Devonian to Carboniferous deformation in Svalbard (Piepjohn 2000) and NW Canada (Lane 2007). 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).

Silurian flysch successions of Ellesmere Island yield detrital zircon provenance signatures that have been previously used to characterize Ellesmerian foreland basin strata and younger clastic rocks 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.

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

involved in the Ellesmerian orogeny. For example, recent palaeogeographical 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. Garzione *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 isotope geochemistry, and detrital monazite U–Pb geochronology and Nd isotope 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 Scandian 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 Scandian collision.

Acknowledgements and Funding

This paper is Natural Resources Canada ESS contribution 20140233, NordSIM publication 384, and a product of the Circum-Arctic Lithosphere Evolution scientific network (www.cale.geo.su.se). The NordSIM facility is operated under a contract between the research funding agencies of Denmark, Iceland, Norway and Sweden, and the Geological Survey of Finland and Swedish Museum of Natural History. Zircon imaging and data collection at the NordSIM facility were greatly aided by M. Whitehouse, L. Ilyinsky and K. Lindén. C. Wohlgemuth-Ueberwasser was very helpful during data collection at the Stockholm University LA-ICP-MS facility. V.P. acknowledges funding from the Swedish Research Council. Thoughtful and constructive reviews by D. Gasser, M. Colpron and Subject Editor B. Bingen improved this paper.

Scientific editing by Bernard Bingen

References

Allen, P.A., Crampton, S.L. & Sinclair, H.D. 1991. The inception and early evolution of the North Alpine Foreland Basin, Switzerland. *Basin Research*, **3**, 143–163.

Amato, J.M., Toro, J., Miller, E.L., Gehrels, G.E., Farmer, G.L., Gottlieb, E.S. & Till, A.B. 2009. Late Proterozoic–Paleozoic evolution of the Arctic Alaska–Chukotka terrane based on U–Pb igneous and detrital zircon ages: Implications for Neoproterozoic paleogeographic reconstructions. *Geological Society of America Bulletin*, **121**, 1219–1235.

Anfinson, O.A., Leier, A.L., Embry, A.F. & Dewing, K. 2012*a*. Detrital zircon geochronology and provenance of the Neoproterozoic to Late Devonian Franklinian Basin, Canadian Arctic Islands. *Geological Society of America Bulletin*, **124**, 415–430.

Anfinson, O.A., Leier, A.L., Gaschning, R., Embry, A.F. & Dewing, K. 2012*b*. U–Pb and Hf isotopic data from Franklinian Basin strata: insights into the nature of Crockerland and the timing of accretion, Canadian Arctic Islands. *Canadian Journal of Earth Sciences*, **49**, 1–13.

Anfinson, O.A., Leier, A.L., Dewing, K., Guest, B., Stockli, D.F. & Embry, A.F. 2013. Insights into the Phanerozoic tectonic evolution of the northern Laurentian margin: Detrital apatite and zircon (U–Th)/He ages from Devonian strata of the Franklinian Basin, Canadian Arctic Islands. *Canadian Journal of Earth Sciences*, **50**, 761–768.

Be'eri-Shlevin, Y., Gee, D.G., *et al*. 2011. Provenance of Neoproterozoic sediments in the Särv nappes (Middle Allochthon) of the Scandinavian Caledonides: LA-ICP-MS and SIMS U–Pb dating of detrital zircons. *Precambrian Research*, **187**, 181–200.

Beranek, L.P. & Mortensen, J.K. 2011. The timing and provenance record of the Late Permian Klondike orogeny in northwestern Canada and arc–continent collision along western North America. *Tectonics*, **30**, TC5017, http://dx.doi.org/10.1029/2010TC002849.

Beranek, L.P., Mortensen, J.K., Lane, L.S., Allen, T.L., Fraser, T.A., Hadlari, T. & Zantvoort, W. 2010*a*. Detrital zircon geochronology of the western Ellesmerian clastic wedge, northwestern Canada: Insights on Arctic tectonics and the evolution of the northern Cordilleran miogeocline. *Geological Society of America Bulletin*, **122**, 1899–1911.

Beranek, L.P., Mortensen, J.K., Orchard, M. & Ullrich, T. 2010*b*. Provenance of North American Triassic strata from west–central and southeastern Yukon: Correlations with coeval strata in the Western Canada Sedimentary Basin and Canadian Arctic Islands. *Canadian Journal of Earth Sciences*, **47**, 53–73.

Beranek, L.P., Van Staal, C.R., Gordee, S.M., McClelland, W.C., Israel, S. & Mihalynuk, M.G. 2012. Tectonic significance of Upper Cambrian–Middle Ordovician mafic volcanic rocks on the Alexander terrane, Saint Elias Mountains, northwestern Canada. *Journal of Geology*, **120**, 293–314.

Beranek, L.P., Pease, V., Scott, R.A. & Thomsen, T.B. 2013*a*. Detrital zircon geochronology of Ediacaran to Cambrian deep-water strata of the Franklinian basin, northern Ellesmere Island, Nunavut: Implications for regional stratigraphic correlations. *Canadian Journal of Earth Sciences*, **50**, 1007–1018.

Beranek, L.P., van Staal, C.R., McClelland, W.C., Israel, S. & Mihyalnuk, M.G. 2013*b*. Baltican crustal provenance for Cambrian–Ordovician sandstones of the Alexander terrane, North American Cordillera: Evidence from detrital zircon U–Pb geochronology and Hf isotope geochemistry. *Journal of the Geological Society, London*, **170**, 7–18.

Beranek, L.P., van Staal, C.R., McClelland, W.C., Israel, S. & Mihalynuk, M.G. 2013*c*. Detrital zircon Hf isotopic compositions indicate a northern Caledonian connection for the Alexander terrane. *Lithosphere*, **5**, 163–168.

Bingen, B. & Solli, A. 2009. Geochronology of magmatism in the Caledonian and Sveconorwegian belts of Baltica: Synopsis for detrital zircon provenance studies. *Norwegian Journal of Geology*, **89**, 267–290.

Bingen, B., Belousova, E.A. & Griffin, W.L. 2011. Neoproterozoic recycling of the Sveconorwegian orogenic belt: Detrital zircon data from the Sparagmite basins in the Scandinavian Caledonides. *Precambrian Research*, **189**, 347–367.

Cawood, P.A., Nemchin, A.A., Strachan, R., Prave, T. & Krabbendam, M. 2007. Sedimentary basin and detrital zircon record along East Laurentia and Baltica during assembly and breakup of Rodinia. *Journal of the Geological Society, London*, **164**, 257–275.

Cawood, P.A., Hawkesworth, C.J. & Dhuime, B. 2012. Detrital zircon record and tectonic setting. *Geology*, **40**, 875–878.

Churkin, M., Jr. & Trexler, J.H., Jr. 1980. Continental plates and accreted oceanic terranes in the Arctic. *In*: Nairn, A.E.M., Churkin, M., Jr & Stehli, F.G. (eds) *The Ocean Basins and Margins, The Arctic Ocean*. Plenum, New York, 1–20.

Cocks, L.R.M. & Torsvik, T.H. 2005. Baltica from the late Precambrian to mid-Palaeozoic times: The gain and loss of a terrane's identity. *Earth-Science Reviews*, **72**, 39–66.

Cocks, L.R.M. & Torsvik, T.H. 2011. The Palaeozoic geography of Laurentia and western Laurussia: A stable craton with mobile margins. *Earth-Science Reviews*, **106**, 1–51.

Colpron, M. & Nelson, J.L. 2009. A Palaeozoic Northwest Passage: Incursion of Caledonian, Baltican, and Siberian terranes into eastern Panthalassa. *In*: Cawood, P.A. & Kröner, A. (eds) *Earth Accretionary Systems through Space and Time*. Geological Society, London, Special Publications, **318**, 273–307.

Colpron, M. & Nelson, J.L. 2011. A Palaeozoic NW Passage and the Timanian, Caledonian, and Uralian connections of some exotic terranes in the North American Cordillera. *In*: Spencer, A.M., Embry, A.F., Gautier, D.L., Stoupakova, A.V. & Sørensen, K. (eds) *Arctic Petroleum Geology*. Geological Society, London, Memoirs, **35**, 463–484.

DeCelles, P.G., Gehrels, G.E., Najman, Y., Martin, A.J., Carter, A. & Garzanti, E. 2004. Detrital geochronology and geochemistry of Cretaceous–Early Miocene strata of Nepal: Implications for the timing and diachroneity of initial Himalayan orogenesis. *Earth and Planetary Science Letters*, **227**, 313–330.

DeGraaff-Surpless, K., Mahoney, J.B., Wooden, J.L. & McWilliams, M.O. 2003. Lithofacies control in detrital zircon provenance: Insights from the Cretaceous Methow basin, southern Canadian Cordillera. *Geological Society of America Bulletin*, **115**, 899–915.

Dewey, J.F. 2005. Orogeny can be very short. *Proceedings of the National Academy of Sciences of the USA*, **102**, 15286–15293.

Dewey, J.F. & Bird, J.M. 1970. Mountain belts and the New Global Tectonics. *Journal of Geophysical Research*, **75**, 2625–2647.

Dewey, J.F. & Strachan, R.A. 2003. Changing Silurian–Devonian relative plate motion in the Caledonides: Sinistral transpression to sinistral transtension. *Journal of the Geological Society*, **160**, 219–229.

Dewing, K., Mayr, U., Harrison, J.C. & de Freitas, T. 2008. Upper Neoproterozoic to Lower Devonian stratigraphy of northeast Ellesmere Island. *In*: Mayr, U. (ed.) *Geology of northeast Ellesmere Island adjacent to Kane Basin and Kennedy Channel, Nunavut*. Geological Survey of Canada Bulletin, **592**, 31–108.

Dickinson, W.R. & Gehrels, G.E. 2008. Sediment delivery to the Cordilleran foreland basin: Insights from U–Pb ages of detrital zircons in Upper Jurassic and Cretaceous strata of the Colorado Plateau. *American Journal of Science*, **308**, 1041–1082.

Dickinson, W.R. & Suczek, C.A. 1979. Plate tectonics and sandstone composition. *AAPG Bulletin*, **63**, 2164–2182.

Dickinson, W.R., Beard, L.S., *et al*. 1983. Provenance of North American Phanerozoic sandstones in relation to tectonic setting. *Geological Society of America Bulletin*, **94**, 222–235.

Embry, A.F. 2009. Crockerland—the source area for the Triassic to Middle Jurassic strata of Northern Axel Heiberg Island, Canadian Arctic Islands. *Bulletin of Canadian Petroleum Geology*, **57**, 129–140.

Fedo, C.M., Sircombe, K.N. & Rainbird, R. 2003. Detrital zircon analysis of the sedimentary record. *In*: Hanchar, J.M. & Hoskin, P.W.O. (eds) *Zircon*. Mineralogical Society of America and Geochemical Society, Reviews in Mineralogy and Geochemistry, **53**, 270–303.

Garzanti, E., Doglioni, C., Vezzoli, G. & Andò, S. 2007. Orogenic belts and orogenic sediment provenance. *Journal of Geology*, **115**, 315–334.

Garzione, C.N., Patchett, P.J., Ross, G.M. & Nelson, J.L. 1997. Provenance of Paleozoic sedimentary rocks in the Canadian Cordilleran miogeocline: A Nd isotopic study. *Canadian Journal of Earth Sciences*, **34**, 1603–1618.

Gasser, D. 2014. The Caledonides of Greenland, Svalbard, and other Arctic areas: Status of research and open questions. *In*: Corfu, F., Gasser, D. & Chew, D. (eds) *New Perspectives on the Caledonides of Scandinavia and Related Areas*. Geological Society, London, Special Publications, **390**, 93–129.

Gasser, D. & Andresen, A. 2013. Caledonian terrane amalgamation of Svalbard: Detrital zircon provenance of Mesoproterozoic to Carboniferous strata from Oscar II Land, western Spitsbergen. *Geological Magazine*, **150**, 1103–1126.

Gee, D.G. 1975. A tectonic model for the central part of the Scandinavian Caledonides. *American Journal of Science*, **275A**, 468–515.

Gee, D.G. & Page, L.M. 1994. Caledonian terrane assembly on Svalbard: New evidence from $^{40}Ar/^{39}Ar$ dating in Ny Friesland. *American Journal of Science*, **294**, 1166–1186.

Gee, D.G. & Teben'kov, A.M. 2004. Svalbard: A fragment of the Laurentian margin. *In*: Gee, D.G. & Pease, V. (eds) *The Neoproterozoic Timanide Orogen of Eastern Baltica*. Geological Society, London, Memoirs, **30**, 191–206.

Gee, D.G., Fossen, H., Henriksen, N. & Higgins, A.K. 2008. From the early Paleozoic platforms of Baltica and Laurentia to the Caledonide orogeny of Scandinavia and Greenland. *Episodes*, **31**, 44–51.

Gee, D.G., Janak, M., Majka, J., Robinson, P. & Van Roermud, H. 2013. Subduction along and within the Baltoscandian margin during closing of the Iapetus Ocean and Baltica–Laurentia collision. *Lithosphere*, **5**, 169–178.

Gehrels, G.E. 2012. Detrital zircon U–Pb geochronology: current models and new opportunities. *In*: Busby, C. & Azor, A. (eds) *Tectonics of Sedimentary Basins: New Methods*. Wiley–Blackwell, Hoboken, NJ, 47–62.

Gradstein, F.M., Ogg, J.G. & Smith, A.G. 2012. *A Geologic Time Scale 2012*. Cambridge University Press, Cambridge.

Hadlari, T., Davis, W.J., *et al*. 2012. Two detrital zircon signatures for the Cambrian passive margin of northern Laurentia highlighted by new U–Pb results from northern Canada. *Geological Society of America Bulletin*, **124**, 1155–1168.

Hadlari, T., Davis, W.J. & Dewing, K. 2014. A pericratonic model for Pearya terrane as an extension of the Franklinian margin of Laurentia, Canadian Arctic. *Geological Society of America Bulletin*, **126**, 182–200.

Harland, W.B. 1971. Tectonic transpression in Caledonian Spitsbergen. *Geological Magazine*, **108**, 27–42.

Hietpas, J., Samson, S., Moecher, D. & Chakraborty, S. 2011. Enhancing tectonic and provenance information from detrital zircon studies: Assessing terrane-scale sampling and grain-scale characterization. *Journal of the Geological Society, London*, **168**, 309–318.

Higgins, A.K., Ineson, J.R., Peel, J.S., Surlyk, F. & Sonderholm, M. 1991. Cambrian to Silurian basin development and sedimentation, north Greenland. *In*: Trettin, H.P. (ed.) *Geology of the Innuitian Orogen and Arctic Platform of Canada and Greenland*. Geological Survey of Canada, Geology of Canada, **3**, 111–161.

Ingersoll, R.V., Kretchmer, A.G. & Valles, P.K. 1993. The effect of sampling scale on actualistic sandstone petrofacies. *Sedimentology*, **40**, 937–953.

Jin, J. & Chatterton, B.D.E. 1997. Latest Ordovician–Silurian articulate brachiopods and biostratigraphy of the Avalanche Lake area, southwestern District of Mackenzie, Canada. *Palaeontographica Canadiana*, **13**, 1–167.

Johansson, Å., Gee, D.G., Larionov, A.N., Ohta, Y. & Tebenkov, A.M. 2005. Grenvillian and Caledonian evolution of eastern Svalbard—a tale of two orogenies. *Terra Nova*, **17**, 317–325.

Kirkland, C.L., Pease, V., Whitehouse, M.J. & Ineson, J.R. 2009. Provenance record from Mesoproterozoic–Cambrian sediments of Peary Land, North Greenland: implications for the ice-covered Greenland Shield and Laurentian palaeogeography. *Precambrian Research*, **170**, 43–60.

Kirkland, C.L., Bingen, B., Whitehouse, M.J., Beyer, E. & Griffin, W.L. 2011. Neoproterozoic palaeogeography in the North Atlantic Region: Inferences from the Akkajaure and Seve Nappes of the Scandinavian Caledonides. *Precambrian Research*, **186**, 127–146.

Klaper, E.M. 1992. The Paleozoic tectonic evolution of the northern edge of North America: A structural study of northern Ellesmere Island, Canadian Arctic Archipelago. *Tectonics*, **11**, 854–870.

Kuznetsov, N.B., Natapov, L.M., Belousova, E.A., O'Reilly, S.Y. & Griffin, W.L. 2010. Geochronological, geochemical and isotopic study of detrital zircon suites from late Neoproterozoic clastic strata along the NE margin of the East European craton: Implications for plate tectonic models. *Gondwana Research*, **17**, 582–601.

Lane, L.S. 2007. Devonian–Carboniferous paleogeography and orogenesis, northern Yukon and adjacent Arctic Alaska. *Canadian Journal of Earth Sciences*, **44**, 679–694.

Lawver, L.A., Pease, V. & Jackson, H.R. 2010. Tectonic development of the Amerasian Basin. *GSA Today*, **20**, 12–13.

Lemieux, Y., Hadlari, T. & Simonetti, A. 2011. Detrital zircon geochronology and provenance of Devono-Mississippian strata in the northern Canadian Cordilleran miogeocline. *Canadian Journal of Earth Sciences*, **48**, 515–541.

Link, P.K., Fanning, C.M. & Beranek, L.P. 2005. Reliability and longitudinal change of detrital-zircon age spectra in the Snake River system, Idaho and Wyoming: An example of reproducing the bumpy barcode. *Sedimentary Geology*, **182**, 101–142.

Lorenz, H., Gee, D.G. & Simonetti, A. 2008. Detrital zircon ages and provenance of the late Neoproterozoic and Palaeozoic succession on Severnaya Zemlya, Kara Shelf: A tie to Baltica. *Norwegian Journal of Geology*, **88**, 235–258.

Ludwig, K.R. 2003. User's manual for Isoplot/Ex, version 3.00, a geochronological tookit for Microsoft Excel. *Berkeley Geochronology Center Special Publication*, **4**.

Majka, J., Mazur, S., Manecki, M., Czerny, J. & Holm, D. 2008. Late Neoproterozoic amphibolite-facies metamorphism of a pre-Caledonian basement block in southwest Wedel Jarlsberg Land, Spitsbergen: New evidence from U–Th–Pb dating of monazite. *Geological Magazine*, **146**, 822–830.

Majka, J., Czerny, J., Mazur, S., Holm, D.K. & Manecki, M. 2010. Neoproterozoic metamorphic evolution of the Isbjørnhamna Group rocks from south-western Svalbard. *Polar Research*, **29**, 250–264.

Majka, J., Larionov, A.N., Gee, D.G. & Czerny, J. 2012. Neoproterozoic pegmatite from Skoddefjellet, Wedel Jarlsberg Land, Spitsbergen: Additional evidence for *c*. 640 Ma tectonothermal event in the Caledonides of Svalbard. *Polish Polar Research*, **33**, 1–17.

Malone, S.J. 2012. *Tectonic evolution of northern Ellesmere Island: insights from the Pearya Terrane, Ellesmerian clastic wedge, and Sverdrup Basin*. PhD thesis, University of Iowa.

Mazur, S., Czerny, J., Majka, J., Manecki, M., Holm, D., Smyrak, A. & Wypych, A. 2009. A strike-slip boundary in Wedel Jarlsberg Land, Svalbard, and its bearing on correlations of SW Spitsbergen with the Pearya terrane and Timanide belt. *Journal of the Geological Society, London*, **166**, 529–544.

McClelland, W.C., Malone, S.J., von Gosen, W., Piepjohn, K. & Läufer, A. 2012. The timing of sinistral displacement of the Pearya terrane along the Canadian Arctic margin. *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften*, **163**, 251–259.

McKerrow, W.S., Mac Niocaill, C. & Dewey, J.F. 2000. The Caledonian orogeny redefined. *Journal of the Geological Society, London*, **157**, 1149–1154.

Miller, E.L., Toro, J., *et al*. 2006. New insights on Arctic paleogeography and tectonics from U–Pb detrital zircon geochronology. *Tectonics*, **25**, TC3013, http://dx.doi.org/10.1029/2005TC001830.

Miller, E.L., Gehrels, G.E., Pease, V. & Sokolov, S. 2010. Stratigraphy and U–Pb detrital zircon geochronology of Wrangel Island, Russia: Implications for Arctic paleogeography. *AAPG Bulletin*, **94**, 665–692.

Miller, E.L., Kuznetsov, N., Soboleva, A., Udoratina, O., Grove, M.J. & Gehrels, G.E. 2011. Baltica in the Cordillera? *Geology*, **39**, 791–794.

Nelson, J.L., Colpron, M. & Israel, S. 2013. The Cordillera of British Columbia, Yukon, and Alaska: tectonics and metallogeny. *In*: Colpron, M., Bissing, T., Rusk, B.G. & Thompson, J.F.H. (eds) *Tectonics, Metallogeny, and Discovery: The North American Cordillera and Similar Accretionary Settings*. Society of Economic Geologists, Special Publication, **17**, 53–109.

Okulitch, A.V., Packard, J.J. & Zolnai, A.I. 1991. Late Silurian–Early Devonian deformation of the Boothia Uplift. *In*: Trettin, H.P. (ed.) *Geology of the Innuitian Orogen and Arctic Platform of Canada and Greenland*. Geological Survey of Canada, Geology of Canada, **3**, 302–307.

Omma, J., Pease, V. & Scott, R.A. 2011. U–Pb SIMS zircon geochronology of Triassic and Jurassic sandstones on northwestern Axel Heiberg Island, northern Sverdrup Basin, Arctic Canada. *In*: Spencer, A.M., Embry, A.F., Gautier, D.L., Stoupakova, A.V. & Sørensen, K. (eds) *Arctic Petroleum Geology*. Geological Society, London, Memoirs, **35**, 559–566.

Park, H., Barbeau, D.L.Jr., Rickenbaker, A., Bachmann-Krug, D. & Gehrels, G.E. 2010. Application of foreland basin detrital-zircon geochronology to the reconstruction of the southern and central Appalachian orogen. *Journal of Geology*, **118**, 23–44.

Patchett, P.J., Roth, M.A., Canale, B.S., de Freitas, T.A., Harrison, J.C., Embry, A.F. & Ross, G.M. 1999. Nd isotopes, geochemistry, and constraints on sources of sediments in the Franklinian mobile belt, Arctic Canada. *Geological Society of America Bulletin*, **111**, 578–589.

Patchett, P.J., Embry, A.F., *et al*. 2004. Sedimentary cover of the Canadian Shield through Mesozoic time reflected by Nd isotopic and geochemical results for the Sverdrup Basin, Arctic Canada. *Journal of Geology*, **112**, 39–57.

Paton, C., Woodhead, J.D., Hellstrom, J.C., Hergt, J.M., Greig, A. & Maas, R. 2010. Improved laser ablation U–Pb zircon geochronology through robust downhole fractionation correction. *Geochemistry, Geophysics, Geosystems*, **11**, Q0AA06, http://dx.doi.org/10.1029/2009GC002618.

Pease, V. 2011. Eurasian orogens and Arctic tectonics: An overview. *In*: Spencer, A.M., Embry, A.F., Gautier, D.L., Stoupakova, A.V. & Sørensen, K. (eds) *Arctic Petroleum Geology*. Geological Society, London, Memoirs, **35**, 311–324.

Pease, V. & Scott, R.A. 2009. Crustal affinities in the Arctic Uralides, northern Russia: Significance of detrital zircon ages from Neoproterozoic and Palaeozoic sediments in Novaya Zemlya and Taimyr. *Journal of the Geological Society, London*, **166**, 517–527.

Pease, V., Lane, L.S., Faliede, J.I., Stephenson, R. & Coakley, B. 2011. Scientific network to decipher crustal evolution of the Arctic. *EOS Transactions, American Geophysical Union*, **92**, 361–363.

Pease, V., Drachev, S., Stephenson, R. & Zhang, X. 2014. Arctic lithosphere—A review. *Tectonophysics*, **628**, 1–25, http://dx.doi.org/10.1016/j.tecto.2014.05.03.

Petrus, J.A. & Kamber, B.S. 2012. VizualAge: A novel approach to laser ablation ICP-MS U–Pb geochronology data reduction. *Geostandards and Geoanalyical Research*, **36**, 247–270.

Pettersson, C.H., Pease, V. & Frei, D. 2010. Detrital zircon U–Pb ages of Silurian–Devonian sediments from NW Svalbard: A fragment of Avalonia and Laurentia? *Journal of the Geological Society, London*, **167**, 1019–1032.

Piepjohn, K. 2000. The Svalbardian–Ellesmerian deformation of the Old Red Sandstone and the pre-Devonian basement in NW Spitsbergen (Svalbard). *In*: Friend, P.F. & Williams, B.P.J. (eds) *New Perspectives on the Old Red Sandstone*. Geological Society, London, Special Publications, **180**, 585–601.

Pojeta, J. & Norford, B.S. 1987. A Bohemian-type Silurian (Wenlockian) pelecypod faunule from Arctic Canada. *Journal of Paleontology*, **61**, 508–520.

Rehnström, E.F. 2010. Prolonged Paleozoic magmatism in the East Greenland Caledonides: Some constraints from U–Pb ages and Hf isotopes. *Journal of Geology*, **118**, 447–465.

Roberts, D. 2003. The Scandinavian Caledonides: Event chronology, palaeogeographic settings and likely modern analogues. *Tectonophysics*, **365**, 283–299.

Røhr, T.S., Andersen, T., Dypvik, H. & Embry, A.F. 2010. Detrital zircon characteristics of the Lower Cretaceous Isachsen Formation, Sverdrup Basin: Source constraints from age and Hf isotope data. *Canadian Journal of Earth Sciences*, **47**, 255–271.

Ross, G.M., Patchett, P.J., Hamilton, M., Heaman, L., DeCelles, P.G., Rosenberg, E. & Giovanni, M.K. 2005. Evolution of the Cordilleran orogen (southwestern Alberta, Canada) inferred from detrital mineral geochronology, geochemistry, and Nd isotopes in the foreland basin. *Geological Society of America Bulletin*, **117**, 747–763.

Shephard, G.E., Muller, R.D. & Seton, M. 2013. The tectonic evolution of the Arctic since Pangea breakup: Integrating constraints from surface geology and geophysics with mantle structure. *Earth-Science Reviews*, **124**, 148–183.

Sláma, J., Košler, J., *et al*. 2008. Plešovice zircon—a new natural reference frame material for U–Pb and Hf isotopic microanalysis. *Chemical Geology*, **249**, 1–35.

Sláma, J., Walderburg, O., Fonneland, H., Košler, J. & Pederson, R.B. 2011. Provenance of Neoproterozoic to upper Cretaceous sedimentary rocks, eastern Greenland: implications for recognizing the sources of sediments in the Norwegian Sea. *Sedimentary Geology*, **238**, 254–267.

Soper, N.J., Strachan, R.A., Holdsworth, R.E., Gayer, R.A. & Greiling, R.O. 1992. Sinistral transpression and the Silurian closure of Iapetus. *Journal of the Geological Society, London*, **149**, 871–880.

Strauss, J.V., Macdonald, F.A., Taylor, J.F., Repetski, J.E. & McClelland, W.C. 2013. Laurentian origin for the North Slope of Alaska: Implications for the tectonic evolution of the Arctic. *Lithosphere*, **5**, 477–482.

Surlyk, F. & Hurst, J.M. 1984. The evolution of the early Paleozoic deep-water basin of North Greenland. *Geological Society of America Bulletin*, **95**, 131–154.

Sweeney, J.F. 1982. Mid-Palaeozoic travels of Arctic-Alaska. *Nature*, **282**, 642–649.

Thomas, W.A. 2011. Detrital-zircon geochronology and sediment provenance. *Lithosphere*, **3**, 304–308.

Thorsteinsson, R. & Tozer, E.T. 1970. Geology of the Arctic Archipelago. *In*: Douglas, R.J.W. (ed.) *Geology and Economic Minerals of Canada*. Geological Survey of Canada, Report, **1**, 547–590.

Trettin, H.P. 1987. Pearya: A composite terrane with Caledonian affinities in northern Ellesmere Island. *Canadian Journal of Earth Sciences*, **24**, 224–245.

Trettin, H.P. 1994. *Pre-Carboniferous Geology of the Northern Part of the Arctic Islands: Hazen Fold Belt and Adjacent Parts of the Central Ellesmere Fold Belt, Ellesmere Island*. Geological Survey of Canada Bulletin, **430**.

Trettin, H.P. 1998. *Pre-Carboniferous Geology of the Northern Part of the Arctic Islands*. Geological Survey of Canada Bulletin, **425**.

Trettin, H.P., Parrish, R. & Loveridge, W.D. 1987. U–Pb age determinations on Proterozoic to Devonian rocks from northern Ellesmere Island, Arctic Canada. *Canadian Journal of Earth Sciences*, **24**, 246–256.

van Staal, C.R. & Hatcher, R.D., Jr 2010. Global setting of Ordovician orogenesis. *In*: Finney, S.C. & Berry, W.B.N. (eds) *The Ordovician Earth System*. Geological Society of America, Special Papers, **466**, 1–11.

van Staal, C.R., Dewey, J.F., Mac Niocaill, C. & McKerrow, W.S. 1998. The Cambrian–Silurian tectonic evolution of the northern Appalachians and British Caledonides: History of a complex, west and southwest Pacific-type segment of Iapetus. *In*: Blundell, D.J. & Scott, A.C. (eds) *Lyell: the Past is the Key to the Present*. Geological Society, London, Special Publications, **143**, 199–242.

van Staal, C.R., Whalen, J.B., Valverde-Vaquero, P., Zagorevski, A. & Rogers, N. 2009. Pre-Carboniferous, episodic accretion-related, orogenesis along the Laurentian margin of the northern Appalachians. *In*: Murphy, J.B., Keppie, J.D. & Hynes, A.J. (eds) *Ancient Orogens and Modern Analogues*. Geological Society, London, Special Publications, **327**, 271–316.

von Gosen, W., Piepjohn, K., McClelland, W.C. & Läufer, A. 2012. The Pearya Shear Zone in the Canadian High Arctic: Kinematics and significance. *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften*, **163**, 233–249.

Whitehouse, M.J. & Kamber, B.S. 2005. Assigning dates to thin gneissic veins in high-grade metamorphic terranes: A cautionary tale from Akilia, southwest Greenland. *Journal of Petrology*, **46**, 291–318.

Whitehouse, M.J., Kamber, B.S. & Moorbath, S. 1999. Age significance of U–Th–Pb zircon data from Early Archean rocks of west Greenland: A reassessment based on combined ion-microprobe and imaging studies. *Chemical Geology*, **160**, 201–224.

Wiedenbeck, M., Allè, P., *et al*. 1995. Three natural zircon standards from U–Th–Pb, Lu–Hf, trace element, and REE analysis. *Geostandards Newsletter*, **19**, 1–23.

Zonenshain, L.P. & Natapov, L.M. 1987. Tectonic history of the Arctic. *In*: Yanshin, A.I. (ed.) *Topical Problems of Ocean and Continent Tectonics*. Nauka, Moscow, 31–57 [in Russian].

Zonenshain, L.P.,, Kuzmin, M.I.,, Natapov, L.M., & Page, B.M., (eds) 1990. *Geology of the USSR: A Plate-tectonic Synthesis*. American Geophysical Union, Geodynamics Series, **21**.