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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

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Abstract: Detrital zircon U–Pb geochronology and Hf isotope geochemistry allow us to decipher the crustal provenance of Cambrian–Ordovician backarc basin strata of the Alexander terrane, North American Cordillera, and evaluate models for its origin and displacement history relative to Baltica, Gondwana, Siberia, and Laurentia. Quartzose shallow-marine sandstones of the Alexander terrane contain a range of Neoproterozoic to Neoarchaean detrital zircons with the most dominant age groupings *c.* 565–760, 1000–1250, 1450, and 1650 Ma. Subordinate volcaniclastic sandstones yield Cambrian and Ordovician detrital zircons with a prominent age peak at 477 Ma. The detrital zircon age signatures resemble coeval strata in the Eurasian high Arctic, and in combination with faunal and palaeomagnetic constraints suggest provenance from local magmatic rocks and the Timanide orogenic belt and Fennoscandian Shield of NE Baltica. The Hf isotopic compositions of Palaeozoic to Neoarchaean detrital zircons strongly favour Baltican crustal sources instead of similar-aged domains of Gondwana. The Alexander terrane formed part of an arc system that fringed the Uralian passive margin, and its position in the Uralian Seaway allowed faunal exchange between the Siberian and Baltican platforms. The available evidence suggests that the Alexander terrane originated in the Northern Hemisphere and migrated to the palaeo-Pacific Ocean by travelling around northern Laurentia.

Supplementary material: U–Pb and Lu–Hf data tables are available at www.geolsoc.org.uk/SUP18557.

The North American Cordillera (Fig. 1) is an active accretionary system that has been the site of continued plate convergence and crustal growth since the late Palaeozoic (Monger *et al*. 1972; Burchfiel & Davis 1975; Samson & Patchett 1991; Ward 1995; Cawood *et al*. 2009; Beranek & Mortensen 2011). This orogen was assembled through the accretion of mobile crustal fragments, or terranes, that comprise a collage of fault-bounded blocks adjacent to the western edge of the Laurentian craton (Coney *et al*. 1980; Saleeby 1983; Colpron *et al*. 2007). Within this framework there is a general lack of consensus about the origins of terranes in the western Cordillera (Alexander, Arctic Alaska–Chukotka and others), and, as a consequence, the global plate motions that transported them to western North America are unresolved (e.g. Miller *et al*. 2011).

The Alexander terrane (Fig. 1), a crustal fragment that underlies 100000 km^2 of Alaska and Canada, presents a superb opportunity to investigate the global tectonic and palaeogeographical significance of the western North American Cordillera. Rocks of the Alexander terrane were regionally deformed and metamorphosed during three time intervals (Neoproterozoic to Cambrian, Late Silurian to Early Devonian, and Late Pennsylvanian to Early Permian) prior to Mesozoic accretionary orogenesis along western North America (Gehrels & Saleeby 1987; van Staal *et al*. 2010). Two scenarios are typically invoked to explain the early evolution of the Alexander terrane. The first scenario calls for the Alexander terrane to share a history with peri-Gondwanan (Avalonian–Cadomian) crustal fragments and predicts lithostratigraphic linkages with the Neoproterozoic orogens of west Gondwana and the mid-Palaeozoic Appalachian orogen of eastern Laurentia (Wright & Wyld 2006). In this model, the Alexander terrane migrated to the palaeo-Pacific by travelling around southern Laurentia (Fig. 2, Model 1). The second scenario considers the Alexander terrane to share a history with the Eurasian high Arctic and predicts lithostratigraphic linkages with Neoproterozoic (Timanian) and mid-Palaeozoic (Caledonian) orogenic belts that underlie the Scandinavian and Arctic Russia sectors of Baltica (Colpron & Nelson 2009). This model requires the Alexander terrane to have been transported to the palaeo-Pacific by travelling around northern Laurentia (Fig. 2, Model 2).

Detrital zircon provenance analysis is an effective method for reconstructing ancient links between sedimentary basins and their source regions (e.g. Cawood *et al*. 2007). Because terranes by definition are tectonically disconnected from the regions where they originally formed, such analysis provides an independent test of crustal provenance that complements other geological, fossil, and palaeomagnetic constraints. Upper Cambrian to Middle Ordovician marine sandstones of the Donjek assemblage, some of the oldest exposed rocks of the Alexander terrane in Canada, are important targets for detrital zircon provenance analysis. For example, quartzose sandstones of the Donjek assemblage were derived from an adjacent continental block, as there are no obvious sources for these compositionally mature strata on the Alexander terrane (Beranek *et al*. 2012). To decipher Gondwanan or Baltican crustal sources for the Alexander terrane and test displacement models proposed by Wright & Wyld (2006) and Colpron & Nelson (2009), Donjek assemblage sandstones from the Saint Elias Mountains of

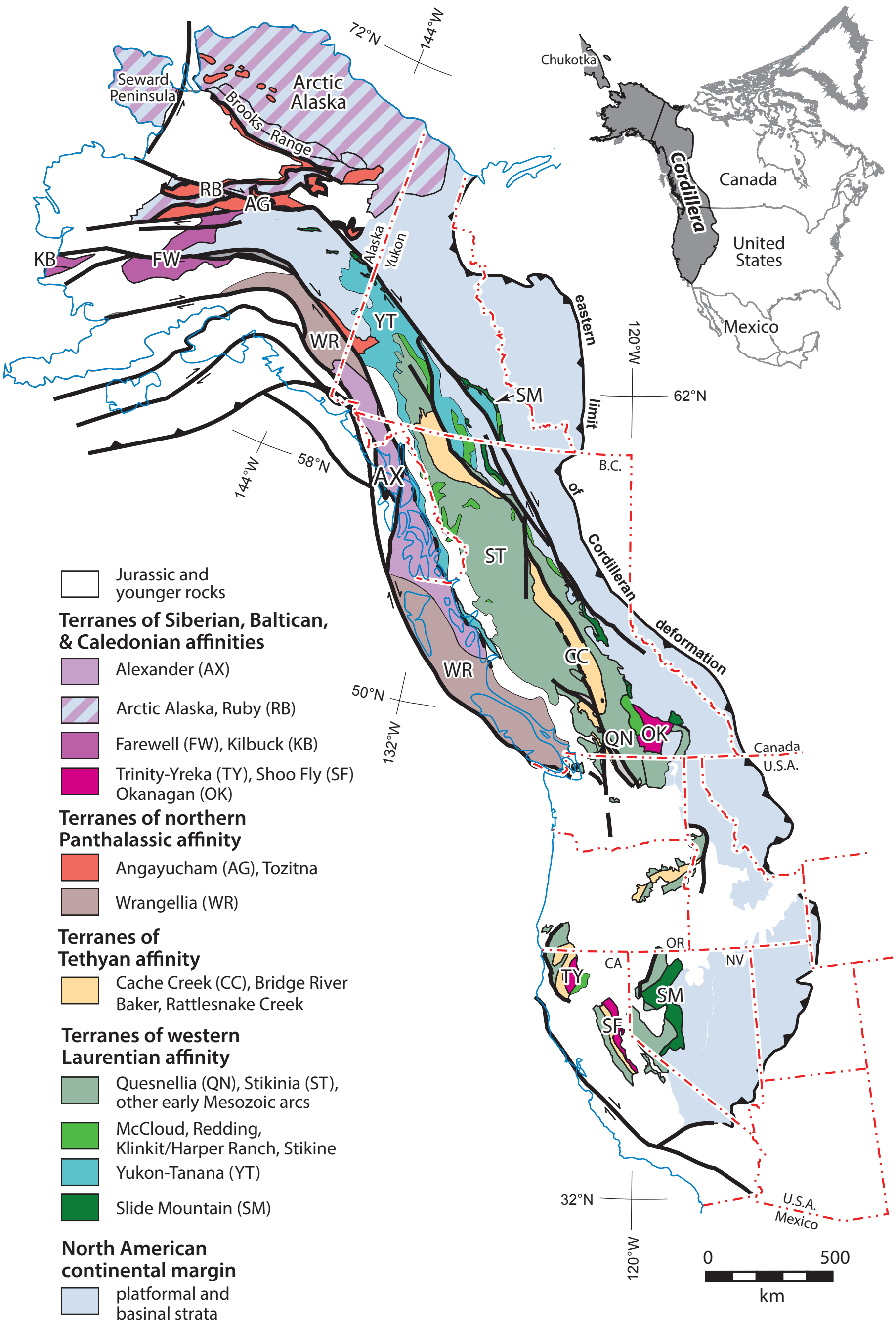

Fig. 1. Palaeozoic to early Mesozoic terranes of the North American Cordillera modified from Colpron & Nelson (2009). Terranes are grouped according to faunal affinity and interpreted positions in early Palaeozoic time. B.C., British Columbia; CA, California; OR, Oregon; NV, Nevada.

Canada (Fig. 3a) were analysed for detrital zircon U–Pb geochronology and Hf isotope geochemistry. The results contribute to a growing detrital zircon database for the western North American Cordillera and provide new ideas on Neoproterozoic–early Palaeozoic global tectonics and palaeogeography.

Background geology

Neoproterozoic arc magmatism and orogeny

Neoproterozoic arc-type metavolcanic and metasedimentary rocks of the Wales Group are the oldest recognized units of the Alexander terrane (Fig. 3b). The depositional age of the Wales Group is constrained by a felsic metavolcanic unit on Prince of Wales Island, southeastern Alaska, dated by U–Pb zircon at 595 ± 20 Ma (Gehrels *et al*. 1996). Wales Group metavolcanic rocks on nearby Dall Island are intruded by 554 ± 4 Ma orthogneiss (Gehrels 1990). The metavolcanic and metaplutonic rocks yield primitive Nd–Sr isotopic compositions that suggest an intraoceanic setting similar to the modern Marianas (Samson *et al*. 1989). Rocks of the Wales Group were penetratively deformed and metamorphosed at greenschist to amphibolite facies during a Neoproterozoic–Cambrian (*c*. 550–500 Ma) event termed the Wales orogeny (Gehrels & Saleeby 1987).

Late Cambrian to Middle Ordovician arc magmatism and sedimentation

Upper Cambrian to Middle Ordovician rocks of the Donjek assemblage (Fig. 3b) form the exposed base of the Alexander terrane in

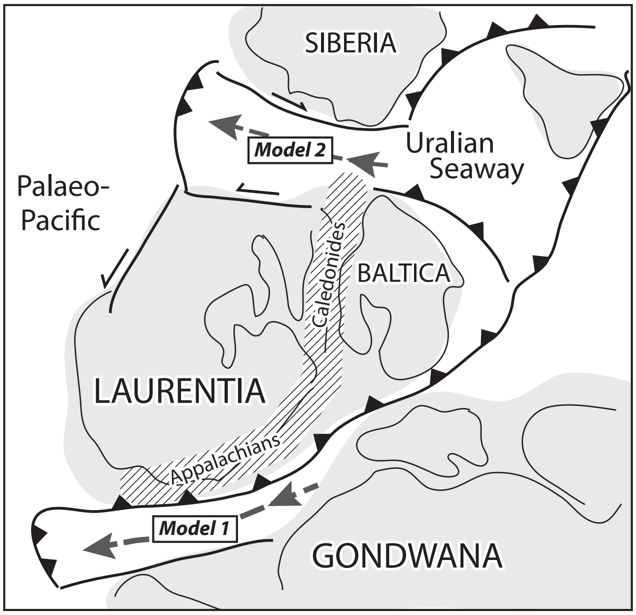

Fig. 2. Proposed mid-Palaeozoic displacement vectors for the Alexander and other terranes in the western North American Cordillera with westward transport from Gondwana south of Laurentia (Model 1) or westward transport from Baltica north of Laurentia (Model 2). Modified from Miller *et al*. (2011).

the Saint Elias Mountains (Dodds & Campbell 1992). The Donjek assemblage primarily consists of planar laminated to ripple cross-laminated quartzose siltstone and sandstone. Mafic sills and pillowed to massive basalts are interbedded with these siliciclastic rocks and locally form up to 80% of the section over intervals of hundreds of metres (Mihalynuk *et al*. 1993). The Field Creek volcanics are a subdivision of the Donjek assemblage in southwestern Yukon (Fig. 3c) that comprise >1500 m of lava flows, volcaniclastic rocks, and limestone. A shallow-marine depositional environment for the Donjek assemblage is most consistent with the sedimentary and volcanic rock types and observed sedimentary structures (Mihalynuk *et al*. 1993; Beranek *et al*. 2012).

Donjek assemblage mafic rocks are geochemically analogous to modern intra-arc rift and backarc basin basalts, and their origin might be linked to a change in plate dynamics after the Wales orogeny (Beranek *et al*. 2012). The Donjek assemblage was most probably deposited along the passive margin side of an ensialic backarc basin that did not evolve into oceanic spreading. Quartzose strata of the Donjek assemblage were sourced from the adjacent continental region, whereas volcaniclastic sandstones of the unit were derived from local magmatic rocks (Beranek *et al*. 2012).

Upper Cambrian(?) to Silurian volcanic and sedimentary rocks of the Descon Formation in southeastern Alaska unconformably overlie the Wales Group (Fig. 3b). The Descon Formation and its coeval calc-alkaline intrusive suite formed part of a continental margin-fringing arc along the trenchward side of an ensialic backarc basin (Beranek *et al*. 2012).

Fossil constraints on terrane palaeogeography

Benthic fossil assemblages that are preserved in shallow-marine rock units constrain the early to mid-Palaeozoic palaeogeography of the Alexander terrane. In the Prince of Wales Island region, Upper Silurian limestones of the Heceta Formation (Fig. 3b) contain stromatolite reefs and mud mounds that were colonized by distinctive sphinctozoan sponges (aphrosalpingids) and hydroids (Soja 1990, 1994; Antoshkina & Soja 2006). These microbial biotas resemble those identified in the Uralian (eastern European) platform of Baltica, Salair Ridge area of SW Siberia, and Siberian-affinity Farewell terrane of Alaska (Antoshkina & Soja 2006). Early to Middle Devonian brachiopod, gastropod, and rugose coral fauna in rocks that overlie the Heceta Formation display qualitative and statistical similarities to fossils of the Uralian platform, Siberian platform of southern Taimyr, and Kolyma–Omolon superterrane (Pedder 2006; Blodgett *et al*. 2011). Larval exchange between the Baltican and Siberian realms strongly argues for a Northern Hemisphere position for the Alexander terrane within the Uralian Seaway, the marine corridor that separated Laurentia and Baltica from Siberia during the early to mid-Palaeozoic (Soja & Antoshkina 1997; Blodgett *et al*. 2002, 2003; Pedder 2006; Soja 2008).

Palaeomagnetic constraints on terrane palaeogeography

Terrigenous red-bed and shallow-marine strata of the Karheen Formation in the Prince of Wales Island region comprise a molasse succession deposited during the Late Silurian to Early Devonian Klakas orogeny (Fig. 3b). This event is characterized by contractional deformation, greenschist- to amphibolite-facies metamorphism, and magmatism (Gehrels & Saleeby 1987). Palaeomagnetic data require an Early Devonian magnetization for the Karheen Formation at 14° ± 4° palaeolatitude in either the Northern or Southern Hemisphere (Bazard *et al*. 1995; Butler *et al*. 1997). Combining the fossils of Baltican–Siberian aspect, timing of the Klakas orogeny, and lithology of Karheen red beds, Bazard *et al*. (1995) favoured a Northern Hemisphere position for the Alexander terrane near the Scandinavian Caledonides.

Detrital zircon samples and methods

Sample collection and preparation

Seven rock samples from the Saint Elias Mountains (Fig. 3c) were collected for detrital zircon U–Pb geochronology and Hf isotope geochemistry. The suite includes five samples of medium- to coarse-grained quartzose sandstone (09VLB30, –31, –34, –41, –42) and two samples of coarse-grained volcaniclastic sandstone (10VLB01, -03). Zircons were separated from 2–5 kg samples using conventional rock crushing, grinding, wet shaking table, heavy liquid, and magnetic methods. A random portion of each of the zircon concentrates was poured onto double-sided tape, mounted in epoxy with standard zircons (R33, Black *et al*. 2004; Plešovice, Sláma *et al*. 2008; Sri Lanka, Gehrels *et al*. 2008), and polished to expose the interior of the grains. Reflected and transmitted light photomicrographs were taken of all grains, and cathodoluminescence imaging of the mounts using an SEM was completed at the Arizona Laserchron Center (ALC), University of Arizona. The images were taken to locate homogeneous regions in the zircons and to avoid complex internal structures, cracks, and zones of potential Pb loss.

U–Pb geochronology

Detrital zircon U–Pb geochronology was conducted by laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) at the ALC. The analyses involved the ablation of zircon with a New Wave UP-213 excimer laser using a spot diameter of 30 µm. The ablated material was transported by helium carrier gas into the plasma source of a Nu Plasma (Nu Instruments Ltd., UK) high-resolution ICP-MS system. Complete descriptions of the U–Th–Pb analytical protocol at the ALC have been given by Gehrels *et al*. (2008, 2011).

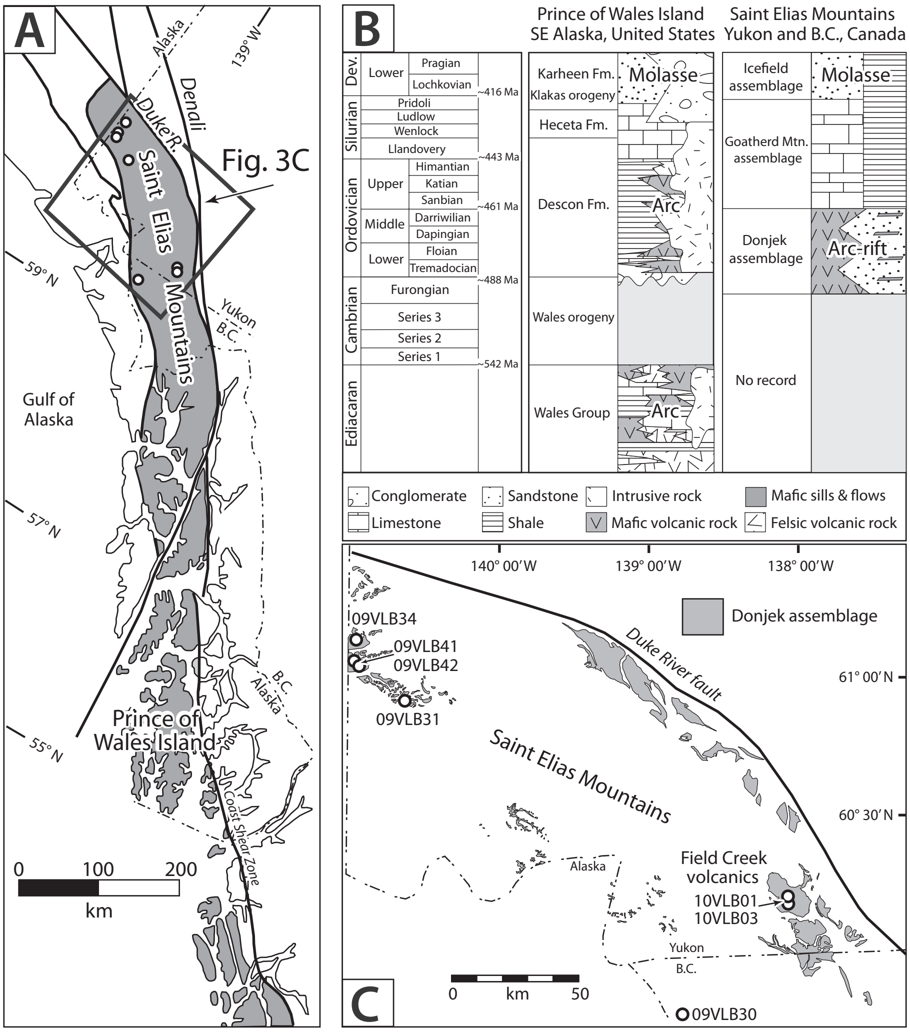

Fig. 3. (**a**) Location map of the Alexander terrane. (**b**) Stratigraphy of the Alexander terrane compiled from Gehrels & Saleeby (1987), Dodds & Campbell (1992), Mihalynuk *et al*. (1993), and Beranek *et al*. (2012). Geological time scale of Gradstein *et al*. (2004). (**c**) Map distribution of Upper Cambrian to Middle Ordovician rocks of the Donjek assemblage in the Saint Elias Mountains. The white circles in (**a**) and (**c**) indicate detrital zircon sample locations discussed in the text.

Detrital zircon age results are presented in relative probability plots with stacked histograms (Figs 4 and 5) made with the Isoplot 3.0 Excel macro of Ludwig (2003). Following data acquisition and reduction protocols at the ALC, analyses with >10% uncertainty or excessive discordance (>20% discordant or >5% reverse discordant) were rejected and not included in the probability plots. Strict uncertainty cutoffs tend to eliminate younger analyses because of low Pb signal intensities, whereas tighter discordance cutoffs tend to eliminate older analyses because of enhanced probability of Pb loss with increasing age (Gehrels 2011).

Comparison of detrital zircon age distributions between samples was accomplished with the Kolmogorov–Smirnov (K–S) two-sample test macro developed by the ALC (Guynn & Gehrels 2010). The K–S test is a nonparametric statistical method that returns a probability value (*P*) for two samples being drawn from the same population (Massey 1951). Two populations are not considered to be statistically different when *P* values exceed 0.05. The higher the *P* value the more likely it is that the two age distributions were drawn from the same population.

Hf isotope geochemistry

Detrital zircon Hf isotope geochemistry was performed at the ALC using laser and ICP-MS routines similar to those described for U–Pb geochronology. *In situ* Hf isotope measurements were conducted on 247 dated zircon grains. A laser spot diameter of 40 μm was used. The beam was typically centred on top of the pit excavated for U–Pb analysis because of limited grain sizes, cracks, inclusions, and other zones of avoidance recognized during imaging. Complete descriptions of the laser ablation routines, data reduction protocols, and interference corrections for ^{176}Yb and ^{176}Lu on ^{176}Hf used at the ALC have been given by Cecil *et al*. (2011).

Initial ^{176}Hf/^{177}Hf ratios are reported as $\varepsilon_{Hf(t)}$, which represents the isotopic composition at the time of crystallization relative to the chondritic uniform reservoir (CHUR). Positive $\varepsilon_{Hf(t)}$ values are consistent with mantle-derived sources, whereas negative values suggest contamination from crustal material. $\varepsilon_{Hf(t)}$ values were calculated using the ^{176}Lu decay constant of Scherer *et al*. (2001) and the chondritic values of Bouvier *et al*. (2008). Hf model ages (Hf_{TDM}) were approximated to the time of crystallization using initial ^{176}Hf/^{177}Hf ratios and ^{176}Lu/^{177}Hf = 0.015 for the present-day crust (Goodge & Vervoort 2006). Hf model ages provide an estimate for the timing of extraction of source rocks from a depleted mantle reservoir.

U–Pb age results

Quartzose sandstones

The quartzose sandstones from southwestern Yukon contain a primary age population from 565 to 760 Ma that forms 40–75% of

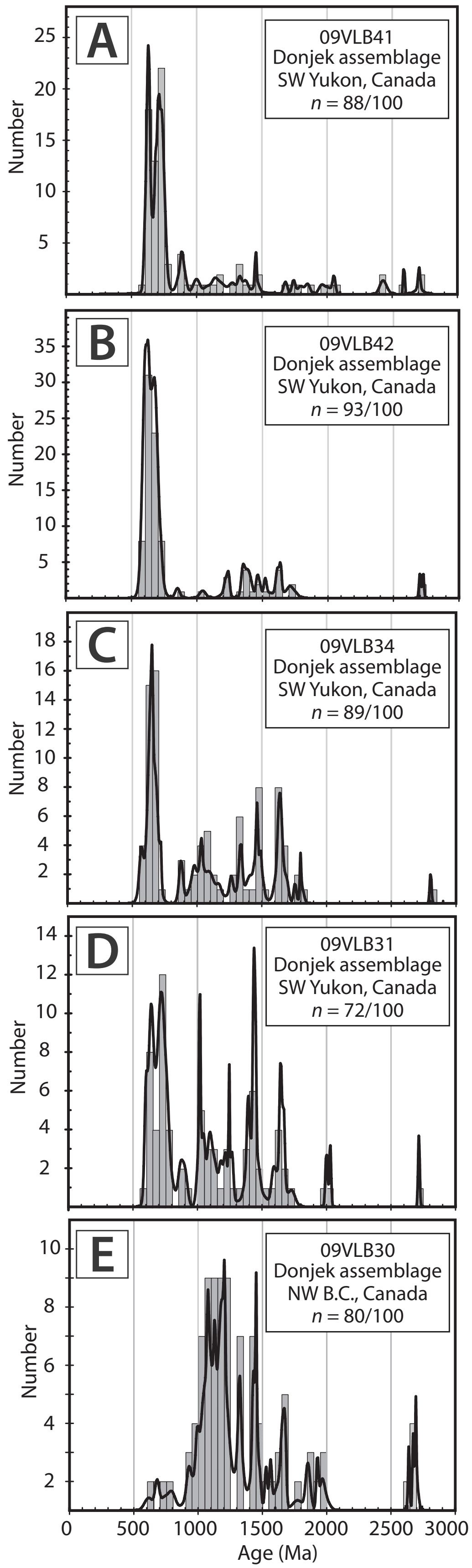

Fig. 4. Detrital zircon U–Pb probability density distribution–histogram plots of quartzose sandstones of the Donjek assemblage.

each sample (Fig. 4a–d). The most dominant probability age peaks in this range occur *c.* 625, 640, 675, 710, and 725 Ma. Small populations of 860–900 Ma zircons generate age peaks *c.* 880 Ma. Meso- to Palaeoproterozoic age groupings *c.* 1000–1250, 1400–1480, and 1600–1680 Ma each comprise up to 10% of the zircons (Fig. 4a–d). Neoarchaean zircons with ages from 2590 to 2800 Ma occur as one to three analyses in each sample. The age distributions of 09VLB31 and 09VLB34 are not statistically different ($P = 0.33$). 09VLB30 from northwestern British Columbia yielded a *c.* 990–1250 Ma age population that forms 58% of the sample (Fig. 4e). The most prominent age peaks *c.* 1330, 1450, and 1650 Ma are similar to those observed in the southwestern Yukon samples. Four Neoarchaean zircons with ages from 2640 to 2700 Ma are present.

Volcaniclastic sandstones

The volcaniclastic sandstones of the Field Creek volcanics are mostly composed of Late Cambrian to Ordovician detrital zircons, with both samples producing a probability age peak at 477 Ma (Fig. 5a and b). A single Palaeoproterozoic (2004 Ma) detrital zircon was analysed in 10VLB03. The age distributions of the two samples are not statistically different ($P = 0.36$).

Hf isotope results

Quartzose sandstones

Ninety-five Hf isotopic analyses were acquired on late Neoproterozoic detrital zircons with ages between 565 and 760 Ma. Detrital zircons in this age bracket yield a wide range of $\varepsilon_{Hf(t)}$ values from −12 to +15 (Fig. 6), with most of the analyses restricted between −3 and +3 (53 of 95 analyses; 55%). Hf_{TDM} values for late Neoproterozoic zircons range from 800 to 1800 Ma.

Early Neoproterozoic to Neoarchaean zircons yield $\varepsilon_{Hf(t)}$ values of −9 to +13 (Fig. 6). Although most of the analyses for any given age group plot both above and below the CHUR line, positive $\varepsilon_{Hf(t)}$ values are generally observed for *c.* 900–1250 Ma (24 of 33 analyses; 72%) and 1400–1470 Ma zircons (16 of 18 analyses; 88%). Early Neoproterozoic (*c.* 880 Ma) and late Mesoproterozoic (1000–1250 Ma) zircons have Hf_{TDM} of 1200–1700 Ma. Early Mesoproterozoic (*c.* 1450 Ma) zircons have Hf_{TDM} of 1800 Ma, whereas *c.* 1650 Ma zircons range in Hf_{TDM} from 2100 to 2300 Ma. Meso- to Palaeoarchaean Hf_{TDM} ages from 2800 to 3500 Ma are observed for *c.* 2700 Ma zircons.

Volcaniclastic sandstones

Fifty-seven Hf isotopic analyses were acquired on Late Cambrian to Ordovician detrital zircons. The results indicate a broad range of $\varepsilon_{Hf(t)}$ values from −0.4 to +18, with 73% of the analyses between +3 and +10 (Fig. 7). The zircons predominantly yield Hf_{TDM} ages of 680–1300 Ma.

Potential source regions and provenance correlations

Quartzose sandstones of the Donjek assemblage are composed of Neoproterozoic to Neoarchaean detrital zircons that have no recognized source from basement rocks of the Alexander terrane, with the exception of *c.* 595 Ma felsic metavolcanic units of the Wales Group. To evaluate potential sources and provenance correlations that are required by the models of Wright & Wyld (2006) and Colpron & Nelson (2009), we compared the detrital zircon signatures of the Alexander terrane with rock units of Gondwana, Baltica, and the western North American Cordillera.

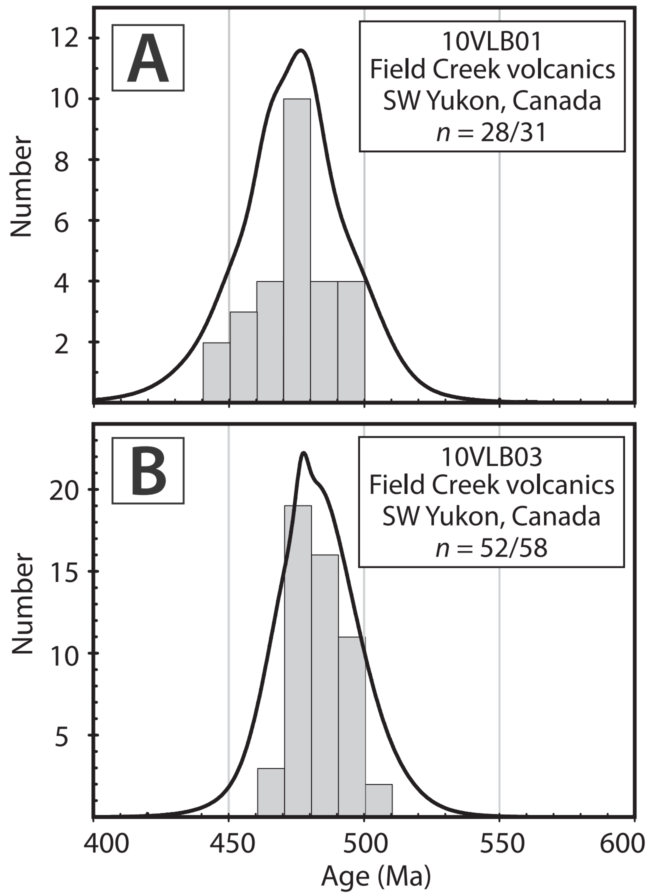

Fig. 5. Detrital zircon U–Pb probability density distribution–histogram plots of volcaniclastic sandstones of the Donjek assemblage.

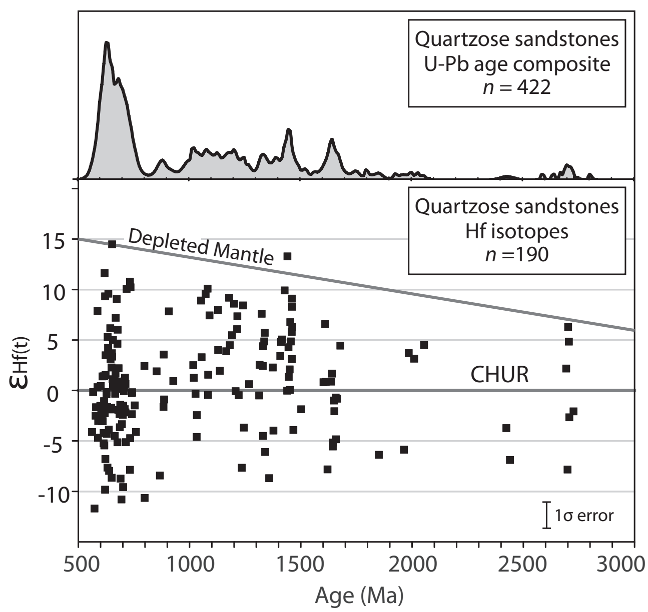

Fig. 6. $\varepsilon_{Hf(t)}$ v. U–Pb age diagrams for detrital zircons in quartzose sandstones of the Donjek assemblage. The depleted mantle Hf evolution curve was calculated from values reported by Vervoort & Blichert-Toft (1999).

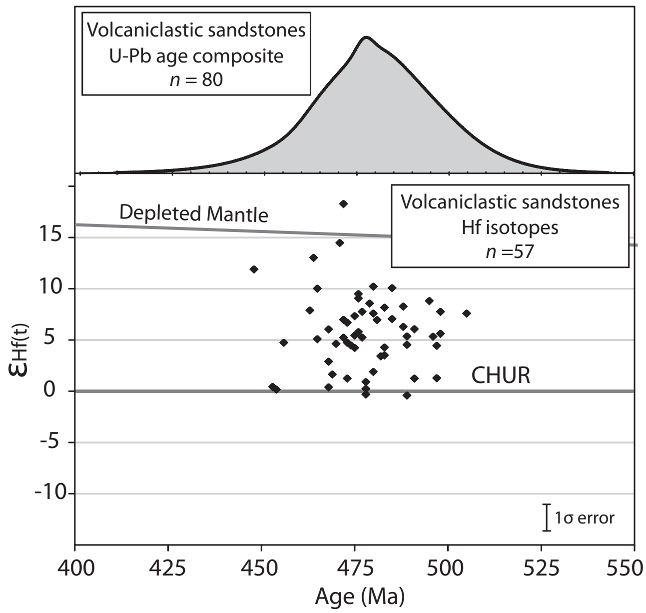

Fig. 7. $\varepsilon_{Hf(t)}$ v. U–Pb age diagrams for detrital zircons in volcaniclastic sandstones of the Donjek assemblage. The depleted mantle Hf evolution curve was calculated from values reported by Vervoort & Blichert-Toft (1999).

West Gondwana

Wright & Wyld (2006) related the Alexander terrane to Gondwanan crustal fragments that now occupy much of eastern North America (Avalonian-type terranes; Hibbard *et al.* 2007) and southern and central Europe (Cadomian-type terranes; Linnemann *et al.* 2008). Wright & Wyld (2006) further proposed that arc-type rocks of the Wales Group record subduction near west Gondwana and that the timing of the Wales orogeny coincided with Neoproterozoic orogenic events along the Amazonian and west African cratons.

The framework geology of the peri-Gondwanan terranes is well understood (Nance *et al.* 2008). Avalonian-type terranes originated from Mesoproterozoic crust and record Cryogenian arc magmatism prior to *c.* 650 Ma collision with Amazonia. Subsequent continental arc magmatism was punctuated by Cambrian–Ordovician rifting and tectonic separation of the Avalonian terranes from the Amazonian margin (van Staal & Barr 2012). Palaeozoic shallow-marine strata of the Avalonian-type terranes contain cool-water, high-latitude fauna (e.g. Nance *et al.* 2008) in contrast to the tropical, Baltican–Siberian fossil affinities of the Alexander terrane.

Detrital zircon ages of the Donjek assemblage (Fig. 8a) broadly resemble those for Palaeozoic strata of the Amazonian margin that were sourced from 450–500 Ma magmatic rocks and the 550–800 Ma Brasiliano, 1000–1400 Ma Sunsas, and 1800–2000 Ma Transamazonian belts of the Brazilian Shield (Fig. 8b–d; Chew *et al.* 2008; Bahlburg *et al.* 2011; Reimann *et al.* 2010). However, 95% (24 of 25 grains) of the 450–500 Ma detrital zircons analysed by Bahlburg *et al.* (2011) yielded $\varepsilon_{Hf(t)}$ values of −0.7 to −32.8. This indicates a significant crustal source for Cambrian and Ordovician magmatic rocks of Amazonia, which is not consistent with our results for 450–500 Ma zircons in the Field Creek volcanics. Late Neoproterozoic zircons described by Reimann *et al.* (2010) also differ from those of the Donjek assemblage as the former are mostly characterized by $\varepsilon_{Hf(t)}$ values of −2.4 to −13 (19 of 31 grains; 61%). Whereas our Hf isotope results from the Alexander terrane indicate that 1000–1650 Ma zircons have positive $\varepsilon_{Hf(t)}$ values and

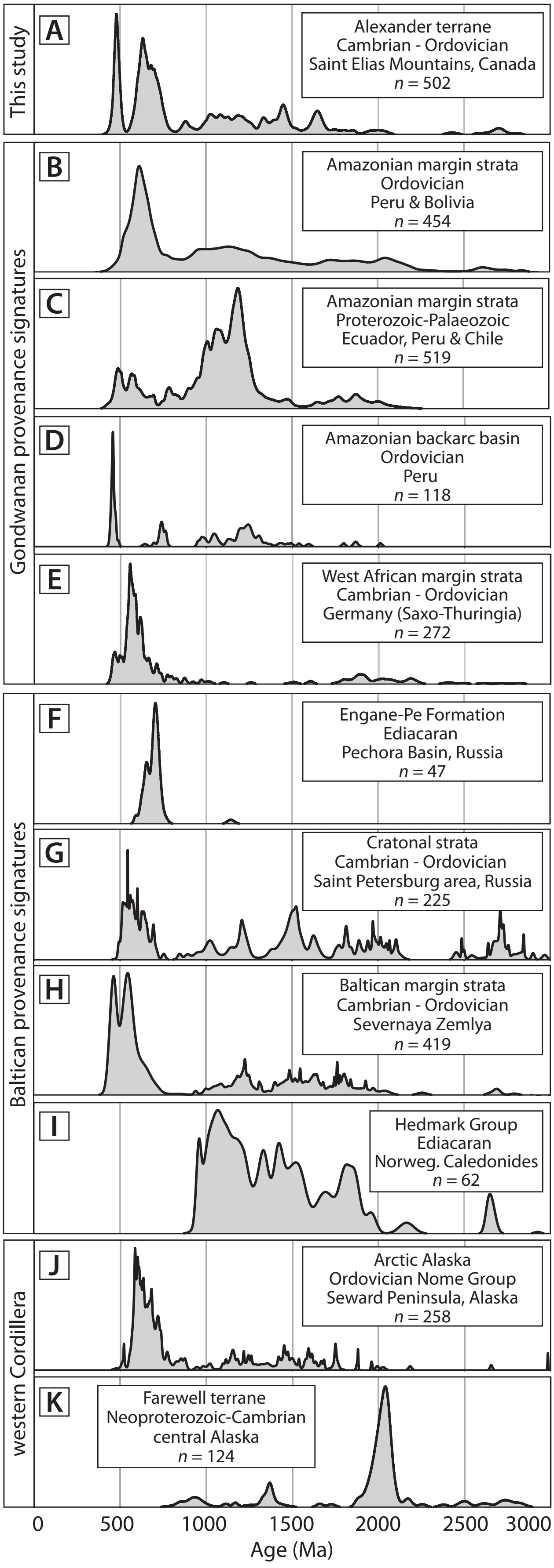

Fig. 8. Detrital zircon reference frames: (**a**) Donjek assemblage, this study; (**b**) Ordovician Amazonian margin (Reimann *et al*. 2010); (**c**) Proterozoic–Palaeozoic Amazonian margin (Chew *et al*. 2008); (**d**) Amazonian backarc basin (Bahlburg *et al*. 2011); (**e**) West African margin (Bahlburg *et al*. 2010); (**f**) Pechora Basin (Kuznetsov *et al*. 2010); (**g**) Baltican craton (Miller *et al*. 2011); (**h**) Baltican continental margin (Lorenz *et al*. 2008*a*); (**i**) Norwegian Caledonides (Bingen *et al*. 2011) (**j**) Seward Peninsula, Arctic Alaska (Amato *et al*. 2009); (**k**) Farewell terrane, central Alaska (Bradley *et al*. 2007).

Mesoproterozoic Hf model ages (Fig. 9a), similar-aged zircons of Amazonia are distinguished by a higher percentage of negative $\varepsilon_{Hf(t)}$ values and Palaeoproterozoic to Archaean Hf model ages (Fig. 9b).

Cadomian-type terranes formed along the west African margin by recycling Palaeoproterozoic crust (Nance *et al*. 2008). In the Cadomian realm of Germany, Cambrian to Ordovician siliciclastic rocks are characterized by 440–540, 540–750, and 1800–2400 Ma detrital zircons (Fig. 8e) that mostly yield $\varepsilon_{Hf(t)}$ values ranging from −5 to −29.9 (Bahlburg *et al*. 2010). All of the Meso- to Palaeoproterozoic zircons analysed by Bahlburg *et al*. (2010) have negative $\varepsilon_{Hf(t)}$ values and nearly half of the Precambrian zircons indicate Archaean model ages (Fig. 9c). The detrital zircon signatures of the Donjek assemblage share few, if any, provenance linkages with the Cadomian realm.

Baltica

Colpron & Nelson (2009) proposed that the timing of the Wales orogeny is reminiscent of the Timanian orogenic belt or Timanides. Named for the type locality in the Timan Range of NW Russia, the Timanides extend >2000 km from northern Norway to the southern Urals (Fig. 10). The Timanides are generally thought to represent an Ediacaran to Cambrian accretionary orogen that developed as a result of subduction beneath, and accretion to, the continental margin of NE Baltica (Gee & Pease 2004; Pease 2011). Other workers have considered the Timanides to be a collisional orogen that resulted from convergence between Baltica and an amalgam of terranes referred to as the Arctida continent (e.g. Kuznetsov *et al*. 2007). Timanide evolution is characterized by contractional deformation, greenschist- to amphibolite-facies metamorphism, and *c*. 550–730 Ma magmatism (Gee *et al*. 2000; Pease *et al*. 2004; Kuznetsov *et al*. 2007; Corfu *et al*. 2010).

Ediacaran and Cambrian–Ordovician siliciclastic rocks derived from the Timanides yield *c*. 550–760 Ma detrital zircon age populations (Fig. 8f–h; e.g. Pease & Scott 2009; Kuznetsov *et al*. 2010; Miller *et al*. 2011) that are similar to those of the Donjek assemblage. Late Neoproterozoic detrital zircons analysed by Kuznetsov *et al*. (2010) yield $\varepsilon_{Hf(t)}$ values of −2.6 to +13, with 88% of grains (40 of 45 analyses) between −2.6 and +6.4. Sixty-one per cent of the late Neoproterozoic zircons in this study accordingly yield $\varepsilon_{Hf(t)}$ values of –2.6 to +6.4, which implies that the Donjek assemblage sandstones have crustal sources that are representative of the Timanides.

Detrital zircon signatures that characterize the Fennoscandian Shield of Baltica compare favourably with the Mesoproterozoic to Neoarchaean age populations in the Donjek assemblage. For example, 1000–1650 and 2700 Ma age populations in our quartzose sandstones are widely recognized in Proterozoic strata that were deposited along the Baltoscandian margin of Baltica (Fig. 8i; Bingen *et al*. 2011). Consistent with our results from the Donjek assemblage, most 1000–1470 Ma zircons of the Fennoscandian Shield yield positive $\varepsilon_{Hf(t)}$ values and Meso- to Palaeoproterozoic Hf model ages (Söderlund *et al*. 2005; Bingen *et al*. 2011), and some *c*. 1500–1650 rapakivi granites have zircons with negative $\varepsilon_{Hf(t)}$ values and Archaean Hf model ages (Heinonen *et al*. 2010; Andersson *et al*.

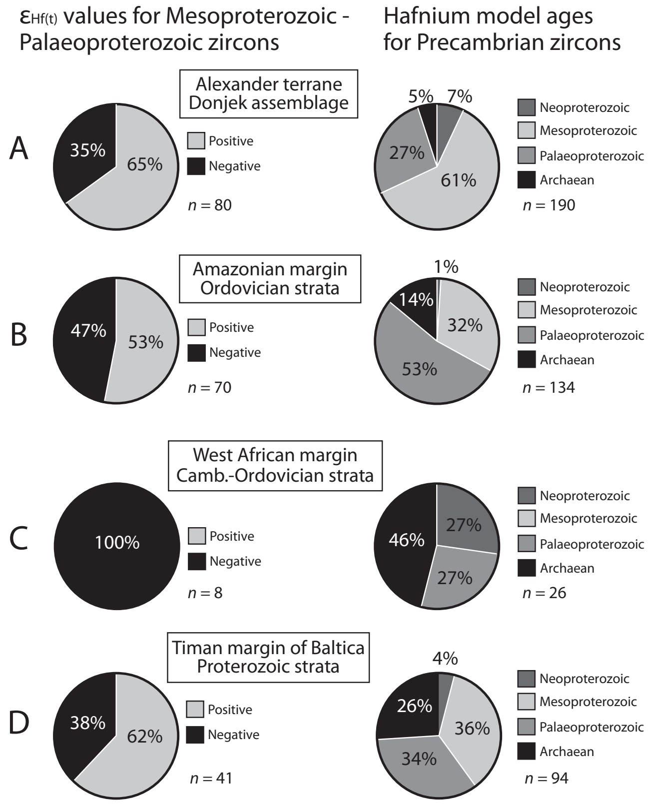

Fig. 9. Distributions of Meso- to Palaeoproterozoic zircons with positive and negative $\varepsilon_{Hf(t)}$ values and Hf model ages of Precambrian detrital zircons: (**a**) Donjek assemblage, this study; (**b**) Amazonian margin (Reimann *et al*. 2010); (**c**) West African margin (Bahlburg *et al*. 2010); (**d**) Timan passive margin of Baltica (Kuznetsov *et al*. 2010).

2011). Timan passive margin strata of NE Baltica described by Kuznetsov *et al*. (2010) are composed of detrital zircons with positive $\varepsilon_{Hf(t)}$ values and Meso- to Palaeoproterozoic Hf model ages that are broadly similar to those of the Donjek assemblage (Fig. 9d).

The rift-related tectonic setting and provenance signatures of the Donjek assemblage are both typical of coeval rocks in the Eurasian high Arctic. For example, Ordovician marine sandstones in Severnaya Zemlya yield 450–500 Ma detrital zircons that were sourced from local magmatic rocks (Fig. 8h; Lorenz *et al*. 2007, 2008*a*, *b*) comparable in age with the Field Creek volcanics. Ordovician magmatism in the Eurasian high Arctic was probably related to rifting and formation of the Uralian passive margin along NE Baltica (e.g. Nikishin *et al*. 1996; Glodny *et al*. 2004). Cambrian to Ordovician arc–backarc assemblages preserved in the Norwegian Caledonides (Stekenjokk and Fundsjø sequences) notably document subduction-related magmatism along Baltica during the formation of the Uralian passive margin (Grenne *et al*. 1999). In combination with the palaeomagnetic and fossil constraints discussed above, the provenance signatures of the Donjek assemblage argue for lithostratigraphic connections with the Uralian passive margin of NE Baltica.

Arctic Alaska–Chukotka and Farewell terranes, North American Cordillera

The detrital zircon signatures of the Donjek assemblage are essential for understanding ancient linkages between the Alexander terrane and other crustal fragments that underlie the western North American Cordillera. The Arctic Alaska–Chukotka and Farewell terranes offer the most advantageous comparisons with the Donjek assemblage as their marine strata have been characterized in terms of detrital zircon provenance and faunal provinciality.

In the Seward Peninsula of Arctic Alaska (Fig. 1), Ordovician volcanic and marine sedimentary strata of the Nome Group make up a continental margin succession that formed in a tectonic setting comparable with the Donjek assemblage (Beranek *et al*. 2012). Nome Group sandstones are mainly composed of 500–750, 880, 1000–1250, 1450, and 1650 Ma detrital zircon populations (Fig. 9j; Amato *et al*. 2009) that resemble the age distributions of the Donjek assemblage (P = 0.34–0.72). Local sources for some zircons include 565, 680, and 870 Ma felsic metaigneous rocks that underlie the Nome Group (Patrick & McClelland 1995; Amato *et al*. 2009). Similarly to the Alexander terrane, these basement ages preclude affinities with the NE Laurentian craton or its supracrustal cover, which also contains 1000–1250, 1450, and 1650 Ma detrital zircon populations (e.g. Kirkland *et al*. 2009). A growing body of detrital zircon evidence suggests that at least the Seward Peninsula region of Arctic Alaska can be restored to the Eurasian high Arctic region of Baltica during the Neoproterozoic–early Palaeozoic (Miller *et al*. 2010, 2011; Till *et al*. 2010).

The Farewell terrane (Fig. 1) of Alaska consists of 980–850 Ma metaigneous rocks overlain by the Nixon Fork passive margin succession (McClelland *et al*. 1999; Bradley *et al*. 2003). Cambrian–Devonian strata of the Nixon Fork share distinctive micro- and macrofossil assemblages with the Alexander and Arctic Alaska terranes and the Baltican and Siberian platforms (Blodgett *et al*., 2002, 2003; Dumoulin *et al*. 2002). Despite its similarities to the Alexander and Arctic Alaska terranes, detrital zircon evidence from the Farewell terrane is at odds with the Baltican provenance signatures of the Donjek assemblage and Nome Group. Nixon Fork sandstones primarily yield 1900–2200 Ma detrital zircons, with minor components in the range of 900–980 Ma and 1360–1380 Ma (Fig. 9k; Bradley *et al*. 2007). This provenance signature resembles that of the Siberian craton described by Khudoley *et al*. (2001).

Neoproterozoic–early Palaeozoic global tectonics and palaeogeography

The available detrital zircon, fossil, and palaeomagnetic evidence strongly favours a Northern Hemisphere location for the Alexander terrane near NE Baltica during Neoproterozoic to early Palaeozoic time. This broadly agrees with the plate-tectonic reconstructions for the western North American Cordillera by Colpron & Nelson (2009) (Fig. 2, Model 2). The Alexander terrane shares robust geological linkages with the Arctic Alaska–Chukotka and Farewell terranes, which together are wholly incompatible with a Southern Hemisphere location, proximity to the Amazonian or west African cratons, or a displacement path around southern Laurentia.

The origin of the Alexander terrane is related to Ediacaran intraoceanic subduction and arc development (Fig. 11a; Gehrels & Saleeby 1987). The initial position of the Alexander terrane relative to other island arcs or continental blocks is unclear. The timing of the Wales orogeny is consistent with late Timanian orogenesis (*c*. 550–500 Ma) inferred in Novaya Zemlya, Severnaya Zemlya, and northern Taimyr (Lorenz *et al*. 2008*b*; Pease & Scott 2009). Further study of the Wales orogeny is needed but the available evidence is compatible with either an accretionary (Pease 2011) or a collisional (Kuznetsov *et al*. 2007) scenario for the Timanides. The latter scenario may require the Alexander terrane to form part of Arctida, an ancient continent whose fragments now form Arctic Alaska–Chukotka, Novaya Zemlya, Severnaya Zemlya, northern Taimyr, Pearya, and Svalbard (Kuznetsov *et al*. 2010).

Fig. 10. Circum-Arctic cratons, orogens, terranes, and locations modified from Colpron & Nelson (2011). AA, Arctic Alaska; AX, Alexander terrane; CH, Chukotka; FW, Farewell terrane; NZ, Novaya Zemlya; PB, Pechora Basin; PE, Pearya; SF, Shoo Fly subterrane; SP, Seward Peninsula region of Arctic Alaska; SV, Svalbard; SZ, Severnaya Zemlya; TY, Trinity and Yreka subterranes.

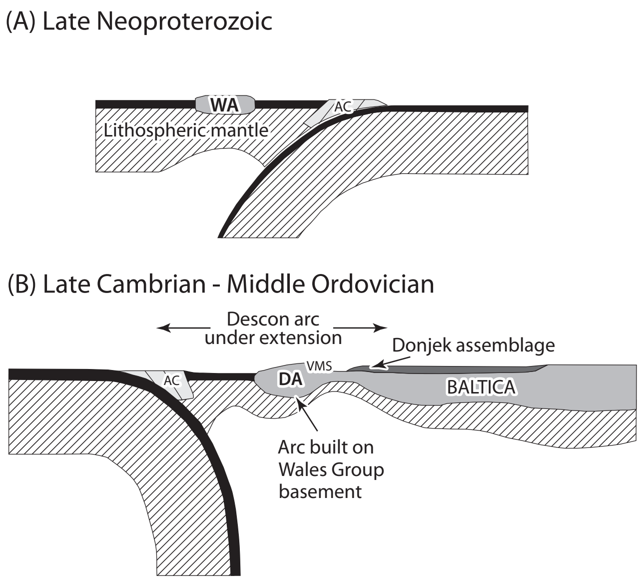

Fig. 11. Schematic models for the tectonic and magmatic evolution of the Alexander terrane based on results from this study. (**a**) Intraoceanic subduction beneath the Wales arc during late Neoproterozoic time. (**b**) Late Cambrian to Middle Ordovician development of the Descon adjacent to NE Baltica after the Wales orogeny. AC, accretionary complex; DA, Descon arc; VMS, volcanogenic massive sulphide deposits in the Descon Formation; WA, Wales arc.

Late Cambrian magmatism resulted from subduction beneath the Alexander terrane after the Wales orogeny (Fig. 11b). The timing of arc flare-up is constrained by *c.* 500 Ma detrital zircons in the Field Creek volcanics (this study) and Descon Formation (Grove *et al.* 2008). In our Late Cambrian palaeogeographical reconstruction, the Alexander terrane is shown adjacent to NE Baltica and in proximity to the Seward Peninsula and Brooks Range regions of Arctic Alaska (Fig. 12a). The onset of Late Cambrian magmatism was followed by, or synchronous with, intra-arc rifting and deposition of the Donjek assemblage. Intra-arc extension was probably aided by dynamic changes associated with the renewal of subduction along NE Baltica (Beranek *et al.* 2012). Rifting drove the exhalation of volcanogenic massive sulphide deposits within the Descon arc (Beranek *et al.* 2012) and the formation of a shallow-marine backarc basin that was connected to the Uralian passive margin (Fig. 11b).

During the Middle Ordovician the Alexander terrane formed part of a continental margin-fringing arc system along NE Baltica (Fig. 12b). This location in the Uralian Seaway promoted early Palaeozoic faunal exchange with the Farewell terrane and Siberian platform to the north and Uralian platform to the south. Ordovician arc-type rocks in the Brooks Range (Doonerak fenster) and mafic volcanic strata of the Nome Group might be the vestiges of this magmatic system in present-day Arctic Alaska (see Colpron & Nelson 2009). Other potential components of this magmatic system include arc-type rocks of the eastern Klamath (Yreka and Trinity subterranes) and northern Sierra (Shoo Fly complex) terranes that are now in California and Oregon (Figs 1 and 10). For example, Upper Ordovician strata of the Yreka subterrane and Shoo Fly

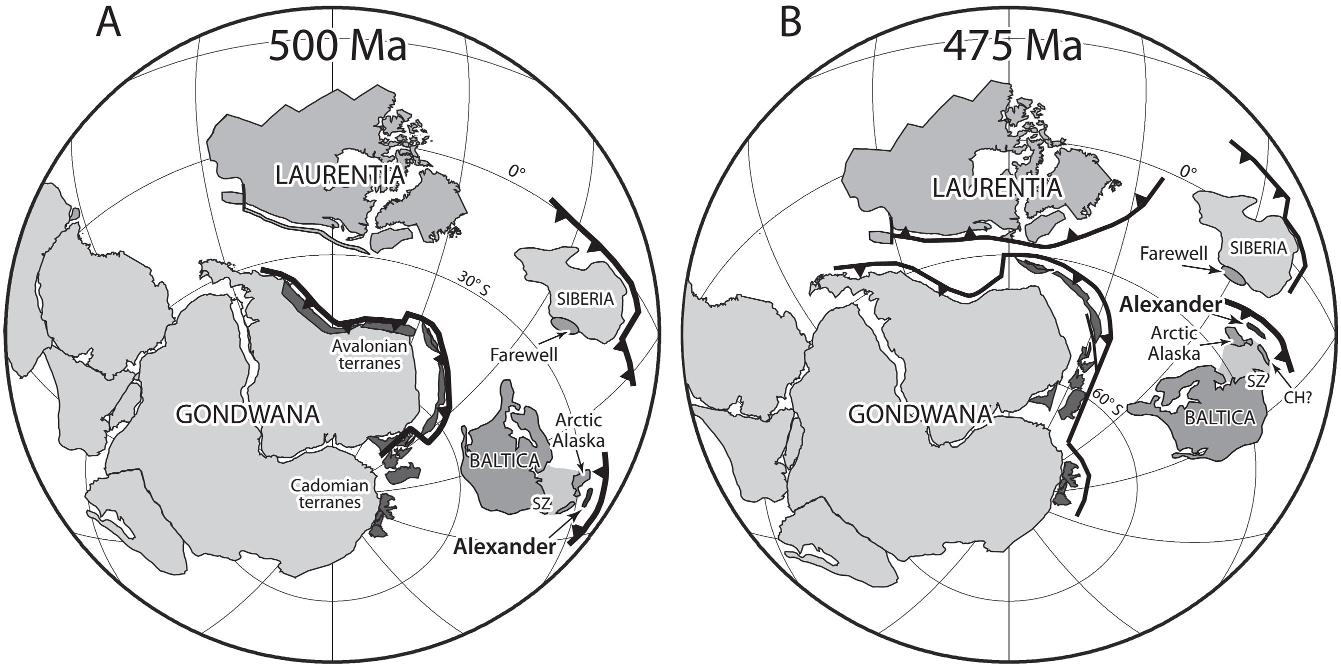

Fig. 12. (**a**) Late Cambrian and (**b**) Middle Ordovician palaeogeographical reconstructions of the Iapetan realm and adjacent continental masses. The position of the Alexander terrane is based on the results of this study. Continental reconstructions are mostly based on the fossil, palaeomagnetic, and detrital zircon data of Soja & Antoshkina (1997), Cocks & Torsvik (2005, 2007), Pisarevsky *et al*. (2008), Miller *et al*. (2011), and van Staal *et al*. (2011). CH, Chukotka; SZ, Severnaya Zemlya.

complex contain sphinctozoan sponge fauna that are known in both the Alexander and Farewell terranes (Potter *et al*. 1990; Rigby *et al*. 2005). Future studies of the western Cordilleran terranes may further decipher the tectonic development of NE Baltica, significance of Cordilleran–Timanian connections, and Neoproterozoic–Palaeozoic global tectonics and palaeogeography.

Conclusions

Upper Cambrian to Middle Ordovician strata of the Donjek assemblage were deposited in a backarc basin that formed as a result of subduction beneath the Alexander terrane after the Wales orogeny. Quartzose sandstones of the basin contain Neoproterozoic to Neoarchaean detrital zircons with a range of Hf isotopic compositions that agree with crustal sources from NE Baltica. These results imply that the Wales orogeny coincides with latest Neoproterozoic to Cambrian Timanian orogenesis in the Eurasian high Arctic. Volcaniclastic sandstones contain Cambrian and Ordovician detrital zircons that were derived from a continental margin-fringing arc system along NE Baltica. The Descon Formation and its calc-alkaline intrusive equivalents in SE Alaska preserve this Palaeozoic arc system on the Alexander terrane, and other vestiges of this arc system may exist in Arctic Alaska (Brooks Range, Seward Peninsula) and western USA (eastern Klamath and northern Sierra terranes). The position of Alexander terrane in the Uralian Seaway allowed faunal exchange between the Uralian passive margin, Siberian platform, and the Farewell terrane. This faunal exchange is one of many lines of evidence that supports a Palaeozoic displacement history for the Alexander terrane within the North Hemisphere.

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