U-Pb and Hf isotope analysis of detrital zircons from the Banks Island assemblage (coastal British Columbia) and southern Alexander terrane (southeast Alaska)

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ABSTRACT

The Banks Island assemblage consists of regionally metamorphosed and deformed metasedimentary rocks that occur in a narrow belt between the Alexander and Wrangellia terranes in coastal British Columbia. In an effort to evaluate potential correlations with adjacent terranes, we conducted U-Pb and Hf isotope analyses on detrital zircons from quartz-rich metasedimentary rocks of the Banks Island assemblage and from Paleozoic strata of the southern Alexander terrane. U-Pb data from the Banks Island assemblage provide maximum depositional ages ranging from Ordovician to Permian; complementary Hf data demonstrate proximity to a continental landmass during accumulation of most strata. These ages and Hf isotope compositions are quite different from the more juvenile signatures of arc-type rocks that characterize the southern Alexander terrane, but they strongly resemble values previously reported from the northern Alexander terrane. We accordingly suggest that the Banks Island assemblage formed as part of the northern Alexander terrane and was offset southward by ~1000 km to now reside adjacent to the southern portion of the terrane. At least some of this motion was accommodated along the Early Cretaceous Kitkattla shear zone, which now forms the inboard margin of the Banks Island assemblage. Deformation and metamorphism of the Banks Island assemblage occurred prior to this sinistral motion, however, as crosscutting dikes yield U-Pb ages as old as ca. 156 Ma. Our data provide support for a circum-Arctic origin of the Alexander terrane, as suggested by many previous workers. U-Pb and Hf data for Ordovician and older rocks of the Banks Island assemblage and the northern Alexander terrane are similar to values from the Timanides, whereas Silurian–Lower Devonian rocks yield values shared with Caledonian rocks in Baltica and northern Greenland. Banks Island assemblage strata of suspected late Paleozoic age are more juvenile, perhaps recording motion of the Alexander terrane from the circum-Arctic into the paleo-Pacific realm.

INTRODUCTION

The Banks Island assemblage occurs as metasedimentary pendants within the western Coast Mountains batholith in coastal British Columbia (Fig. 1; Wheeler and McFeely, 1991; Boghossian and Gehrels, 2000; Gehrels and Boghossian, 2000; Gehrels et al., 2009). Most exposures consist of highly deformed and metamorphosed metatlastic quartzite interbedded with marble and subordinate metapelite (Rodrick, 1970; Baer, 1973; Hutchison, 1982). Prior to this study, the only constraint on protolith age was provided by the Late Jurassic–Early Cretaceous age of surrounding plutons (van der Heyden, 1989, 1992; Butler et al., 2006; Gehrels et al., 2009; Cecil et al., 2011). Several correlations have been proposed between the Banks Island assemblage and other terranes in coastal British Columbia and southeastern Alaska. Woodsworth and Orchard (1985) and Wheeler et al. (1991) proposed that the Banks Island assemblage is part of the Alexander terrane to the east, while van der Heyden (1989, 1992) suggested that these rocks were associated with the Wrangellia terrane to the west. Gehrels and Boghossian (2000) and Boghossian and Gehrels (2000) raised the possibility that the Banks Island assemblage is a fragment of the Yukon-Tanana terrane, displaced from inboard of the Alexander terrane (Fig. 1), based on the abundance of highly folded metatlastic quartzite and marble in both assemblages.

This study presents U-Pb ages and Hf isotope data for 21 metasedimentary samples from the Banks Island assemblage and 10 sandstone samples from the southern Alexander terrane in an effort to evaluate potential correlations and displacement histories. We also report U-Pb ages on five crosscutting quartz diorite dikes to place a minimum age on the deformation and metamorphism that affect rocks of the Banks Island assemblage.

GEOLOGIC SETTING

The Banks Island assemblage is an enigmatic assemblage in the Canadian Cordillera because it consists of quartz-rich (mature) metasedimentary rocks and has evolved Nd-Sr isotopic signatures from arc-type rocks (Boghossian and Gehrels, 2000), which are in contrast to arc-type rocks and juvenile Nd-Sr isotopic signatures of adjacent terranes (Samson and Patchett, 1991). Continental affinities are also suggested by the εNd(t) values of plutonic rocks intruding the Banks Island assemblage, which are more evolved than plutonic rocks intruding the adjacent Alexander terrane (Cecil et al., 2011).

Inboard of the Banks Island assemblage, there are rocks of the southermost Alexander terrane (Figs. 1 and 2). In contrast to the quartz-rich metasediments of the Banks Island assemblage, the Alexander terrane consists primarily of arc-type volcanic, plutonic, and volcanioclastic rocks of Neoproterozoic–Silurian age, and Devonian–Triassic conglomerate, shale,
The Alexander and Wrangellia terranes have been together since late Paleozoic time (Gardner et al., 1988), forming the Insular terrane of Monger et al. (1982). This composite terrane may have been accreted to the western margin of North America during mid-Cretaceous time, resulting in the widespread metamorphic and magmatic events of this age observed throughout coastal British Columbia and southeast Alaska (Monger et al., 1982; Crawford et al., 1987). McClelland and Gehrels (1991), McClelland et al. (1991), 1992; Gehrels, 2001). Quartz-rich layers in this terrane are similar lithologically to quartz-rich metasedimentary rocks (Gehrels et al., 1991). Like the Alexander terrane, these rocks have juvenile Nd-Sr signatures, characteristic of assemblages formed in a volcanic arc setting (Samson and Patchett, 1991). At present, there are no available U-Pb or Hf data available from detrital zircons of the Wrangellia terrane. The Alexander and Wrangellia terranes have an origin of the Alexander terrane. Suggested origins include the Klamath region of northern California (Jones et al., 1972), a location similar to its current position followed by accordion-style rifting and re-accretion (Churkin and Eberlein, 1977), the Austral-Asia region (Gehrels and Saleeby, 1987), and the peri-Gondwana/Appalachian region (Wright and Wyld, 2006). Many workers now favor an origin for the terrane in the Arctic realm on the basis of geologic, geochronologic, paleomagnetic, and paleontologic data (Soja, 1994; Bazard et al., 1995; Gehrels et al., 1996; Blodgett et al., 2002; Soja and Kru- tikov, 2008; Grove et al., 2008; Blodgett, 2010; Miller et al., 2010, 2011; Colpron and Nelson, 2009, 2011; Beranek et al., 2013a, 2013b).

East of the Alexander terrane, rocks are assigned to the Yukon-Tanana terrane, which consists of Proterozoic–Lower Paleozoic quartz-rich metasedimentary rocks overlain unconformably by Middle–Upper Paleozoic metavolcanic and metasedimentary rocks (Gehrels et al., 1992; Gehrels, 2001). Quartz-rich layers in this terrane are similar lithologically to quartzites in the Banks Island assemblage. Nd-Sr signatures of these rocks also point to a continental affinity for this terrane (Samson and Patchett, 1991), as do the abundant Paleoproterozoic detrital zircons that occur in all assemblages of the Yukon-Tanana terrane (Gehrels et al., 1991, 1992; Gehrels, 2001).

Directly west of the Banks Island assemblage is the Wrangellia terrane, which consists of Middle- to Upper Paleozoic arc-type metavolcanic and metasedimentary rocks overlain by Triassic–Jurassic volcanics (Wheeler et al., 1991). Like the Alexander terrane, these rocks have juvenile Nd-Sr signatures, characteristic of assemblages formed in a volcanic arc setting (Samson and Patchett, 1991). At present, there are no available U-Pb or Hf data available from detrital zircons of the Wrangellia terrane.

The Alexander and Wrangellia terranes have been together since late Paleozoic time (Gardner et al., 1988), forming the Insular terrane of Monger et al. (1982). This composite terrane may have been accreted to the western margin of North America during mid-Cretaceous time, resulting in the widespread metamorphic and magmatic events of this age observed throughout coastal British Columbia and southeast Alaska (Monger et al., 1982; Crawford et al., 1987). McClelland and Gehrels (1990), McClelland et al. (1992), and van der Heyden (1992) suggested that mid-Cretaceous collid-
sional accretion was preceded by initial juxtaposition during mid-Jurassic time, followed by extension to form the Late Jurassic–Early Cretaceous Gravina basin (Fig. 1).

**Samples and Methods**

Twenty-one samples of metasedimentary rocks, five samples of quartz diorite/tonalite from crosscutting dikes, and one sample of quartz dioritic orthogneiss were collected from outcrops of the Banks Island assemblage for U-Pb and Hf isotope analysis. Ten additional samples of sandstone were collected and analyzed by laser ablation–multicollector–inductively coupled plasma–mass spectrometry (LA-MC-ICP-MS), as described by Gehrels et al. (2008). Grains too small for a 30 μm spot were analyzed with a 12 μm beam diameter using ion counters for Pb isotopes.

Images of zircon grains were acquired prior to U-Pb analysis using a Hitachi 3400N scanning electron microscope (SEM) equipped with a Gatan Chroma cathodoluminescence (CL) system at the University of Arizona (www.geosarnasem.org). CL imaging was conducted on all igneous and most detrital samples to identify grains suitable for U-Pb analysis and to characterize the internal structures and domains of each grain. In two Banks Island assemblage detrital samples (11TC15 and 11TC16), nearly all of the zircon grains were very small (less than 50 μm in length) and highly altered. For these samples, high-resolution backscattered electron (BSE) imaging provided a clearer display of each grain’s internal structure. These CL and BSE images were used to guide the placement of analytical locations on each zircon grain, as many grains contained complex zoning patterns, inherited cores, or high levels of alteration.

The U-Pb data from many of the Banks Island assemblage metasedimentary samples are complicated due to the presence of zircon grains that yield ages similar to the crosscutting dikes, or ages that are older but highly discordant. The young grains are interpreted to be igneous in origin because they have moderate U concentration, low U/Th, euhedral to subhedral shape, and typical oscillatory CL zoning, and they are coeval with the known or suspected age of nearby dikes or plutons. Such grains are interpreted to have been derived from narrow dikesets of igneous rock that were not recognized during sample collection. These young ages are retained in Table DR1 (see footnote 1) but are omitted from discussions of detrital ages.

Several Banks Island assemblage samples yielded analyses that are analytically discordant from grains that have high (e.g., >500 ppm) U concentrations, high (e.g., >5) U/Th, anhedral form, and irregular zoning in CL images. Such

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**Figure 2. Sketch map of the Banks Island assemblage and sample localities (adapted from Wheeler and McFeely, 1991).**

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1GSA Data Repository Item 2014168, Tables DR1–DR4, is available at www.geosociety.org/pubs/f2014.htm, or on request from editing@geosociety.org, Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.
RESULTS FROM THE BANKS ISLAND ASSEMBLAGE

U-Pb and Hf of Igneous Samples

U-Pb analyses of igneous zircons from five crosscutting dikes yield Late Jurassic–Early Cretaceous ages (Table DR1). The ages (and 2σ uncertainties) for these dikes, from oldest to youngest, are 156.2 ± 2.5 Ma (11TC09), 149.6 ± 1.4 Ma (11TC03), 144.4 ± 2.8 Ma (11TC05), 121.5 ± 1.7 Ma (07GJ201), and 116.0 ± 2.3 Ma (11TC12). Outcrop photographs of these dikes are shown in Figures 6A (sample 11TC05), 6B (sample 11TC09), and 6C (sample 07GJ201). These ages are generally younger eastward across the study area, and they are a good match for the ages of surrounding plutons (Gehrels et al., 2009). Our sample of quartz dioritic orthogneiss (07GJ201) yields concordant analyses that result in a weighted mean age of 359.1 ± 3.9 Ma (2σ; Table DR1).

Hf isotopic analyses from crosscutting dikes yield ε<sub>Hf(T)</sub> values that range from +8 to −10 (with one grain at −32) for grains that are interpreted to record the age of crystallization (Fig. 7; Table DR2). As shown on Figure 7, the ε<sub>Hf(T)</sub> values for these dikes overlap with the ε<sub>Hf(T)</sub> values for plutons that intrude the Banks Island assemblage (from Cecil et al., 2011) and also extend to considerably more negative values. Inherited grains from sample 11TC05, which are commonly seen as cores in CL images, yield variable ε<sub>Hf(T)</sub> values (Fig. 7).

U-Pb and Hf of Metasedimentary Samples

Most Banks Island assemblage metasedimentary samples yield one dominant peak of Paleozoic age and scattered older grains (Fig. 4; Table DR1). Because we have no stratigraphic information about the units sampled, we order samples in the following discussion, and on Figures 3 and 4, in terms of the age of the peak in probability density of the main age group. Given that this main age group generally contains the
youngest grains from each sample, this essentially orders the samples in terms of maximum depositional age.

Samples are further divided into five different groups on the basis of observed peak ages (Fig. 4) and Hf isotopic compositions (Fig. 8). The primary distinguishing characteristics of each group are as follows:

1. Two samples (JN0201 and 07GJ231; gray shading on Figs. 4 and 8) contain only Pre-cambrian grains.
2. Six samples (JN0202, 11TC10, 11TC19, 11TC14, 11TC15, and 11TC18; blue shading on Figs. 4 and 8) are dominated by 500–450 Ma grains (Fig. 4) that yield moderately evolved Hf isotopic signatures (Fig. 8) and also contain significant populations of Paleoproterozoic grains (Fig. 4).
3. Three samples (11TC07, Banks, and 04GJ54; purple shading on Figs. 4 and 8) are dominated by 450–438 Ma grains (Fig. 4) that yield highly evolved Hf isotopic signatures (Fig. 8) and also contain significant populations of Paleoproterozoic grains (Fig. 4).
4. Four samples (11TC01, 87JBM09, 11TC17, and 11TC02; red shading on Figs. 4 and 8)

Figure 3. Schematic columns showing stratigraphy and interpreted sample positions for the Banks Island assemblage (this study), strata of the Alexander terrane in SE Alaska (Gehrels and Saleeby, 1987), and strata of the Alexander terrane in the Saint Elias Mountains (Beranek et al., 2012, 2013a, 2013b). Stratigraphy of the Banks Island assemblage is interpreted largely from the U-Pb geochronology and Hf isotope data in this study.
Figure 4. Normalized age distribution diagrams for detrital zircon grains from the Banks Island assemblage. Main age peaks are noted for each sample. For all samples, proportions of older grains are enhanced by factor of two relative to younger grains (locations of cutoffs shown by black zigzags). Sample order is based on the peak age of the dominant cluster in each sample. The number of analyses and the peak age are shown for each sample.

Figure 5. Composite age distribution diagrams for detrital zircon grains from the Banks Island assemblage, with proportions of older grains (to right of zigzags) enhanced by factor of four relative to younger grains. Samples are combined according to the divisions shown in Figure 4. The peak ages and number of constituent analyses are indicated for each age distribution.
Figure 6. Photographs of typical lithic types in the Banks Island assemblage. (A) Crosscutting quartz diorite dike with age of 144.4 ± 2.8 Ma (sample 11TC05). (B) Crosscutting quartz diorite dike with age of 156.2 ± 2.5 Ma (sample 11TC09). (C) Crosscutting quartz diorite dike with age of 121.5 ± 1.7 Ma (sample 07GJ201). (D) Typical interbedded quartzite and marble of the Banks Island assemblage (sample 11TC14). (E) Typical folds in the Banks Island assemblage. (F) Sedimentary breccia sampled as 07GJ231 and 10JN0201.
Figure 7. Hf isotope compositions of crosscutting quartz diorite dikes, of young analyses in metasedimentary assemblages, and of surrounding plutons (from Cecil et al., 2011). DM—depleted mantle, CHUR—chondritic uniform reservoir. Overlap of the three data sets supports the interpretation that some metasedimentary samples contain veins, dikelets, or pods of igneous material. Average uncertainty of all analyses shown is 3.6 epsilon units (at 2σ). Gray arrow shows interpreted crustal evolution trajectory assuming present-day \(^{176}\)Lu/\(^{177}\)Hf = 0.0115 (Vervoort and Patchett, 1996; Vervoort et al., 1999).

Figure 8. Hf isotope data from metasedimentary units of the Banks Island assemblage. Samples are divided according to the scheme shown in Figure 4. Probability plots are from Figure 5 (with heights of older grains enhanced by 2x relative to younger grains). Average uncertainty of all analyses shown is 3.4 epsilon units (at 2σ). DM—depleted mantle, CHUR—chondritic uniform reservoir. Gray arrow shows interpreted crustal evolution trajectory assuming present-day \(^{176}\)Lu/\(^{177}\)Hf = 0.0115 (Vervoort and Patchett, 1996; Vervoort et al., 1999).
are dominated by 438–400 Ma grains (Fig. 4) that yield moderately juvenile Hf isotope compositions (Fig. 8).

(5) Four samples (11JN10–09, Union, 11TC20, and 11TC13; shown with green shading on Figs. 4 and 8) contain significant populations of younger than 400 Ma grains (Fig. 4) with mostly juvenile Hf isotope compositions (Fig. 8).

Characteristics of samples in each of these groups are described in more detail in the following.

The oldest interpreted group consists of two samples (JN0201 and 07GJ231) that lack Paleozoic grains and yield a nearly continuous distribution of ages between 1.8 and 1.0 Ga (black curves, Fig. 4). When the two age distributions are combined, there are three main age groups of 1.82–1.58 Ga, 1.53–1.30 Ga, and 1.19–0.98 Ga and two smaller groups of 2.87–2.54 and 2.02–1.87 Ga (Fig. 5). These samples also differ from the others in terms of lithology—they are from a sedimentary breccia that consists of clasts of quartzite and subordinate marble and amphibolite (Fig. 6F). Clasts reach up to 80 cm in length and are hosted in a quartz-rich sandy matrix. Sample 07GJ231 consists mainly of quartzite clasts, whereas sample JN0201 consists mainly of matrix sandstone; there appears to be no significant difference in age distribution between the clasts and matrix. Hf isotope compositions are juvenile to evolved for older than 1.6 Ga and younger than 1.2 Ga grains and somewhat more juvenile for 1.6–1.2 Ga grains (Fig. 8).

The next youngest samples are those with maximum depositional ages between 500 and 450 Ma (blue curves, Fig. 4). Four of these samples (JN0202, 11T1C10, 11T1C4, 11T1C5) also contain grains of ca. 800 Ma, whereas two samples (11T1C9 and 11T1C8) do not. Collectively, these five samples yield a dominant age group of 542–428 Ma (peak age of 478 Ma), a subordinate age group of 870–710 Ma (peak age of 798 Ma), and scattered older than 1.0 Ga grains (Fig. 5). Figure 6D is an example of banded quartzite and marble, typical of most Banks Island assemblage outcrops, from sample 11T1C14. Hf isotope compositions from these samples are mainly juvenile to somewhat evolved for Precambrian grains and moderately evolved (average \( \epsilon_{Hf} \) of ~0.3) for younger than 500 Ma grains (Fig. 8; Table 2).

Next youngest are three samples (11T1C7, Banks, and 04GJ54) that yield maximum depositional ages between 450 and 438 Ma. These samples also contain a significant fraction of Precambrian ages (purple curves, Fig. 4), particularly Paleoproterozoic, in contrast to the Mesoproterozoic to Neoproterozoic grains in the 500–450 Ma samples. Collectively, these samples yield a single dominant age group of 476–418 Ma, with an age peak of 442 Ma (Fig. 5). The one sample from this group that has been analyzed for Hf isotopes (sample 11T1C07) yields a range of \( \epsilon_{Hf} \) values for the younger than 500 Ma grains analyzed from strata belonging to each group. Banks Island assemblage analyses are from this study. Alexander terrane in Banks Island data are from Beranek et al. (2013a, 2013b). Alexander terrane in SE Alaska data are from this study.

**Results from the Alexander Terrane in Southeast Alaska**

U-Pb analyses have been conducted on sandstones of Ordovician \((n = 2)\), Silurian \((n = 1)\), Devonian \((n = 4)\), Permian \((n = 3)\), and Triassic \((n = 1)\) age. Many of these samples were analyzed previously by isotope dilution–thermal ionization mass spectrometry (ID-TIMS; results reported by Gehrels et al., 1996), and several have also been analyzed by LA-ICP-MS (results reported by Grove et al., 2008). U-Pb data from all analyses are summarized on Figure 9, and reported in Table DR3. Hf isotope analyses have been conducted on six of the 10 samples, with results shown on Figure 10 and reported in Table DR4.

As shown on Figure 9, all samples are dominated by peaks of Ordovician–Silurian age, which is not surprising given the abundance of plutonic and volcanic rocks of this age in the southern Alexander terrane (Gehrels and Saleeby, 1987). Ordovician strata yield peak ages of 558 Ma (Neoproterozoic) and 463 Ma, whereas Silurian, Devonian, and Permian strata yield nearly identical age peaks of 432–429 Ma. Devonian strata also have minor proportions of Precambrian grains that are commonly pinkish in color, rounded in morphology, and smaller in size. These grains were oversampled during grain selection and are shown with expanded vertical scale on Figure 9. Permian strata have additional age peaks of 366 and 288 Ma and a
Banks Island assemblage | RESEARCH

significant proportion of older grains. Our one sample of Triassic strata yields only one age peak of 417 Ma, which is not surprising given that the conglomeratic sandstone rests unconformably on a trondhjemite pluton of similar age.

Hf data for detrital zircons from these strata are shown on Figure 10. Unfortunately, few analyses could be conducted on Precambrian grains from the Devonian strata because of their small size. The Hf isotope compositions for younger than 600 Ma grains are mostly juvenile, which is consistent with the juvenile Hf signature of zircon grains from nearby plutons (Cecil et al., 2011; Fig. 10). The average $\epsilon_{Hf(T)}$ values for detrital grains are +11.1 for Ordovician strata and +10.7 for Devonian strata (Table 2).

**Comparison with Alexander Terrane in Saint Elias Mountains**

U-Pb geochronologic and Hf isotopic data are also available from the northern Alexander terrane in the Saint Elias Mountains of northern British Columbia and Yukon (Fig. 1). Beranek et al. (2013a) reported data from Cambrian–Ordovician strata of the Donjek assemblage, and Beranek et al. (2013b) reported data from Silurian–Lower Devonian and Middle Devonian strata of the Icefield assemblage (Figs. 1 and 3).

The data from strata of known age in the Saint Elias Mountains provide critical insights into the terrane affiliation of the Banks Island assemblage, and the ages of the metasedimentary units sampled. As shown on Figures 11 and 12, both data sets show generally similar patterns of U-Pb ages and Hf isotope compositions. Of particular significance is the pronounced negative excursion of Hf isotope compositions displayed by zircons from strata of Silurian–Early Devonian age from the Saint Elias Mountains and from strata with 450–438 Ma peak ages in the Banks Island assemblage (Fig. 12). As reported on Table 2: (1) Saint Elias Mountains strata of Cambrian–Ordovician age and Banks Island assemblage strata with 500–450 Ma peak ages yield peak ages of 477 and 478 Ma (respectively) and moderately juvenile average $\epsilon_{Hf(T)}$ values of +5.8 and −0.3 (respectively); (2) Saint Elias Mountains strata of Silurian–Early Devonian age and Banks Island assemblage strata with 450–438 Ma peak ages yield similar peak ages of 443 and 442 Ma and moderately evolved average $\epsilon_{Hf(T)}$ values of −7.3 and −12.0 (respectively); and (3) Saint Elias Mountains strata of Middle Devonian age and Banks Island assemblage strata with 438–400 Ma peak ages yield similar peak ages of 420 and 434 Ma and average $\epsilon_{Hf(T)}$ values of +4.9 and +6.6 (respectively).

The remarkable similarity of these patterns lends strong support to previous interpretations...
Figure 11. Hf isotope composition of detrital zircons from the Banks Island assemblage and the Alexander terrane in the Saint Elias Mountains. Data from the Saint Elias Mountains are from Beranek et al. (2013a, 2013b). DM—depleted mantle, CHUR—chondritic uniform reservoir. Gray arrow shows interpreted crustal evolution trajectory assuming present-day $^{176}\text{Lu}/^{177}\text{Hf} = 0.0115$ (Vervoort and Patchett, 1996; Vervoort et al., 1999).

Figure 12. Hf isotope composition for young grains shown on Figure 11 and also data from the Alexander terrane of SE Alaska. Data from the Saint Elias Mountains are from Beranek et al. (2013a, 2013b). DM—depleted mantle, CHUR—chondritic uniform reservoir. Gray arrow shows interpreted crustal evolution trajectory assuming present-day $^{176}\text{Lu}/^{177}\text{Hf} = 0.0115$ (Vervoort and Patchett, 1996; Vervoort et al., 1999).
(e.g., Wheeler and McFeely, 1991) that the Banks Island assemblage is a portion of the Alexander terrane. These patterns also suggest that Banks Island assemblage strata with 500–450 Ma peak ages are Cambrian–Ordovician, strata with 450–438 Ma peak ages are Silurian–Lower Devonian, and strata with 438–400 Ma peak ages are Middle Devonian. The stratigraphic assignments shown for Banks Island assemblage strata on Figure 3 are based largely on these interpretations. These patterns also fit a simple pattern geographically, with maximum depositional ages that generally are younger northward.

It is interesting that a similar negative deflection in $\varepsilon_{Hf(T)}$ values is not apparent in Lower Devonian strata from the Alexander terrane in SE Alaska (Fig. 12), where average $\varepsilon_{Hf(T)}$ values from Lower Devonian strata are all quite juvenile (Table 2). Instead, increased involvement of continental material during Early Devonian time is apparently recorded by the presence of small/round zircon grains of Precambrian age in the Lower Devonian strata. This may be a more distal expression of the same continental involvement given that Precambrian grains in Silurian–Lower Devonian strata of the Banks Island assemblage, Saint Elias Mountains, and southern Alexander terrane all have generally similar ages (Fig. 13), but grains in the Banks Island assemblage and Saint Elias Mountains are larger and more abundant.

**Comparison with Yukon-Tanana Terrane**

Comparison with data from the Yukon-Tanana terrane is relevant given the suggestion by Gehrels and Boghossian (2000) that the two assemblages may be related. This possibility was based on the presence in both assemblages of deformed and metamorphosed quartz-rich metapelitic rocks. Similarities with the Yukon-Tanana terrane can now be tested by comparison of U-Pb ages from both assemblages; Hf data from the Yukon-Tanana terrane are not yet available. As shown on Figure 14, U-Pb ages from the two assemblages are quite different, with dissimilarities in both dominant Paleozoic age peaks (351 Ma for Yukon-Tanana terrane vs. 441 Ma for Banks Island assemblage) and in Precambrian age distributions. These data do not support primary connections between the Banks Island assemblage and the Yukon-Tanana terrane.

**Comparison with the Wrangellia Terrane**

Comparisons of geochronologic and Hf isotopic data are not yet possible because there are no published data available from rocks that are known to belong to Wrangellia.

**Comparison with Circum-Arctic Regions**

Comparison with circum-Arctic assemblages is appropriate given the paleontologic (Soja, 1994; Blodgett et al., 2002; Blodgett, 2010; Soja and Krutikov, 2008), paleomagnetic (Bazard et al., 1995), and detrital zircon (Gehrels et al., 1996; Grove et al., 2008; Miller et al., 2010, 2011; Beranek et al., 2012, 2013a, 2013b) data, which suggest that the Alexander terrane may have formed in this area. Colpron and Nelson (2009, 2011) have provided excellent recent syntheses of these relations and presented a model for early Paleozoic formation of the Alexander terrane along the Arctic margin of Baltica and northeastern Laurentia.

U-Pb and Hf data from the Banks Island assemblage and the Alexander terrane are compared with several data sets from circum-Arctic regions on Figure 15. Included for comparison are U-Pb and Hf data from detrital zircons in Neoproterozoic clastic strata of the Timanides (Kuznetsov et al., 2010), early Paleozoic plutonic rocks in East Greenland (Rehnström, 2010), detrital zircons in Cretaceous strata near northern Greenland (Rohr et
al. [2010] data for the Sverdrup basin and Rohr et al. [2008] data for the Wandel Sea basin), detrital zircons from Permian strata of Baltica (Andersen et al. [2011] data for the Oslo rift), and early Paleozoic plutons of the Scottish Caledonides (Appleby et al., 2010).

This comparison supports the conclusions of Beranek et al. (2013a, 2013b) and Colpron and Nelson (2009, 2011), that U-Pb ages and Hf isotope signatures of detrital zircons from the Banks Island assemblage and Alexander terrane share similarities with data from circum-Arctic regions. The strongest similarities are in the timing of Neoproterozoic and early Paleozoic plutons (Andersen et al. [2011] data for the Oslo rift), and early Paleozoic plutons of the Scottish Caledonides (Appleby et al., 2010).

Our data yield new insights into: (1) the chronology of deformation in this portion of the Cordilleran orogen; (2) the depositional age of various Banks Island assemblage metasedimentary assemblages; (3) potential correlations among the Banks Island assemblage and strata of the Alexander terrane in SE Alaska and the Saint Elias Mountains; and (4) possible displacement histories of the Alexander terrane. Each of these dimensions is described in turn next.

**Deformational Chronology**

Crystallization ages of 156–116 Ma for crosscutting dikes indicate that the main phase of deformation and metamorphism of rocks of the Banks Island assemblage occurred prior to Late Jurassic–Early Cretaceous time. This significantly predates the main phase of deformation in the Coast Mountains, which is traditionally interpreted to record initial mid-Cretaceous accretion of the Alexander and Wrangellia terranes with inboard terranes (e.g., Monger et al., 1982; Crawford et al., 1987). A likely possibility is that this deformation is related to mid-Jurassic deformation observed within the Alexander terrane in SE Alaska (McClelland and Gehrels, 1990), which may record an earlier phase of initial accretion of the outboard terranes (McClelland et al., 1992; van der Heyden, 1992). An earlier phase of deformation and metamorphism has also been proposed in coastal British Columbia on the basis of geochemical data, which indicate that Late Jurassic–Early Cretaceous plutons intruding the Banks Island assemblage were generated during a period of significant crustal thickening (Girardi et al., 2012). The moderately negative \( \epsilon_{Hf} \) values for the dikes (Fig. 7) indicate that considerable crustal melting accompanied this Late Jurassic–Early Cretaceous deformation.

**Depositional Chronology**

Given that fossils have not been recovered from Banks Island assemblage protoliths, and that stratigraphic relations are obscured by the deformation, metamorphism, and widespread intrusive bodies, our U-Pb geochronologic and Hf isotopic data provide critical constraints on the ages of deposition. Our proposed stratigraphic order (Fig. 3) is based largely on the peak age of the youngest significant group of detrital zircons in each sample (Fig. 4), which provides a maximum depositional age (e.g., Dickinson and Gehrels, 2009). Samples are accordingly assigned to groups with similar maximum depositional ages, with additional information provided by Hf isotopic data.

Assignment of stratigraphic ages (Fig. 3) is aided by comparison of U-Pb ages and Hf isotope compositions from metasedimentary rocks of the Banks Island assemblage and fossiliferous strata of the Alexander terrane in SE Alaska and the Saint Elias Mountains. For Banks Island assemblage rocks with peak ages between 500 and 400 Ma, the key to this correlation is the recognition of negative Hf isotopic excursions in Silurian–Lower Devonian strata of the Saint Elias Mountains and in Banks Island assemblage strata with 450–438 Ma peak ages (Fig. 12; Table 2). This correlation is supported by similarities in the age distributions of detrital zircons from 450 to 438 Ma Banks Island assemblage strata and from Silurian–Lower Devonian strata of both the Saint Elias Mountains and southern SE Alaska (Fig. 13).

Banks Island assemblage strata with younger than 400 Ma peak ages are interpreted to be at least in part of Permian age (Fig. 3), on the basis of the similarity with U-Pb ages from Permian strata in central SE Alaska (Fig. 16), and the occurrence of one sample (11TC13) with a peak age of 306 Ma and individual ages as young as 256 Ma.

Finally, one of our samples (Absalom) yields a peak age of 119 Ma, which indicates that this unit is significantly younger than the
Paleozoic and early Mesozoic strata that characterize the Banks Island assemblage (Fig. 3) and Alexander terrane (Gehrels and Saleeby, 1987). One possibility is that these strata belong to the Gravina belt, which consists of Upper Jurassic–Lower Cretaceous strata that occur along the inboard (eastern) margin of the Alexander terrane (Gehrels and Berg, 1994) and are known to contain plutonic clasts of Cretaceous age (Kapp and Gehrels, 1998; Gehrels, 2001). An alternative is that these strata accumulated in a pull-apart basin along the Kitkatla shear zone, given that the sample was collected from metasedimentary rocks within this fault system (Fig. 2). The Kitkatla shear zone is known to have experienced significant sinistral motion during Early Cretaceous time (Butler et al., 2006; Chardon et al., 1999).

Correlation with Rocks of the Alexander Terrane

The similarities in U-Pb ages and Hf isotopic compositions noted previously indicate that Lower Paleozoic metasedimentary rocks of the Banks Island assemblage may be directly correlative with less-deformed strata of the Alexander terrane in the Saint Elias Mountains. In contrast, Lower Paleozoic strata in the Banks Island assemblage and Saint Elias Mountains differ from the more juvenile units of the Alexander terrane in southeast Alaska, which (1) include abundant volcanic and plutonic rocks and lack quartz-rich sandstones, (2) contain less abundant Precambrian detrital zircons, and (3) yield more juvenile Hf isotope compositions for early Paleozoic zircon grains (Figs. 11 and 12).

These comparisons raise the possibility that the Banks Island assemblage was located adjacent to the Saint Elias Mountains portion of the Alexander terrane during early Paleozoic time, and it has been displaced southward, to a position outboard of the southern Alexander terrane, by ~1000 km of sinistral displacement. This possibility was first suggested by B. Mahoney (2011, verbal commun.). At least some of this sinistral displacement may have occurred along the Kitkatla shear zone (Fig. 2), which is known to have been active during Early Cretaceous time (Butler et al., 2006; Chardon et al., 1999). This timing and sense of offset are consistent with previous suggestions of large-scale sinistral motion along this segment of the Cordilleran margin (Monger et al., 1994; Pfafker and Berg, 1994; Chardon et al., 1999; Gehrels et al., 2009; Angen et al., 2012).

Origin of the Banks Island Assemblage and Alexander Terrane

Given that our geochronologic and Hf isotopic data from the Banks Island assemblage are very similar to data from the Saint Elias Mountains (Beranek et al., 2013a, 2013b) and share similarities with a variety of circum-Arctic assemblages, we concur with Soja (1994), Bazard et al. (1995), Gehrels et al. (1996), Blodgett et al. (2002), Soja and Krutikov (2008), Grove et al. (2008), Blodgett (2010), Miller et al. (2010, 2011), Colpron and Nelson (2009, 2011), and Beranek et al. (2012, 2013a, 2013b) that the Banks Island assemblage–Alexander terrane may have formed in proximity to the Arctic margin of Baltica and eastern Laurentia. As shown on Figure 15, however, all portions of the Alexander terrane also record the presence of more juvenile early Paleozoic magmatism than is recorded in any of the circum-Arctic assemblages. Our data are accordingly consistent with a model in which the Banks Island assemblage and northern Alexander terrane formed along the paleo-Arctic margin of Baltica, Greenland, and northeastern Laurentia, built in part on older continental crust and blanketed by detritus from the Timanides and Caledonides, whereas the southern part of the terrane formed farther offshore in a juvenile magmatic arc and was shielded from significant cratonic input. Younger Paleozoic strata of the Banks Island assemblage and Alexander terrane may record migration of the terrane out of the Arctic realm and into the Cordilleran realm (e.g., Colpron and Nelson, 2009, 2011).

CONCLUSIONS

Metasedimentary rocks of the Banks Island assemblage yield detrital zircon ages ranging from ca. 3.3 Ga to ca. 250 Ma, but most samples are dominated by a single dominant group with peak ages between 486 and 306 Ma (Fig. 4). The peak ages of these dominant groups are used to order the samples by maximum depositional age, and stratigraphic ages can be inferred on the basis of correlation with strata of known age in the Alexander terrane along strike to the north. Similarities in Hf isotopic patterns for Cambrian–Ordovician through Middle Devonian strata in the Banks Island assemblage and the Saint Elias Mountains are striking and raise the possibility that the Banks Island assemblage was originally located adjacent to the northern portion of the Alexander terrane. Approximately 1000 km of sinistral displacement is needed to bring the Banks Island assemblage adjacent to the southern portion of the terrane—one of this displacement may have occurred along the Kitkatla shear zone, which is known to have experienced sinistral displacement during Early Cretaceous time (Butler et al., 2006; Chardon et al., 1999).

The abundance of Precambrian detrital zircons and the highly evolved Hf isotope compositions of early Paleozoic zircons in the Banks Island assemblage and Saint Elias Mountains indicate that these regions were located near an ancient cratonic region during early Paleozoic time. Based on similarities in U-Pb ages and Hf isotopic data, as well as abundant paleomagnetic and faunal data (as recently summarized by Colpron and Nelson, 2009, 2011; Beranek et al., 2012, 2013a, 2013b), it is plausible that the Banks Island assemblage and northern Alexander terrane were located along the paleo-Arctic margin of Baltica, Greenland, or northeast Laurentia during Cambrian–Ordovician through Early Devonian time. The northern portion of the Alexander terrane and the Banks Island assemblage were apparently also near a juvenile volcanic arc that extended sufficiently far from the continental margin that some regions (e.g.,...
south-east SE Alaska) were shielded from significant crustal influence.

Less geochronologic and isotopic information is available from the Banks Island assemblage and Alexander terrane following Early Devonian time, although Middle Devonian strata in the Saint Elias Mountains and strata with peak ages of 388–306 Ma in the Banks Island assemblage yield mainly juvenile Hf isotope compositions (Figs. 11 and 12). The displacement scenario proposed by Colpron and Nelson (2009, 2011), where the Alexander terrane was moving from the paleo-arc into the paleo-Pacific realm during this time, appears consistent with the available data. The ca. 359 Ma orthogneiss that intrudes rocks of the Banks Island assemblage (sample 07GJ208) may have formed within a magmatic arc that was active at this time.

The next phase recorded in the study area is the regional deformation and metamorphism that affect all rocks of the Banks Island assemblage. Constraints on this tectonism demonstrate that it occurred between ca. 306 Ma (the maximum depositional age of deformed rocks) and ca. 156 Ma (the oldest crosscutting dike). We postulate that this tectonism may have been related to mid-Jurassic deformation recorded within the Alexander terrane (e.g., McClelland and Gehrels, 1990) and inferred to exist during generation of the Late Jurassic–Early Cretaceous plutons that intrude the Banks Island assemblage (Girardi et al., 2012).

Finally, our sample “Abalon” records accumulation of plutonic-clast conglomerate during Early Cretaceous time. These strata may have accumulated in part of the regionally extensive Gravina belt, or in a more restricted pull-apart basin along the sinistral Kitkatla shear zone.

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