Research Article

U-Th-Pb Geochronology and Lu-Hf Isotope Geochemistry of Detrital Zircons in Metasedimentary Rocks of the Southern Coast Mountains Batholith

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Most metasedimentary rocks in the southern Coast Mountains batholith are of uncertain tectonic affinity because they occur in discontinuous pendants surrounded by large intrusive bodies, and many protolith features are obscured by regional deformation and metamorphism. This study uses U-Th-Pb ages and Lu-Hf isotope signatures of detrital zircons in metasedimentary rocks in Bute, Loughborough, and Knight Inlets in an effort to test possible correlations with the adjacent Wrangellia, Alexander, Taku, Yukon-Tanana, and Stikine terranes. Detrital zircons from metasedimentary samples yield ages that belong to age groups of 590-528 Ma (peak age of 560 Ma), 485-432 Ma (peak age of 452 Ma), 356-286 Ma (peak age of 307 Ma), and 228-185 Ma (peak ages of 215 and 198 Ma). A small number of ~1.1-1.9 Ga grains are also present. εHf values of the 590-185 Ma grains yield a progression from intermediate (0 to +5) values to more juvenile (mostly +4 to +15) values from Neoproterozoic through early Mesozoic time. The Comparison of these results with similar data sets from adjacent terranes demonstrates that primary connections with the Yukon-Tanana and Taku terranes are unlikely but are consistent with primary connections with the Wrangellia, Stikine, and/or Alexander terranes. Unfortunately, the available constraints are not sufficient to eliminate any of these options or the possibility that the pendants are a unique tectonic fragment. Zircons from the metasedimentary samples also yield U-Th-Pb ages of 165-128 Ma (peak age of 152 Ma) and 114-88 Ma (peak age of 102 Ma). εHf, values of these zircon domains are mostly juvenile (+7 to +13). Comparison of U concentrations, U/Th values, and CL textures of zircons from the metasedimentary samples, leucocratic sills that intrude the pendants, and surrounding plutonic bodies suggests that most of the young grains, as well as widespread younger rims on older grains, grew during metamorphism associated with emplacement of the adjacent plutonic bodies. Some young grains were derived from thin felsic sills or veins that were unintentionally included in the sampled material.

1. Introduction

The Coast Mountains of western British Columbia and southeast Alaska are underlain mainly by Jurassic, Cretaceous, and early Tertiary plutons that intrude a variety of metasedimentary and metavolcanic rocks (Figure 1). In the northern and central Coast Mountains, the tectonic affinity of metasedimentary and metavolcanic pendants has been reconstructed on the basis of lithic characteristics combined with U-Th-Pb geochronology and Hf isotope analyses of
detrital zircons [1–5]. From west to east, the main terrane-assemblages include the Alexander, Taku, Yukon-Tanana, and Stikine terranes (Figure 1).

The tectonic affinity of metasedimentary assemblages in the southern Coast Mountains was originally assigned on the basis of protolith characteristics by Wheeler and McFeely...
2. Geology of Bute, Loughborough, and Knight Inlets

Rocks of the Coast Mountains batholith are spectacularly exposed along the glacially scoured and wave-washed fjord walls of Bute, Loughborough, Knight, and associated smaller inlets (Figure 2). As reported by Cecil et al. [11], the batholith in this region consists mainly of dioritic, tonalitic, and granodioritic plutons and intrusive complexes that range in age from ~170 Ma to ~85 Ma. Metasedimentary and metavolcanic rocks occur as highly elongate pendants separating plutons that are also elongate northwest-southeast [11]. The width of the pendants is highly variable, with most on the order of 10s to 100s of meters, but some over a kilometer in width. All rocks are strongly foliated parallel to the pendant margins, which is parallel to the foliation in all but the youngest plutons in the area (Figure 3(a)).

Metasedimentary and metavolcanic rocks in the study area have been divided into three assemblages that have varying proportions of quartzite, marble, pelitic schist, and metabasalt and a fourth assemblage that lacks these lithic associations and consists only of fine-grained metaclastic and metavolcanic rocks (Figure 2). All four assemblages are found entirely east of low-grade sedimentary and volcanic rocks of the Karmutsen, Quatsino, Parsons Bay, and Harbledown formations ([12, 13]; Figure 2), which belong to the Wrangellia terrane.

The first assemblage, extending across the southwestern part of the study area and in upper Knight Inlet, is found in pendants that consist mainly of interlayered quartzite and marble (Figure 3(b)) with subordinate pelitic schist and local calc-silicate. Layering is on a 1-3-cm scale, and quartzite is generally more abundant than marble. The quartzite layers are quite pure, consisting almost exclusively of quartz and calcite. Sampling these rocks for detrital zircons is challenging because most outcrops are intruded by swarms of intrusions which occur as several cm-thick aplite sills. In most cases, these bodies share the regional foliation exhibited in their host rocks. In rare exposures, they can be seen to intrude at oblique angles across the metasedimentary layering.

A second assemblage, tracing northwest-southeast across upper Bute Inlet, consists of pelitic schist and quartzite that are interlayered on a cm scale (Figure 3(c)). Interlayered quartzite and marble, similar to the unit described above, is a minor component of this assemblage. In most outcrops, pelitic schist is dominant over thin (cm-thick) layers of quartzite (Figure 3(c)). Garnet is present in some outcrops. These pendants also include foliated leucocratic sills, but they are easy to distinguish from the dominantly pelitic host rock (e.g., Figure 3(c)).

A third assemblage consists of two belts of metabasalt and subordinate marble that crop out in Bute and Knight Inlets (Figure 2). These layers are present near sequences dominated by quartzite and marble, but continuity with adjacent units could not be established. The metabasalt is dominantly massive, with pillows observed locally. Meter-thick layers of white marble are locally interlayered with the metabasalt.

The fourth assemblage, extending across the middle of the study area, consists of several pendants that are dominantly intermediate-composition metavolcanic rocks with subordinate metasedimentary layers. Most metavolcanic rocks are tuffaceous and interlayered with fine-grained volcanic-rich strata. Several outcrops also include more massive layers that display relict pillows and fragmental textures. No occurrences of quartzite, marble, or pelitic schist have been found in this assemblage, suggesting that these rocks comprise a distinct tectonostratigraphic unit.

3. Previous Interpretations of Tectonic Affinity

Most previous workers have suggested that metamorphic rocks in the study area belong to the Wrangellia terrane and overlying strata of the Gambier Group (Figure 1). Journeay et al. [8] assigned the quartzite-marble-metapelite-metabasalt assemblages described above to the Karmutsen Formation, which consists mainly of Triassic basalt flows and subordinate sedimentary units that are exposed on much of Vancouver Island (Figure 1). Extensive Triassic basalts are one of the hallmarks of the Wrangellia terrane [14, 15]. Roddick and Woodsworth [16] expanded this assignment to include the possibility that some protoliths may be Paleozoic (pre-Karmutsen) in age.

Volcanic-rich rocks that occur in the middle portion of the study area were assigned to the Lower Cretaceous Gambier Group by Journeay et al. [8] and Roddick and Woodsworth [16]. The Gambier Group is interpreted as a basinal arc that accumulated along the inboard margin of the Wrangellia terrane [17, 18].

Rusmore et al. [9] suggested instead that pendants in the study area may belong to terranes that are located inboard of the Coast Mountains (e.g., the Stikine terrane) on the basis of (1) the occurrence of plutons with distinctive Early Cretaceous ages that, to the north, intrude rocks of the Stikine terrane and (2) paleomagnetic inclinations of plutons in the study area that are more similar to inboard terranes than outboard terranes.
4. Samples

Seventeen samples were collected and analyzed in an effort to test the interpretations noted above. Most samples were collected from quartz-rich layers that are interpreted to be metaclastic based on the low abundance of mafic minerals, cm-scale interlayering with marble and/or pelitic schist, and lack of cross-cutting relations with adjacent compositional layers. As noted above, one of the challenges in collecting metasedimentary samples is the common occurrence of foliated leucocratic sills that resemble the quartz-rich metaclastic layers in low color index, orientation (generally parallel to layering), degree of development of foliation and lineation, and resistance to weathering. In an effort to determine whether our metasedimentary samples also contained igneous material, we collected three samples of leucocratic sills to serve as a reference for comparison. Recognition of zircons with similar ages and Hf isotope signatures in both metasedimentary and metaplutonic samples would indicate that our metasedimentary samples contained unrecognized igneous material. Conversely, grains in the metasedimentary samples that are older than the intrusive bodies (and surrounding plutons) would be confidently interpreted as detrital components. The ages of the sills also provide a minimum depositional age for the metasedimentary pendants. Approximately 5-10 kg of rock was collected for each sample.

Samples are described in DR Table 1; locations are shown in Figure 2.

Considerable time was spent examining the metavolcanic pendants in the study area (Figure 2). Samples were not collected from these strata, however, because of the fine grain size and quartz-poor composition of the rare metaclastic strata.

5. Analytical Methods

Samples were processed and analyzed at the Arizona LaserChron Center utilizing methods of Gehrels [19], Gehrels et al. [20], Cecil et al. [21], Gehrels and Pecha [22], and Pullen et al. [23] (https://www.laserchron.org). Zircons were extracted with a jaw crusher and a roller mill and then separated from lighter minerals with a Wilfley table. The resulting heavy mineral fraction was further separated with a Frantz LB-1 magnetic barrier separator and methylene iodide.

Several hundred grains from each sample were mounted along with three zircon standards (Sri Lanka, FC-1, and R33) for U-Th-Pb analyses and six zircon standards (R33, Mud Tank, FC-1, Plesovice, Temora2, and 91500) for Lu-Hf isotopes. Mounts were polished to a depth of ~20 microns in order to reveal grain interiors and then imaged with back-scattered electron (BSE) and Cathode Luminescence.
(CL) detector systems connected to a Hitachi S-3400N scanning electron microscope.

5.1. U-Th-Pb Geochronologic Analysis. All U-Th-Pb analyses were performed by laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) using a Photon Machines G2 excimer laser connected to either a Nu multicollector ICPMS [20, 22] or an Element2 single-collector ICPMS [23]. For an initial set of analyses, the Element2 ICPMS was used to analyze between 110 and 315 zircon grains per detrital sample and ~35 zircon grains per igneous sample. One spot was analyzed per grain using a laser beam diameter of 20 microns. Details of the analytical methodology are reported in DR Table 2. Results of the U-Th-Pb analyses are reported in DR Table 3.

As described below, this first set of analyses yielded ages of ~151, 150, 150, 104, and 102 Ma for the leucocratic sill samples and ages that range from ~1948 to ~88 Ma for metasedimentary samples. The occurrence of ages in metasedimentary samples that overlap with ages of the sills indicated that igneous material may have been incorporated into the samples during collection and/or that the young ages record growth of metamorphic zircon. In an effort to distinguish between these two explanations, the following sections explore the CL characteristics of the analyzed grains [as described by Corfu et al. [24]] as well as their Hf isotope signatures, U concentrations, and U/Th values. In regard to the latter, we follow Rubatto [25], Kirkland et al. [26], and Yakymchuk et al. [27] in recognizing that metamorphic zircon commonly has higher U concentration and higher U/Th than igneous zircon. We also compare our data with values from nearby plutonic bodies given the possibility that sills of other ages are present in the metasedimentary samples. In conducting these comparisons, we use 170 Ma as the cutoff between older grains that are likely detrital in origin and younger grains that may be igneous and/or metamorphic in origin given that metasedimentary pendants in the study area are intruded by plutons as old as ~167 Ma [11] and yield few ages between ~185 Ma and 165 Ma.

Figure 3: Photographs of metasedimentary assemblages in the study area. (a) Typical shoreline exposure of metasedimentary rocks intruded by more massive plutons and swarms of dikes and sills of variable composition. (b) Typical exposure of the quartzite-marble assemblage in the southern and northern parts of the study area. (c) Typical exposure of the pelitic schist-quartzite assemblage in upper Bute Inlet. Leucocratic sills are present in all of outcrops shown but are easily distinguished from the metasedimentary host rocks only in the pelitic schist-quartzite assemblage.
In an effort to further explore the possibility that some of the analyzed domains are metamorphic in origin, we conducted a second set of analyses that involved acquiring high-resolution CL images to examine grain textures and conducting U-Th-Pb analyses on each of the domains recognized on CL images. These age-mapping analyses were conducted with the Nu multicollector ICPMS utilizing a 10 µm laser beam diameter. Between 5 and 33 analyses were conducted on each grain. Spot locations were determined from postanalysis BSE images. Details of the analytical procedures are reported in DR Table 2, and the analytical results are reported in DR Table 3.

U-Th-Pb ages of zircons from the metasedimentary samples are summarized in Figure 4, following the interpretation that >170 Ma grains are detrital and <170 Ma grains are igneous and/or metamorphic in origin. Maximum depositional ages are determined from the peak ages on probability density plots [e.g., Gehrels [19], Dickinson and Gehrels [28], Gehrels [22]]. Figure 5 explores the origin of the <170 Ma grains by comparing the age versus U/Th of zircons from the three samples of leucocratic sills, the metasedimentary rocks intruded by these sills, and nearby plutons. Figure 6 presents images and age information for several of the more informative grains that have been analyzed by age mapping.

5.2. Hf Isotopic Analysis. Hf isotopic analyses were carried out utilizing methods reported by Cecil et al. [21] and Gehrels and Pecha [22], using settings reported in DR Table 2. Analyses were conducted on grains from each age group from each sample. Hf analyses were conducted with a 40 µm laser beam, with the Hf pit located on top of the U-Th-Pb pit. This increases the likelihood that the U-Th-Pb and Hf data are from the same age domain. All of the Hf isotopic data are presented in Table DR 4, including Hf-evolution plots for each sample.

Figure 7 displays the Lu-Hf isotopic data from all samples. This diagram reports the data in terms of εHf, which is the 176Hf/177Hf ratio relative to the chondritic uniform reservoir (CHUR) [29] at the time of crystallization. Also shown on this diagram are the depleted mantle array (DM) from Vervoort and Blichert-Toft [30] and the Hf isotopic evolution of average continental crust, which is based on a 176Lu/177Hf ratio of 0.0115 [31, 32]. The average precision of our measurements is 2.2 epsilon units (at 2σ).

6. U-Th-Pb Geochronologic Results and Interpretations

As noted above and shown in Figure 4, nearly all of the metasedimentary samples yield both >170 Ma grains that overlap with the ages of nearby plutons, as well as >170 Ma grains that are interpreted to be detrital in origin. Each set of ages is described in a separate section below.

6.1. >170 Ma Ages. Twelve samples collected from pendants dominated by quartzite and marble yield variable proportions of ages that range from ~590 Ma to ~185 Ma, with dominant peak ages for each sample of 560, 452, 411, 345, 331, 322, 319, 216, 209, and 198 Ma (Figure 4). Three samples from the pelitic schist-quartzite pendant consist mainly of grains in the 370-270 Ma range, with dominant age peaks of 349, 310, and 302 Ma. With all ages combined (upper curve of Figure 4), there are four main age groups of 590-528 Ma (peak age of 560 Ma), 485-432 Ma (peak age of 452 Ma), 356-286 Ma (peak age of 307 Ma), and 228-185 Ma (peak ages of 216 and 199 Ma). Although each sample is dominated by grains from only one of these age groups, most samples contain subordinate populations from other age groups: three samples contain ages in the 590-528 Ma range, five samples contain 485-432 Ma ages, thirteen samples yield 356-286 Ma ages, and twelve samples contain 228-185 Ma ages.

Maximum depositional ages are assigned for the metasedimentary protoliths using the rubric that the most reliable age is determined from the youngest cluster of at least three ages that overlap within 2-sigma uncertainty [28]. This yields maximum depositional ages of 349, 310, and 302 Ma for the three pelitic schist-quartzite samples, with ages that decrease northeastward across the pendant (Figure 2). Maximum depositional ages for the quartzite-marble samples are 345, 341, 319, and 216 Ma for the southern pendant and 333, 331, 322, 209, and 198 Ma for the northern pendant. Given that four of the six samples with >300 Ma maximum depositional ages also contain individual ages between 250 and 170 Ma, it is likely that all of the quartzite-marble samples accumulated after 250 Ma. No spatial pattern of dominant or maximum depositional ages within or between the two quartz-marble pendants is apparent. The comparison of maximum depositional ages of the pelitic schist-quartzite versus quartzite-marble pendants suggests that pelitic schist-quartzite protoliths likely accumulated during late Paleozoic time, whereas quartzite-marble protoliths likely accumulated during Triassic-Early Jurassic time. In addition to these <590 Ma ages, six older grains were found in the quartzite-marble samples, with ages of ~1948, ~1845, ~1775, ~1701, ~1429, and ~1109 Ma. Only one age of ~1119 Ma was found in a sample from the pelitic schist-quartzite assemblage.

6.2. <170 Ma Ages. All of the quartzite-marble samples, and one of the three pelitic schist-quartzite samples, also yield a significant number of <170 Ma ages (Figure 4). Most samples display two sets of ages that range from 165 to 128 Ma and from 114 to 88 Ma. As noted above, these cannot be detrital ages given that the pendants are intruded by plutons that are as old as ~167 Ma. The following sections highlight the available U-Th-Pb, U/Th, U concentration, and CL textural information that constrains the origin of these young grains. Information from three pendants with both igneous and metasedimentary samples is described first to provide interpretive guides for pendants that do not have igneous samples.

6.3. U-Th-Pb Analyses of Leucocratic Sills and Host Metasediments. Figure 5 summarizes the ages, U concentrations, and U/Th values of zircons from leucocratic sills and host-rock metasedimentary samples from three outcrops. The results presented in this section are from our first set of analyses, which consisted of one analysis per grain. For each
sample, patterns of age, U concentration, and U/Th are evaluated in an effort to distinguish whether ages from the metasedimentary samples record igneous versus metamorphic crystallization. In distinguishing between the two, we follow Rubatto [25], Kirkland et al. [26], and Yakymchuk et al. [27] in the interpretation that metamorphic zircon commonly has higher U concentration and higher values of U/Th than igneous zircon.

**Figure 4:** Probability density plots that show the ages and numbers of analyses of detrital zircons from metasedimentary samples. Ages younger than 170 Ma are interpreted to record igneous or metamorphic crystallization, whereas >170 Ma ages are interpreted to be detrital in origin. Lightly shaded curves show age distributions for individual samples, and darker shades represent sets of combined analyses. Interpreted maximum depositional ages are shown for individual samples. Peaks in age probability are shown for the upper curve, which includes all analyses. >170 Ma portions of curves are exaggerated by 2x relative to <170 Ma portions of curves. The uppermost (combined) curve is exaggerated by 4x relative to other curves.
For locality 15KN63 (Figures 5(a) and 5(b)), the igneous sample (15KN63C) yields thirty-two younger ages (peak age of ~104 Ma) and three older ages (peak age of ~149 Ma) (DR Table 3). The three older ages are from clearly visible cores in CL images. Analyses from both age groups yield relatively low U concentrations and U/Th values, which suggests that all analyzed domains are igneous in origin. Zircons in the metasedimentary samples from this outcrop (15KN63A...

Figure 5: (a–f) show relations between age, U concentration, and U/Th for zircons from three different metasedimentary samples and for leucocratic sills that intrude the sampled metasedimentary rocks. (g, h) show similar information from the other twelve metasedimentary samples. Black dashed lines represent the average U concentration and U/Th of zircons from plutons in the study area (from [11]).
and B) yield similar age groups (peak ages of ~153 and ~104 Ma), with a greater proportion of older ages. Most of the younger grains yield U concentrations and U/Th values suggestive of igneous crystallization, whereas some older grains yield higher values suggestive of metamorphic crystallization.

For locality 15KN68 (Figures 5(c) and 5(d)), the igneous sample (15KN68B) yields both older and younger ages, with
peak ages of ~102 Ma (dominant, mostly from rims) and ~151 Ma (subordinate, mostly from cores) (DR Table 3). There also are cores that yield considerably older detrital ages. U concentrations and U/Th values for all grains in this sample are typical of igneous zircon. The metasedimentary sample from this outcrop yields similar age groups, with most ages defining a peak age of ~153 Ma, as well as a smaller proportion of ages with a peak age of ~107 Ma. There are a small number of older detrital grains that range in age from ~1109 to ~173 Ma. U concentrations and U/Th values for most grains are low, suggestive of igneous crystallization, although some range to higher values suggestive of metamorphic crystallization.

For locality 15KN69 (Figures 5(e) and 5(f)), the igneous sample (15KN69B) yields only one main age group with a peak age of ~149 Ma, plus two older core ages of ~215 and ~365 Ma (DR Table 3). Metasedimentary sample 15KN69A yields subequal proportions of older and younger grains (peaks at ~149 and ~92 Ma). Most analyses from both igneous and metasedimentary samples yield low U concentrations and U/Th values, suggestive of igneous crystallization.

6.4. U-Th-Pb Analyses of Other Metasedimentary Samples. Zircon grains with <170 Ma ages were also found in most of the other metasedimentary samples (Figure 4). The ages, U concentrations, and U/Th values from analyses of these grains are shown in Figures 5(g) and 5(h). These samples yield a subequal proportion of grains with ages between 167 and 125 Ma (peaks at ~150 and ~142 Ma) and between 115 and 84 Ma (peak at ~101 Ma). Most U/Th values are low, and presumably igneous in origin, but a significant number have considerably higher values consistent with a metamorphic origin.

6.5. Age-Mapping Analyses. In an effort to further constrain the origin of the <170 Ma grains in these samples, we conducted age-mapping analyses on 16 zircon crystals from five samples (one igneous and four metasedimentary). Details of these analyses are presented in DR Tables 2 and 3. Figure 6 summarizes results of our findings, with one grain from a leucocratic sill that records igneous crystallization at ~101 Ma, two grains from metasedimentary samples that record igneous crystallization at ~151 and ~104 Ma, and two grains from metasedimentary samples that are interpreted to record metamorphic crystallization at ~155 Ma and ~103 Ma.

The grain shown in Figures 6(a) and 6(b) is from a leucocratic sill (15KN63C) that intrudes metasedimentary rocks (15KN63A and B). The oscillatory and sector zoning (cf. Corfu et al., 2013) seen in the CL image combined with the
low U/Th values suggest that this grain is igneous in origin, with an age of ~101 Ma. Figures 6(c) and 6(d) show a grain from the host metasedimentary rocks (sample 15KN63A), which has similar oscillatory zoning, an age of ~104 Ma, and a typical igneous U/Th average value of ~3.0. The similarity in characteristics of these two grains suggests that metasedimentary sample 15KN63A included unrecognized igneous material from one or more leucocratic sills.

The grain shown in Figures 6(e) and 6(f) is from metasedimentary sample 15KS51. This grain has a highly disaggregated core with ages of 236-198 Ma (average of ~212 Ma) that is surrounded by a rim with an average age of ~103 Ma. The convolute texture (cf. [24]) of this outer rim, combined with U/Th values of 46-14 (average of ~24.2), suggests that this grain records growth of metamorphic zircon during mid-Cretaceous time.

The grain shown in Figures 6(g) and 6(h) is also from metasedimentary sample 15KN63A. It has convolute zoning and low U/Th values, similar to the grain shown in Figures 6(c) and 6(d), but it yields an age of ~151 Ma. The occurrence of this grain, and others with similar properties (DR Tables 2 and 3), suggests that Late Jurassic igneous components are also present in some of the metasedimentary samples.

In contrast, a metamorphic origin for other Late Jurassic grains is suggested by the grain shown in Figures 6(i) and 6(j), which is from metasedimentary sample 15KN73. This grain contains a core with an average age of ~559 Ma and a rim with an average age of ~155 Ma. U/Th values suggest that the core is igneous in origin, whereas the rim grew during regional metamorphism. Between the two is an intermediate domain that yields ages ranging from 457 to 230 Ma, presumably due to the analysis of a mixture of material from older and younger domains. Relations displayed by this grain suggest that some Late Jurassic zircon is metamorphic in origin.

6.6. Summary of U-Th-Pb Age, U/Th, and U Concentrations of <170 Ma Zircon Grains. Figures 8(a) and 8(b) present a comparison of the ages, U/Th values, and U concentrations of zircons from metasedimentary samples, leucocratic sills, and plutons near the sample sites [pluton data from Cecil et al. [11]]. The overlap of ages, U/Th values, and U concentrations of the leucocratic sills and adjacent plutons suggest that the sills are genetically related to the adjacent plutonic bodies. The similarity of ages, U/Th values, U concentrations, and CL textures in zircons from the metasedimentary samples and leucocratic sills suggest that many of the grains in our metasedimentary samples are igneous in origin and were inadvertently incorporated into the samples despite careful selection of material on the outcrop and during sample processing. On subsequent inspection, a 5 mm wide aplite vein was discovered in a hand sample from sample 15KN73—similar veins may have been the source of igneous material in this and other samples. The higher U/Th values, U concentrations, and convolute CL textures seen in some whole grains and the rims of many grains indicate that metamorphic zircon is also present. The presence of metamorphic zircon in these samples is not surprising given the occurrence of garnet in the northeastern pendants.

Given the interpretation that zircons (or zircon rims) with high U/Th and high U concentration are metamorphic in origin, the patterns shown in Figures 8(a) and 8(b) are interpreted to provide a record of the spatial and temporal distribution of metamorphism in the study area. Assuming that a U/Th value of 8 is a reasonable cutoff for igneous versus metamorphic zircon growth (Figure 8(a)), 425 of the 1074 analyses (~40%) are metamorphic in origin. Although we cannot assume that new zircon growth was associated with all metamorphic events, these data indicate that metamorphism occurred between ~111 and ~90 Ma, with peaks at 106, 101, and 92 Ma, and between ~171 and ~127 Ma, with peaks at 153 and 136 Ma. Assuming instead that a U concentration of 1100 ppm is a reasonable cutoff for igneous versus metamorphic zircon growth (Figure 8(b)), 572 of the 1074 analyses (~53%) are metamorphic in origin. Metamorphism appears to have occurred between ~115 and ~86 Ma, with peaks at 107, 101, and 93 Ma, and between ~168 and ~131 Ma, with peaks at 152 and 136 Ma.

7. Lu-Hf Isotope Results and Interpretations

eHf, values for our metasedimentary and igneous samples are shown in Figure 7. Shown separately are >170 Ma analyses that are interpreted to be detrital and <170 Ma analyses from leucocratic sills versus metasedimentary samples. The latter are further divided into analyses with U/Th > 8 (interpreted to be of metamorphic origin) versus analyses with U/Th < 8 (interpreted to be igneous in origin).

Analyses from metasedimentary samples yield a progressive evolution from more evolved to more juvenile through time. As shown in Figure 7, the sliding window average of eHf values increases from ~three for 590-528 Ma grains to ~eight for 485-432 Ma grains to ~twelve for 356-286 Ma grains. This is interpreted to record a progressive increase in the proportion of juvenile material through time. The eHf values remain juvenile through time in the 228-185 Ma grains.

Average eHf values for <170 Ma grains show slightly lower average values for 165-128 Ma grains and then a return to more juvenile values for 114-88 Ma grains. For 165-128 Ma analyses, eHf values from grains that are interpreted to be of igneous origin (grains from sills and from metasedimentary samples with low U/Th) are more negative than eHf values from grains interpreted to be of metamorphic origin (Figure 7). This suggests that the grains (or rims) of metamorphic origin were derived from a different source than the grains of igneous origin. Assuming that the metamorphic zircon grew at the presently exposed crustal level, whereas the igneous zircons grew primarily at deeper crustal levels (where the magmas were generated), the occurrence of more negative eHf values for igneous zircons may reflect the presence of somewhat more evolved crustal materials at lower crustal levels during 165-128 Ma magmatism. One possibility is that these more evolved crustal materials included rocks from which the 600-400 Ma grains in our samples were derived (Figure 7).

It is also possible that metamorphic zircons yield higher eHf values than igneous zircons due to interaction with other minerals (e.g., apatite or amphibole) during metamorphism.
Figure 8: Comparison of ages and U/Th values and U concentration for zircons from metasedimentary samples, leucocratic sills, and nearby plutons. All analyses from this study are included in these plots. Pluton data are from all ages shown in Figure 2 [data from Cecil et al. [11]]. Contours show increasing values of bivariate normalized kernel density estimates using HafniumPlotter version 1.4 (http://github.com/kurtsundell/HafniumPlotter) created by Kurt Sundell (written communication, 2018). (a) Plot comparing U/Th as a function of age. Analyses of zircons from metasedimentary samples are interpreted to be of metamorphic versus origin using a cutoff of 8, which approximates the highest value from sills and plutons. (b) Plot comparing U concentration as a function of age. Analyses of zircons from metasedimentary samples are interpreted to be of metamorphic versus origin using a cutoff of 1100 ppm, which approximates the highest value from sills and plutons.
This interpretation is not supported by the observation that igneous and metamorphic grains of both ~165-128 Ma and ~114-88 Ma age yield similar ranges and average values of $^{176}\text{Lu}/^{177}\text{Hf}$ (DR Table 5).

8. Comparison of Geologic Characteristics, U-Th-Pb Ages, and Lu-Hf Results with Data from Other Terranes

Our results are compared with data from relevant terranes in Figures 9–11 and in the following sections. Most appropriate for comparison are the Wrangellia and Stikine terranes given the previous interpretations that pendants in Bute, Loughborough, and Knight Inlets are metamorphic equivalents of strata belonging to these terranes. We also compare with (1) strata of the Alexander terrane, which occur outboard of the Coast Mountains north of the study area, and (2) the Taku and Yukon-Tanana terranes, which occur within and along the western flank of the Coast Mountains north of the study area (Figure 1).

8.1. Comparison with Wrangellia. The Vancouver Island portion of Wrangellia, as described by Yorath et al. [15] and Ruks [14], contains several exposures of Paleozoic rocks that include Upper Devonian-Lower Mississippian (366-336 Ma) bimodal volcanic rocks of the Sicker Group, Mississippian-Pennsylvanian argillite, shale, chert, limestone, and sandstone of the Fourth Lake and Thelwood Formations, upper Pennsylvanian-Lower Permian (312-292 Ma) mostly felsic volcanic rocks, and Lower-Middle Permian carbonate rocks of the Buttle Lake Formation. These rocks are overlain by a regionally extensive cover that consists, from oldest to youngest, of Middle and Upper Triassic basalt (Karmsutsen Formation), thick-bedded to massive limestone (Quatsino Formation), and thin-bedded siltstone, shale, and limestone (Parson Bay Formation). These rocks are overlain by Lower Jurassic (~200-170 Ma) basaltic to rhyolitic volcanic rocks and subordinate volcanic-rich sedimentary rocks of the Bonanza Group [15, 33].

Jurassic and older rocks are overlain along the eastern margin of Vancouver Island by unconformably overlying Upper Cretaceous conglomerate, sandstone, mudstone, and shale of the Nanaimo Group [15], the basal unit of which contains abundant ~400-170 Ma detrital zircon grains that are interpreted to have been derived from rocks of Wrangellia [34]. Intrusive components include the latest Devonian-earliest Mississippian Saltspring Intrusive Suite [359-356 Ma; Ruks [14]] and the Early-Middle Jurassic Island Intrusions [190-165 Ma; DeBari et al. [33]].

In the study area (Figure 2), strata along the eastern edge of Wrangellia [12, 13] include the following, from oldest to youngest:

(i) ~6 km of massive lava flows, pillow basalt, and fragmental breccia of the Karmsutsen Formation (Upper Triassic)
(ii) 0-800 m of thick-bedded to massive gray limestone of the Quatsino Formation (Upper Triassic)
(iii) Up to 600 m of gradationally overlying calcareous siltstone, shale, graywacke, and limestone of the Parsons Bay Formation (Upper Triassic)
(iv) Up to 500 m of black argillite and subordinate fine-grained graywacke of the Harbledown Formation (Lower Jurassic)

Although Wheeler and McFeely [6], Wheeler et al. [7], and Journey et al. [8] have proposed that metasedimentary and metavolcanic rocks in the pendants are metamorphic equivalents of strata belonging to Wrangellia, our field studies do not support these correlations. Primary differences are that (1) protoliths for the quartzite-marble assemblage have not been described in previous studies on Vancouver Island (or any other portion of Wrangellia) and were not recognized during our detailed mapping of lower Mesozoic strata belonging to Wrangellia within the study area; (2) protoliths for the pelitic schist-quartzite assemblage also have not been recognized in the study area, on Vancouver Island, or anywhere else in Wrangellia; and (3) mafic- to intermediate-composition volcanic rocks are widespread on Vancouver Island (and most other portions of Wrangellia) but are a minor component of the pendants in the study area.

In contrast to these geologic differences, our U-Pb ages and Hf isotopic results are very similar to the results available from Vancouver Island, which include U-Pb ages on Paleozoic igneous rocks [14] and U-Pb/Lu-Hf data from detrital zircons extracted from Mississippian-Pennsylvanian sandstone layers of the Fourth Lake and Thelwood Formations and from Upper Cretaceous sandstone layers of the overlying Comox Formation of the Nanaimo Group [34]. As part of this project, we attempted to complement these results by analyzing detrital zircons from strata of the Karmsutsen, Quatsino, Parsons Bay, and Harbledown Formations (Figure 2) but were unable to identify quartz-rich clastic strata in any of these units. Two samples of the coarsest-available graywacke horizons of the Harbledown Formation failed to yield zircons of sufficient size for analysis. Data from Ruks [14] and Alberts et al. [34] are summarized in Figure 9, with the age distributions of igneous and detrital zircons in the lower panel and $\epsilon$Hf values of detrital zircons in the upper panel.

U-Pb (zircon) ages from metasedimentary rocks in Bute and Knight Inlets show considerable overlap with ages from igneous and sedimentary rocks of Wrangellia (Figure 9(b)). Both sets display two dominant sets of ages, with age peaks of 307, 215, 198, and 179 Ma in the Bute-Knight pendants and age peaks of 341, 195, and 171 Ma for detrital grains and age peaks of 357, 308, 199, and 176 Ma for igneous grains from Wrangellia. Most impressive are the nearly identical age peaks of 307-308 Ma and 198-199 Ma for Bute-Knight pendants and igneous rocks of Vancouver Island. Both detrital zircon data sets also contain scattered >400 Ma grains, with age peaks of 560 and 452 Ma from Bute-Knight pendants but no distinct groups from Vancouver Island. $\epsilon$Hf values from <400 Ma grains in the two regions are also similar, with highly juvenile values for both (Figure 9(a)).

On the basis of these comparisons, we conclude that the metasedimentary and metavolcanic rocks in the study area
may have primary connections with upper Paleozoic-lower Mesozoic strata on Vancouver Island. Such connections would require significant lateral changes in stratigraphy, including an eastward increase in the abundance of quartz-rich clastic strata and decrease in the proportion and extent of volcanic rocks.

8.2. Comparison with the Stikine Terrane. The Stikine terrane consists of Devonian limestone and marine clastic strata, Upper Devonian-Lower Mississippian volcanic rocks and associated 380-345 Ma plutons, Mississippian mafic volcanic rocks and marine strata, Pennsylvanian bimodal volcanic rocks (319-312 Ma), Permian carbonates, Middle and Upper Triassic volcanic rocks and associated plutons (226-200 Ma), and Lower-Middle Jurassic volcanic rocks and associated plutons (195-176 Ma) [35–40]. These rocks are overlain by Upper Jurassic through mid-Cretaceous marine strata of the Bowser Lake Group [41].

Data from rocks of the Stikine terrane are relevant for comparison given that they occur along the eastern margin of the Coast Mountains batholith (Figure 1) and at least locally consist of upper Paleozoic-lower Mesozoic quartz-rich metaclastic strata, marble, and metapelite [35–40]. In addition, Rusmore et al. [9] report geochronologic and paleomagnetic data which they interpret as evidence that intrusive rocks in the study area were emplaced into these inboard assemblages. As shown in Figure 9(b), 380-170 Ma ages in the Bute-Knight pendants overlap to a significant degree with the main phases of igneous activity in the Stikine terrane, as recorded by detrital zircon ages [35–38, 40]. These similarities support the conclusion of Rusmore et al. [9] that the prebatholithic rocks in the study area may belong to inboard terranes (e.g., Stikine terrane or Intermontane superterrane). εHf data that could be used as an additional means of comparison are not available from strata of the Stikine terrane, although the juvenile signatures of Sr

Figure 9: U-Pb ages and εHf, values of detrital zircons from Bute-Knight samples and Wrangellia [14, 34], as well as detrital zircon U-Pb ages from strata of the Stikine terrane [from Figure 4 of Evenchick et al. [41]]. (b) lists peak ages for each age distribution and also shows periods of widespread magmatic activity within the Stikine terrane (with stars; [35–38, 40]). Dashed lines in (a) are sliding window averages of the closest 20 analyses.
and Nd data from rocks of the Stikine terrane [37, 42] suggest that $\varepsilon$Hf values would likely overlap with juvenile values from the metasedimentary pendants. On the basis of the geologic, geochronologic, and potential isotopic similarities, we conclude that possible correlations with rocks of the Stikine terrane are also supported by our data.

8.3. **Comparison with Alexander Terrane.** The Alexander terrane consists of Neoproterozoic through Upper Triassic rocks that can be divided into three distinct assemblages. Nearest the study area is the Banks Island assemblage, which consists of quartzite, marble, and metapelite that are interpreted to range in age from Ordovician to Permian [3]. As shown in Figures 6(d) and 6(e) of Tochilin et al. [3], this assemblage consists primarily of interlayered quartzite and marble that are very similar to the quartzite-marble assemblage in the study area. The youngest components of the Banks Island assemblage, interpreted to be late Paleozoic in age, occur in pendants of the westernmost Coast Mountains batholith north of Vancouver Island (Figure 1).

In southeast Alaska, the Alexander terrane is characterized by Neoproterozoic-Cambrian and Ordovician-Silurian volcanic and plutonic rocks that are interpreted to have formed in juvenile magmatic arc systems [4, 43]. These rocks are overlain by a variety of middle and upper Paleozoic marine strata and an Upper Triassic bimodal volcanic sequence. Rocks belonging to this portion of the terrane are found in much of southeast Alaska and continue southeastward along the western margin of the Coast Mountains batholith, inboard of the Banks Island assemblage, to the central coast of British Columbia (Figure 1).
To the north, in the Saint Elias Mountains, the terrane consists of lower Paleozoic mafic volcanic rocks overlain by middle-upper Paleozoic marine clastic strata and limestones and an Upper Triassic rift assemblage [44–46]. Similarities in lithic types, ages of detrital zircons, and εHf isotopic values suggest that the Banks Island assemblage formed adjacent to the Saint Elias Mountains assemblage prior to ~800 km of southward (relative) motion of the Banks Island assemblage in Early Cretaceous time [3, 47]. The Alexander terrane is known to have been located next to Wrangellia by Permian time [48] and most likely Late Devonian time [49].

Figure 10 compares the information from Bute-Knight pendants with U-Pb ages and Hf isotope ratios from the Banks Island [3], Saint Elias Mountains [44–46], and southeast Alaska [4, 21] portions of the Alexander terrane. Rocks of the Banks Island assemblage are emphasized in our comparison because they contain abundant quartzite and marble, are at least locally of late Paleozoic age, and are the closest portion of the Alexander terrane to the study area (Figure 1). The Saint Elias Mountains assemblage is included because it is interpreted to have been adjacent to the Banks Island assemblage during Paleozoic-early Mesozoic time [3]. Geochronologic and isotopic results from the southeast Alaska portion of the terrane are included because these rocks yield similar age distributions and trace southeastward toward the study area.

As shown in Figure 10(b), most ages from Bute-Knight metasedimentary rocks are younger than zircon ages from rocks of the Alexander terrane, which is not surprising given that most rocks analyzed from the Alexander terrane are early to mid-Paleozoic in age, whereas strata in this study are interpreted to be upper Paleozoic-lower Mesozoic. Although the proportions of ages are quite different, some age groups overlap, for example, the 560, 452, and 307 Ma age peaks in our samples; 630, 468-441, and 304 Ma age peaks in strata of the Banks Island Assemblage-Saint Elias Mountains; and 574, 446-431, 363, and 288 Ma age peaks in rocks from southeast Alaska. As shown in Figure 10(a), εHf values for older zircons from the Bute-Knight metasedimentary rocks are intermediate between more evolved and more juvenile components of the Alexander terrane. In contrast, εHf values for ~330-280 Ma grains in the pendants and in upper Paleozoic strata of the Banks Island assemblage are nearly identical (filled symbols in Figure 10(a)).
These comparisons raise the possibility that Bute-Knight metasedimentary rocks may have primary connections with at least some portions of the Alexander terrane. The strongest similarities are with the upper Paleozoic quartzite-marble unit in the southern portion of the Banks Island assemblage, which occurs north of Vancouver Island and projects southeastward toward the study area (Figure 1). The U-Pb ages and εHf results from these rocks are very similar to values from the Bute-Knight pendants (Figure 10(a)). Other potential connections include the occurrence in both assemblages of 500–400 Ma ages (with somewhat similar εHf values) and 600–550 Ma ages (with very different εHf values) (Figure 10(a)).

8.4. Comparison with Yukon-Tanana and Taku Terranes. The Yukon-Tanana terrane consists of Neoproterozoic(?)-lower Paleozoic quartzite, marble, and metapelite overlain by middle Paleozoic volcanic-rich strata and Carboniferous limestone, conglomerate, basalt, and pelitic strata [2, 50]. The Taku terrane consists of Carboniferous strata that are equivalent to upper units of the Yukon-Tanana terrane, plus overlying Permian and Triassic mafic volcanic rocks, pelitic strata, and limestone [1]. Comparison with data from the Taku and Yukon-Tanana terranes is appropriate given that these terranes contain abundant quartzite and marble of Paleozoic and early Mesozoic age [2] and occur along the western flank of the Coast Mountains north of the study area (Figure 1).

As shown in Figure 11(b), U-Pb ages from rocks of the Taku and Yukon-Tanana terranes overlap to some degree with the older age groups of the Bute-Knight pendants. As shown in Figure 11(a), however, the Lu-Hf data are quite different, with more juvenile values for >360 Ma grains and more negative values for <360 Ma grains. We accordingly conclude that rocks of the Bute-Knight pendants do not have primary connections with rocks of the Taku and Yukon-Tanana terranes.

8.5. Summary of Regional Comparisons and Tectonic Implications. The geologic, U-Pb geochronologic, and Lu-Hf isotopic relations described above suggest that primary connections with the Yukon-Tanana terrane are unlikely given the very different U-Pb ages and Lu-Hf isotope signatures (Figure 11).

Connections with the Wrangellia terrane are supported by the similar U-Pb ages and εHf values (Figure 9) but are problematic given the abundance of quartz-rich metasedimentary rocks and scarcity of metabasalt in the pendants versus the lack of quartz-rich clastic strata and abundance of mafic volcanic rocks on Vancouver Island. Primary connections would require significant lateral facies changes between strata of the Karmutsen, Quatsino, Parsons Bay, and Harbledown Formations (in the southwest corner of the study area) and the metasedimentary pendants now tens of km to the northeast (Figure 2).

Primary connections with the Stikine terrane are also plausible but are difficult to fully evaluate given the lack of Lu-Hf data from Stikine strata. The occurrence of similar U-Pb ages in the two assemblages and the presence of quartz-rich clastic strata in upper Paleozoic Stikine strata are consistent with the geochronologic and paleomagnetic ties reported by Rusmore et al. [9].

An additional possibility, not considered by previous workers, is that the Bute-Knight metasedimentary rocks have primary connections with the Alexander terrane. Although most strata of the Alexander terrane lack quartz-rich clastic horizons and yield primarily >400 Ma detrital zircons, metasedimentary rocks in the southern portion of the terrane consist mainly of interlayered quartzite, marble, and metapelite that yield mainly 400–270 Ma detrital zircon grains with juvenile εHf values (Figure 10(a)). Rocks of the Alexander terrane also contain ~550 Ma and ~450 Ma detrital zircons, although εHf values for most of these grains do not overlap with εHf values for grains of these ages in the Bute-Knight pendants. These similarities raise the possibility that the Bute-Knight pendants may be a southeastern continuation of the Alexander terrane.

Given the geologic, U-Pb geologic, and Lu-Hf isotopic differences noted above, it is also possible that the Bute-Knight pendants are not correlative with rocks in any of these nearby terranes. Perhaps, connections with more distant Cordilleran terranes will emerge when additional U-Pb geochronologic and Lu-Hf isotopic data become available, or the pendants may be recognized as a distinct terrane. An additional possibility is that the metasedimentary rocks belong to several different tectonostratigraphic units with differing tectonic affinities. Structural boundaries separating the various components may have been obliterated by the widespread plutons that separate the pendants. This possibility is consistent with the observation that the quartzite-marble samples yield a surprisingly broad range of age distributions (Figure 4).

9. Implications

9.1. Tectonic Implications. As noted above, the available geologic, U-Pb geochronologic, and Lu-Hf isotopic data do not establish or rule out primary connections with the Wrangelia terrane [as suggested by Wheeler and McFeely [6], Wheeler et al. [7], and Journeay et al. [8]] or the Stikine terrane [as suggested by Rusmore et al. [9]]. The available data also raise the possibility that connections may have existed with rocks of the Banks Island assemblage of the Alexander terrane.

Given that the Wrangellia and Alexander terranes belong to the Insular superterrane whereas Stikine belongs to the Intermontane superterrane, we are unable to document whether the Insular-Intermontane boundary traces inboard or outboard of the Bute-Knight pendants. The two possible locations for this boundary are shown with dashed lines in Figure 1. This is unfortunate given the tectonic significance of this boundary, as noted above and discussed recently by Pavlis et al. [51].

9.2. Implications for Metamorphic and Magmatic Histories. The interpretation that ~50% of the <170 Ma analyses from metasedimentary samples record growth of metamorphic zircon provides an opportunity to use the patterns of age
versus U/Th and U concentration to reconstruct the history of metamorphism along the western flank of the Coast Mountains batholith. Such an approach has been used by Rubatto [25], Kirkland et al. [26], Yakymchuk et al. [27], and many others to reconstruct the metamorphic history of other orogens.

The patterns shown in Figures 8(a) and 8(b) suggest that metamorphism occurred primarily between ~170 and ~130 Ma and between ~110 and ~87 Ma, with apparent peaks at ~153, ~136 Ma, and ~101 Ma. The younger age range is an excellent match with the main age of metamorphism along the western flank of the Coast Mountains near Prince Rupert (e.g., [52]) and to the north (e.g., [53]). In contrast, evidence for the older phase of metamorphism has been recognized only locally on outer islands northwest of the study area (Figure 1), where [3] report that metamorphic rocks of the Banks Island assemblage are intruded by nondeformed dikes as old as ~156 Ma.

The similarity between this interpreted record of metamorphism and the timing of plutonism in the study area [Figure 8; Cecil et al. [11]] suggests that metamorphism was driven largely by heat from the adjacent plutons. The apparent pull-down of εHf values for 165-128 Ma igneous zircons suggests that both metamorphism and plutonism may have been related to Late Jurassic-Early Cretaceous crustal thickening [e.g., Girardi et al. [54], Tochilin et al. [3], Beranek et al. [55]].

9.3. Implications for Sampling of Batholithic Terranes. The analysis of leucocratic sills as well as metasedimentary samples indicates that ~50% of the <170 Ma ages (~28% of the total ages) generated from our metasedimentary samples are igneous in origin. Despite careful examination of the sampled material on the outcrop and inspection of the sampled material during processing, we inadvertently incorporated material from leucocratic sills or veins into several of our samples during collection. This suggests that extreme care must be used when collecting metasedimentary samples in batholithic terranes.

10. Summary and Conclusions

Our geologic observations combined with U-Th-Pb geochronologic and Lu-Hf isotopic results lead to several first-order conclusions regarding the tectonic affinity of metasedimentary pendants in the Bute-Knight area:

1. Approximately 2/3 of the U-Th-Pb ages generated from zircons from Bute-Knight metasedimentary samples are <170 Ma, with two main groups of 165-128 Ma (peak age of 152 Ma) and 114-88 Ma (peak age of 102 Ma). These ages match well with the ages of plutons [11] and sills that intrude the metamorphic pendants, which indicates that the <170 Ma ages must record pre depositional igneous and/or metamorphic processes. Conversely, >170 Ma ages in the samples are interpreted to provide a reliable record of the crystallization ages of detrital zircons.

2. Most of the >170 Ma detrital zircons in our metasedimentary samples belong to four main groups of 590-
528 Ma (peak age of 560 Ma), 485-432 Ma (peak age of 452 Ma), 356-286 Ma (peak age of 307 Ma), and 228-185 Ma (peak ages of 216 and 198 Ma) (Figure 4). Three samples collected from the pelitic schist-quartzite pendant are all dominated by ages between 365 and 285 Ma, with individual age peaks (interpreted to be maximum depositional ages) at 349, 310, and 302 Ma. These maximum depositional ages, combined with the scarcity of ages belonging to the 228-185 Ma group (Figure 4), suggest that these strata accumulated during late Paleozoic time. Samples collected from the quartzite-marble pendants yield a range of ages, with dominant age peaks of 560, 452, 314, 351, 321, 319, 216, 209, and 198 Ma. Maximum depositional ages for these samples include an older group of 345, 341, 333, 331, 322, and 319 Ma ages and a younger group of 246, 216, 209, and 198 Ma ages. The presence of at least a few 228-185 Ma ages in nearly all samples suggests that these strata accumulated during early Mesozoic time. Several samples yield older single-grain ages of approximately 1948, 1845, 1775, 1701, 1429, 1119, and 1109 Ma.

3. Many of the <170 Ma analyses yield U concentrations and U/Th values and display zonation patterns in CL images that are similar to values and CL patterns from zircons in leucocratic sills which intrude the metasedimentary rocks. Conversely, many of the young analyses yield higher U concentrations and U/Th values and display convolute zoning in CL images, which suggests that the grains (or in many cases just thin rims) are metamorphic in origin.

A comparison of U/Th values (Figure 8(a)) and U concentrations (Figure 8(b)) of analyses of zircons from plutons, leucocratic sills, and metasedimentary samples provides a means of estimating the proportion of metamorphic versus igneous zircon. As shown in Figure 8(a), a cutoff of U/Th = 8 suggests that 60% of the analyses record igneous zircon growth, whereas 40% are metamorphic. Instead, a cutoff of U concentration = 1100 ppm suggests that 47% of the analyses are igneous and 53% are igneous in origin.

4. Given that zircon commonly grows during moderate to high-grade metamorphism [e.g., Rubatto [25], Kirkland et al. [26], Yakymchuk et al. [27]], the age distribution of zircon grains (or rims) that are interpreted to be metamorphic in origin provides an opportunity to reconstruct the metamorphic history in the study area. As shown in Figures 8(a) and 8(b), it appears that metamorphism occurred primarily between ~170 and ~130 Ma and between ~110 and ~87 Ma, with apparent peaks at 153, 136 Ma, and 101 Ma. The occurrence of very similar ages of plutons and sills (Figure 8) raises the possibilities that metamorphism may have been caused mainly by heat related to the adjacent plutons and/or that both metamorphism and plutonism may have resulted from crustal thickening.
(5) The occurrence of a significant number of <170 Ma zircons in our metasedimentary samples that are interpreted to be of igneous origin demonstrates that most of our samples included igneous material (e.g. felsic veins or sills) that was incorporated during sample collection. This suggests that our procedure of checking the outcrop for igneous material during collection and inspecting each rock fragment during processing was not sufficient to ensure that only metasedimentary material was analyzed.

(6) εHf values of the zircon grains from metasedimentary samples record a trend from intermediate values (0 to +5; average of +3) for 590-528 Ma grains, through highly variable but generally more juvenile values (+2 to +13; average of +8) for 485-432 Ma grains, to highly juvenile values (mostly +4 to +15; average of +12) for 356-286 Ma and 228-185 Ma grains (Figure 7). εHf values of <170 Ma grains from metasedimentary samples that are interpreted to be of metamorphic origin (e.g., U/Th > 8 and U concentration > 1100 ppm) remain juvenile (Figure 7), suggesting that the zircons grew during metamorphism of the surrounding (juvenile) metasedimentary rocks. εHf values of <170 Ma grains from sills and from igneous zircons in the metasedimentary samples are less positive for 165-128 Ma ages and return to more juvenile values for 114-88 Ma ages. The slight pull-down of 165-128 Ma εHf values may record melting of more evolved rocks at deeper crustal levels during Late Jurassic-Early Cretaceous time.

(7) Comparisons of our U-Th-Pb and Lu-Hf results with (e.g., [51, 56]) the occurrence of a significant number of <170 Ma zircons in our metasedimentary samples that are interpreted to be of igneous origin demonstrates that most of our samples included igneous material (e.g. felsic veins or sills) that was incorporated during sample collection. This suggests that our procedure of checking the outcrop for igneous material during collection and inspecting each rock fragment during processing was not sufficient to ensure that only metasedimentary material was analyzed.

Data Availability

Data are available from the Supplementary Files associated with this manuscript.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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Supplementary Materials

Supplementary 1. DR Table 1: Information about analyzed samples.

Supplementary 2. DR Table 2: Information about analytical methods used for U used for U-Th-Pb geochronology.

Supplementary 3. DR Table 3: U-Th-Pb geochronologic data.

Supplementary 4. DR Table 4: Diagrams showing CL images, pit locations, U-Pb ages, U/Th ratios, and U concentrations of zircons with multiple analyzes.

Supplementary 5. DR Table 5: Lu-Hf isotope geochemistry.

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