Transfer of Metasupracrustal Rocks to Midcrustal Depths in the North Cascades Continental Magmatic Arc, Skagit Gneiss Complex, Washington

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Abstract The metasupracrustal units within the north central Chelan block of the North Cascades Range, Washington, are investigated to determine mechanisms and timescales of supracrustal rock incorporation into the deep crust of continental magmatic arcs. Zircon U-Pb and Hf-isotope analyses were used to characterize the protoliths of metasedimentary and metagneous rocks from the Skagit Gneiss Complex, metasupracrustal rocks from the Cascade River Schist, and metavolcanic rocks from the Napeequa Schist. Skagit Gneiss Complex metasedimentary rocks have (1) a wide range of zircon U-Pb dates from Proterozoic to latest Cretaceous and (2) a more limited range of dates, from Late Triassic to latest Cretaceous, and a lack of Proterozoic dates. Two samples from the Cascade River Schist are characterized by Late Cretaceous protoliths. Amphibolites from the Napeequa Schist have Late Triassic protoliths. Similarities between the Skagit Gneiss metasediments and accretionary wedge and forearc sediments in northwestern Washington and Southern California indicate that the protolith for these units was likely deposited in a forearc basin and/or accretionary wedge in the Early to Late Cretaceous (circa 134–79 Ma). Sediment was likely underthrust into the active arc by circa 74–65 Ma, as soon as 7 Ma after deposition, and intruded by voluminous magmas. The incorporation of metasupracrustal units aligns with the timing of major arc magmatism in the North Cascades (circa 79–60 Ma) and may indicate a link between the burial of sediments and pluton emplacement.

1. Introduction

The continental crust has a bulk andesitic composition (Rudnick & Gao, 2003) even though mantle-derived magmas produced in continental magmatic arcs, the main tectonic setting where new continental crust is produced, have a mafic composition (Kelemen et al., 2003). Both geological observations, such as crustal signatures in arc magmas (e.g., Behn et al., 2011; Buys et al., 2014; Chapman et al., 2013; Lackey et al., 2005; Plank & Langmuir, 1998; Wetmore & Duca, 2011) and numerical modeling (e.g., Castro et al., 2013; Currie et al., 2007; Scholl & von Huene, 2007), indicate that subducted continental material interacts with the mantle wedge and/or the overlying active arc system. Some subducted continental material is recycled into the mantle (e.g., Hilde, 1983; Scholl & von Huene, 2007; von Huene & Scholl, 1991), but other material is also likely added to the active continental magmatic arc. This incorporation of supracrustal material may occur through (1) underthrusting or imbrication of backarcwhile or forearc sediments into the core of the arc system (Chin et al., 2013; Duca, 2001; Duca & Barton, 2007; Matzel et al., 2004) (Figures 1a and 1b), (2) subduction and subsequent low-angle underplating of sediment into the arc (Duca et al., 2009; Saleeby, 2003; von Huene & Scholl, 1991) (Figure 1c), and/or (3) subduction and subsequent diapirc rise of unstable sediment detached from the subducting plate, leading to "relamination" at the base of the arc crust (Behn et al., 2011; Castro et al., 2013; Chapman et al., 2013; Hacker et al., 2011) (Figure 1d). The introduction of fertile, sedimentary material into arc systems has major consequences as it drives the crust toward a more felsic composition (e.g., Behn et al., 2011; Hacker et al., 2011), may fuel magmatic flares-ups (DeCelles et al., 2009; Duca, 2001; Duca & Barton, 2007), and may affect the rheology of the arc crust (Hollister & Crawford, 1986; Miller & Paterson, 2001).

The North Cascades Range, Washington, is an exhumed Cretaceous-Eocene continental magmatic arc system. It represents an ideal natural laboratory to test sediment incorporation and the role of metasedimentary rocks in the evolution of the arc system because a large volume of metasedimentary rocks is exposed within the northern portion of this arc (Misch, 1966, 1968; Tabor et al., 1989). The tectonostratigraphic framework of...
the North Cascades arc consists of a variety of accreted terranes, mostly of oceanic and island-arc affinity; thus, the arc was not likely constructed on crust already containing voluminous amounts of continental material (Tabor et al., 1989). This study investigates the processes involved in the incorporation of metasedimentary rocks to midcrustal structural levels by using detrital zircon age and Hf-isotope composition as a “fingerprint” to link the metasedimentary rocks to potential protoliths with known affinity (i.e., forearc, backarc, and/or accretionary wedge).

Uranium-Pb and Hf-isotope compositions were determined for zircon from 12 metaigneous and metasedimentary samples from the Skagit Gneiss Complex, 4 metavolcanic samples from the Napeequa Schist, and 2 metasupracrustal samples from the Cascade River Schist. Detrital zircon ages and Hf-isotope signatures were used to characterize the provenance and maximum depositional age of the sedimentary protolith. Some samples contain zircons interpreted to have crystallized in situ; ages of these grains relate to the timing of metamorphism and/or melt crystallization and, therefore, bracket the burial of metasupracrustal units into the crystalline core of the North Cascades arc. The zircon results link the metasedimentary rocks to their likely protoliths, providing insight into the mechanism of sediment burial. The timing of sediment incorporation is compared with the occurrence of a major magma emplacement event in the North Cascades to investigate if these events are likely genetically linked.

2. Evolution of the North Cascades Arc System

The North Cascades Range is the southernmost extension of the Coast Plutonic Complex, which is an exhumed continental magmatic arc that stretches >1,500 km from Alaska to Washington. The Coast Plutonic Complex arc was active from the Jurassic to the Eocene (circa 155–45 Ma; Gehrels et al., 2009), but major arc magmatism did not begin in the North Cascades until circa 96 Ma (Matzel et al., 2006; Miller, Paterson, et al., 2009; Walker & Brown, 1991). Mid-Cretaceous terrane accretion and/or increased plate coupling caused folding, thrusting, and metamorphism within the North Cascades. Combined with abundant plutonism, the arc crust was likely >55 km thick by circa 90 Ma (DeBari et al., 1998; Journeay & Friedman, 1993; Miller & Paterson, 2001; Miller, Paterson, et al., 2009; Monger et al., 1982). Magmatism, metamorphism, and ductile deformation continued until circa 47–45 Ma (Gordon, Bowring, et al., 2010; Haugerud et al., 1991; Mattinson, 1972; Miller & Bowring, 1990; Miller et al., 1989). The Skagit Gneiss Complex (650–725°C and 8–10 kbar; Whitney, 1992a) and the Swakane Gneiss (640–750°C and 9–12 kbar; Valley et al., 2003) represent the highest-grade exposures of midcrustal metasedimentary rocks within the North Cascades crystalline core.
Two strike-slip fault zones bound the crystalline core of the arc: the Straight Creek fault zone to the west, which records Eocene dextral motion, and the Ross Lake fault zone to the northeast, which records mostly dextral strike slip with components of reverse and normal motion (Baldwin et al., 1997; Gordon, Whitney, et al., 2010; Miller, 1994; Miller & Bowring, 1990; Misch, 1966; Umhoefer & Miller, 1996) (Figure 2a). These major structures separate the crystalline core from low grade to nonmetamorphosed, Paleozoic oceanic
and arc rocks and Jura-Cretaceous forearc and accretionary wedge units to the west and Methow terrane sediments to the east (Miller et al., 2016; Misch, 1966). These flanking strata are dominated by mid-Cretaceous to Late Cretaceous shortening structures, the timing of which aligns with ductile deformation and metamorphism within the crystalline core (Brown, 1987; Journeay & Friedman, 1993; McGroder, 1991; Miller et al., 2016, 2006; Misch, 1966).

2.1. Metasupracrustal Rocks of the Crystalline Core

The postmetamorphic Entiat fault divides the North Cascades crystalline core into the Wenatchee and the Chelan blocks (Tabor et al., 1989) (Figure 2a). These blocks have different magmatic and metamorphic histories: both blocks record circa 96–86 Ma magmatism, whereas younger magmatism was focused in the Chelan block from circa 79 to 45 Ma (Gordon, Bowring, et al., 2010; Haugerud et al., 1991; Miller et al., 2016, 2003; Tabor et al., 1989).

A variety of accreted oceanic terranes, plutons, orthogneisses, and metasedimentary rocks are exposed within the two blocks. Paleozoic-Mesozoic oceanic terranes were accreted onto the North American plate margin before the mid-Cretaceous and were later intruded by major arc magmatism (Haugerud et al., 1991; Miller et al., 1993; Misch, 1966; Tabor et al., 2002, 1989) (Figure 2). Two of these accreted terranes, the Napeequa Schist and Cascade River Schist, are found in the Chelan block. In addition, the Skagit Gneiss Complex is exposed within the north and central parts of the Chelan block and mostly to the northeast of the major bodies of Napeequa Schist and Cascade River Schist (Figure 2a). The Wenatchee block also contains the Napeequa Schist, Cascade River Schist, and the Nason terrane. The Nason terrane includes the Chiwaukum Schist and is dominantly metapsammitic gneiss and schist and plutonic bodies. The detrital zircon signature of the Chiwaukum Schist is characterized by Early Cretaceous and Jurassic age peaks with some Precambrian ages (Brown & Gehrels, 2007; Paterson, 2014). Both the Chelan and Wenatchee blocks contain the deep-crustal Swakane Gneiss (Figure 2a). The Swakane Gneiss is a metapsammitic unit that contains detrital zircons with Proterozoic to Late Cretaceous ages. The protolith of the Swakane is interpreted to have been deposited in a forearc basin and emplaced into the arc system shortly after its protolith was deposited in the Late Cretaceous (Gatewood & Stowell, 2012; Matzel et al., 2004).

This study investigates the provenance of metasupracrustal rocks along a transect across the north central Chelan block (Figure 2b), including the Napeequa Schist, the Cascade River Schist, and the Skagit Gneiss Complex (herein referred to as the Skagit Gneiss). The following describes the lithology and structural setting of these metasupracrustal units.

The Napeequa Schist consists predominantly of micaceous quartzite (metachert), amphibolite, and biotite schist with lesser marble and metaperidotite and rare metapelite (Cater, 1982; Miller et al., 1993; Misch, 1966; Tabor et al., 2002, 1989). This unit is interpreted to represent a metamorphosed oceanic accretionary complex with minor continental input. It is correlated with the Mississippian-Jurassic Bridge River Complex (Brown et al., 1994; Miller et al., 1993; Monger, 1986; Tabor et al., 1989). The Napeequa rocks in the northern Chelan block were buried to peak pressure-temperature (P-T) conditions of 625–680°C at ~9 kbars (Brown et al., 1994) between circa 91–88 Ma and circa 76 Ma, as bracketed by the crystallization of the Eldorado (Brown et al., 1994; Miller et al., 1993; Walker & Brown, 1991) and Marble Creek orthogneisses (Haugerud et al., 1991), respectively, which both crosscut the Napeequa. The Napeequa is intruded by variably deformed and metamorphosed plutons of the Skagit Gneiss in the north central Chelan block and structurally overlies and is fault bounded with the Swakane Gneiss in both the Wenatchee and Chelan blocks (Figure 2a).

In the north central Chelan block, the Cascade River Schist is dominantly composed of fine-grained mica schist and biotite paragneiss, with lesser metaconglomerate and metavolcanic rocks and rare metaperidotite (Brown et al., 1994; Tabor et al., 2003). The protolith for the Cascade River Schist is interpreted to have been deposited in a forearc or intra-arc basin associated with a Triassic arc system, represented by the spatially associated Marblemount-Dumbell plutonic belt (Tabor et al., 1989). There are contrasting interpretations for the relationship between the Cascade River Schist and the Napeequa Schist. Some studies interpret that the protolith for the Cascade River Schist was deposited unconformably on the Napeequa oceanic basement (Tabor et al., 2002) or instead that the Napeequa Schist was imbricated through thrusting with the Cascade River Schist prior to metamorphism (Brown et al., 1994). Zircon grains from a metadacite, interpreted to be from near the base of the Cascade River Schist and near the contact with the Marblemount Pluton, yield circa 220 Ma U-Pb isotope dilution-thermal ionization mass spectrometry (ID-TIMS) dates (Cary, 1990). The Cascade
River Schist likely underwent a high-pressure metamorphic event at the same time as the Napeequa Schist based on local kyanite and staurolite replacing andalusite and core to rim zoning in garnet that indicates increases in pressures of ~6 kbars (Brown et al., 1994; McShane, 1992). The metamorphic grade of the Cascade River Schist in the crystalline core increases from greenschist to upper-amphibolite facies from NW to SE (Brown et al., 1994).

The Skagit Gneiss in the north central Chelan block is exposed in a ~10 km wavelength NW-SE trending antiform that is bound by the Straight Creek and Ross Lake fault zones to the west and northeast, respectively (Figure 2). It was metamorphosed to upper-amphibolite facies conditions and consists of tonalitic orthogneiss with lesser amounts of amphibolite, calc-silicate rock, biotite paragneiss, and rare metapelite and mafic peridotite (Haugerud et al., 1991; Misch, 1966; Tabor et al., 1989, 2003). Within the north central Skagit Gneiss, both orthogneiss and paragneiss are migmatitic (Gordon, Bowring, et al., 2010; Misch, 1966; Whitney, 1992b). The orthogneiss crystallized from circa 90 to 45 Ma (Haugerud et al., 1991; Mattinson, 1972; Miller & Bowring, 1990; Miller et al., 2016), and metamorphism, deformation, and partial melting occurred from circa 71 to 45 Ma (Gordon, Bowring, et al., 2010). Previous workers have proposed several potential protoliths based on similarities in lithology for the metasedimentary material within the Skagit Gneiss, including the Cascade River Schist (Brown et al., 1994; Miller et al., 1994; Tabor et al., 2003) and/or the Napeequa Schist (Misch, 1968; Tabor et al., 2002). In addition to these units, we investigate other potential protoliths that are presently exposed adjacent to the North Cascades arc.

2.2. Units Surrounding the North Cascades

Surrounding the crystalline core of the North Cascades are sedimentary basins that formed before and during Cretaceous to Eocene arc activity. These basins include weakly to nonmetamorphosed units that were located in backarc (Methow terrane), accretionary wedge (western mélangé belt), and forearc (northwest Cascade thrust system and Nanaimo Group) regions during the Late Cretaceous.

The Methow terrane is located east of the crystalline core and is a thick (~15–20 km), Jurassic to Early Cretaceous sequence of sedimentary and subordinate volcanic material. It is interpreted to have formed as a forearc basin (Barksdale, 1975; Coates, 1974) but reached a backarc position with respect to the North Cascades by circa 91 Ma (Miller, 1994). The detrital zircon signature of the Jurassic Methow section is characterized by unimodal peaks between 170 and 150 Ma (Sauer et al., 2017), whereas the Cretaceous strata have distinctive bimodal age peaks at circa 115 and 160 Ma with very minimal (<1%) input from cratonic sources (DeGraaff-Surpless et al., 2003; Surpless et al., 2014).

The northwest Cascades thrust system (NWCS) is composed of a stack of fault-bounded nappes located to the west of the Straight Creek fault zone. The assemblage of the nappe stack is loosely bracketed between the circa 114 Ma maximum depositional age of the youngest nappe component (Brown & Gehrels, 2007) and the circa 57 Ma unconformable deposition of the Chuckanut Formation on top of the nappe stack (Eddy et al., 2015), but the majority of thrusting is thought to have occurred in the Late Cretaceous (circa 100–84 Ma) (Brandon et al., 1988; McGroder, 1991; Tabor, 1994). The nappes are dominantly composed of immature clastic strata related to arc activity (Brandon et al., 1988) and have unimodal or bimodal Mesozoic detrital zircon age peaks (Brown, 2012; Brown & Gehrels, 2007). However, the Yellow Aster Complex and Bell Pass mélangé within the nappe stack are characterized by Paleozoic and older detrital zircons (Brown, 2012; Brown & Gehrels, 2007; Schermer et al., 2015).

The Nanaimo Group is outboard of and contains clasts interpreted to be derived from the NWCS (Brown, 2012). It consists dominantly of Late Cretaceous marine and nonmarine clastic sediments deposited in a foreland basin to the thrust system and to the Coast Plutonic Complex (Brandon et al., 1988; Brown, 2012; Mustard et al., 1995). Basin subsidence began during the Turonian, and pre-mid Campanian (circa 80–72 Ma) Nanaimo strata are characterized by a Jurassic to Cretaceous detrital zircon signature (Mahoney et al., 2014; Matthews et al., 2017; Mustard et al., 2006). In comparison, Nanaimo strata younger than circa 80–72 Ma have a mix of arc-related and Proterozoic dates (Mahoney et al., 2014; Matthews et al., 2017; Mustard et al., 2006). The appearance of Proterozoic zircons in the Late Cretaceous strata indicates that fluvial systems transported cratonic material west of the arc by mid-Campanian time (Mahoney et al., 2014). The western mélangé belt (WMB) is an accretionary complex also located west of the Straight Creek fault zone. The WMB is dominantly composed of a weakly metamorphosed argillite matrix with blocks of
marble, metagabbro, arkosic sandstone, metadiabase, and chert (Tabor et al., 1993, 1989). Sandstones from the WMB have a mix of Mesozoic and Proterozoic dates (Brown, 2012; Dragovich et al., 2009; Sauer et al., 2017), with the relative abundance of Proterozoic detrital zircons increasing with younger maximum depositional ages (Sauer et al., 2017).

### 2.3. Margin-Parallel Translation Hypotheses

Analogues to the sedimentary material adjacent to the North Cascades core are exposed along the present-day North American plate margin, from Southern California to Alaska. Multiple lines of evidence point to between ~2,300 and 700 km of margin-parallel translation during the Cretaceous for both arc-related igneous and sedimentary rocks in northwestern Washington and southern British Columbia (i.e., Beck, 1976; Irving et al., 1985; Kim & Kodama, 2004; Miller et al., 2006; Wyld et al., 2006). Reconstructions based on known fault offsets place parts of the Coast Plutonic Complex-North Cascades arc, WMB, Nanaimo Group, and components of the NWCS ~700 km to the south at the latitude of southern Oregon (Wyld et al., 2006), whereas models based on paleomagnetic data require ~2,000–1,700 km of translation from the latitude of the southern Sierra Nevada for the Nanaimo Group and the Methow terrane (Enkin et al., 2001; Kim & Kodama, 2004; Krijgsman & Tauxe, 2006; Rusmore et al., 2013). Rocks in southwestern Oregon have been correlated with parts of the NWCS based on lithologic and detrital zircon similarities (Brandon et al., 1988; Brown, 2012). The presence of Archean zircons in the Nanaimo Group has been previously used to argue for (Housen & Beck, 1999) and against (i.e., Mahoney et al., 1999) large-scale margin-parallel translation. In addition, recent studies link the presence of two distinct Proterozoic age peaks from forearc and accretionary wedge rocks from Washington to Alaska (i.e., the WMB, Yakutat Terrane, and Nanaimo Group) to sedimentary sources located in Southern California and southwestern Laurentia (Garver & Davidson, 2015; Matthews et al., 2017; Sauer et al., 2017) or southern Idaho and northwestern Laurentia (Dumitru et al., 2016). The same pair of Proterozoic age peaks and similar detrital zircon signatures are also observed in coeval sedimentary units in the accretionary wedge (Franciscan Complex), forearc (Great Valley), and underplated trench sediments (Pelona-Orocopia-Rand schist) near the southern end of the Sierra Nevada (Chapman et al., 2016; Dumitru et al., 2016; Jacobson et al., 2011; Sharman et al., 2014). Based on these observations, rocks now present in northwestern Washington and southern British Columbia potentially originated between the latitude of southern Oregon and southern Sierra Nevada and were translated northward. Thus, forearc, backarc, and accretionary wedge units distributed along the continental margin and their sediment sources are also potential protoliths for the metasedimentary units within the North Cascades crystalline core.

### 3. Methods

Zircon has been shown to retain its isotopic signature through granulite-facies metamorphism (Cherniak & Watson, 2003; Hoskin & Schaltegger, 2003) and melting (e.g., Buys et al., 2014); thus, U-Pb and Hf-isotope analyses of detrital zircon are an applicable tool to characterize metasedimentary units in terms of their provenance. Eighty samples from within the crystalline core (Figure 3 and Table 1) were processed for zircon separates using standard mineral separation techniques, mounted in epoxy, and polished to expose the center of the grains at the University of Nevada, Reno. Samples included 11 samples from the Skagit Gneiss, 4 samples from the Napeequa Schist, and 2 samples from the Cascade River Schist (Figure 2b). The lithology and location of each sample is listed in Table 1. Zircon mounts were imaged using a cathodoluminescence (CL) detector on scanning electron microscopes located at the University of Nevada, Reno, and University of California, Santa Barbara. The CL images revealed internal textures and growth zones that were used to guide the analyses.

Both the U-Pb and Hf-isotope data were collected via laser ablation multicollector inductively coupled mass spectrometry. Zircon was first analyzed for U-Pb isotopes at University of California, Santa Barbara, using a ~15 μm laser spot. The U-Pb data typically revealed clusters of ages; representative grains from each main age population were subsequently targeted for Hf-isotope analyses. The Hf-isotope analyses were conducted at the Radiogenic Isotope and Geochronology Laboratory at Washington State University. For the Hf-isotope analyses, a ~40 μm laser spot was placed over the previous U-Pb ablation pit. Detailed methodology and description of results for both the U-Pb and Hf-isotope analyses can be found in Text S1 and Tables S1 and S2 in the supporting information (Bouvier et al., 2008; Fisher et al., 2011; Fisher, Vervoort, & Dufrane, 2014; Fisher, Vervoort, & Hanchar, 2014; Gehrels, 2012; Gehrels et al., 2008; Jackson et al., 2004; Paton et al., 2010;
Slama et al., 2008; Söderlund et al., 2004; Wiedenbeck et al., 1995; Woodhead & Hergt, 2005). A summary of the U-Pb and Hf-isotope results is presented below, in Table 1 and in Figures 3–6.

4. Results

Overall, the metasupracrustal rocks reached a variety of peak metamorphic conditions and have heterogeneous detrital zircon U-Pb and Hf-isotope characteristics. The Napeequa Schist and Skagit Gneiss samples have metamorphic mineral assemblages consistent with upper-amphibolite facies conditions, and some are migmatitic. One of 4 Napeequa Schist samples and 10 out of 11 Skagit Gneiss samples are melanosome from migmatitic outcrops. Both samples from the Cascade River Schist preserve lower-grade, likely greenschist-facies, assemblages.

Figure 3. U-Pb and Hf results with representative CL-images from (a) Napeequa amphibolites and an orthogneiss sheet and (b) the Cascade River Schist samples. In both Figures 3a and 3b, the red text and circle within the zircon-CL images correspond to the Hf-isotope composition and Hf-analysis spot, respectively, and white text and black circle correspond to the U-Pb results. In Figure 3b, the vertical lines correspond to calculated maximum depositional ages and 2 sigma uncertainties and the black points correspond to U/Th values for each analysis.
4.1. Napeequa Schist

Zircon U-Pb dates from the two garnet-hornblende gneisses (SK13-112 and SK13-136A) and one garnet-biotite schist (SK13-176) from the Napeequa Schist are dominantly Late Triassic (circa 260–220 Ma) (Figure 3a). Zircon grains have U/Th ratios mostly below ~3, are CL bright, and are either sector zoned or weakly oscillatory zoned. Migmatitic garnet-hornblende gneiss SK13-112 has a small Late Cretaceous population that yields a weighted mean 206U/238Pb age of 76 ± 1 Ma (MSWD = 1.9, mean square weighted deviation). Only zircons from this sample (SK13-112) were analyzed for Hf isotopes. Analyses from the Late Triassic population have near-depleted mantle Hf-isotope compositions (\(\varepsilon_{Hf}=+13\) to +10) and one Late Cretaceous zircon has an \(\varepsilon_{Hf}\) of +10 (Figure 3a).

A dioritic orthogneiss sheet that intrudes the Napeequa Schist (NC-771) yields dates between circa 79 and 69 Ma that form a circa 75 Ma population (Figure 3a). Zircon grains are dominantly oscillatory zoned; some have a thin, CL-bright rim. The Hf-isotope compositions of most zircon grains from this sample are between \(\varepsilon_{Hf}=+8\) and +5, with one more radiogenic value of +11 (Figure 3a).

4.2. Cascade River Schist

Two samples from the Cascade River Schist collected ~2 km apart (SK13-27 and SK16-05A) have very different zircon age distributions. The majority of U/Th ratios for Cascade River Schist zircons are below ~5. Quartz-plagioclase schist SK13-27 has multiple Mesozoic age peaks centered at circa 120, 165, 195, and 230 Ma and scattered Proterozoic ages (Figure 3b). Zircon grains have diverse CL textures including oscillatory, sector, and flat (unzoned) that do not correlate with age. Zircons from this schist have \(\varepsilon_{Hf}\) values that mostly plot between depleted mantle and chondritic uniform reservoir (CHUR), with the exception of one circa 97 Ma. In comparison, sample SK16-05A is a fine-grained (<100 \(\mu\)m) schist composed of quartz and potassium feldspar. Zircons from SK16-05A only yield Mesozoic dates, with a main age peak at circa 93 and a smaller population at circa 165 Ma (Figure 3b). Zircon grains from the circa 93 Ma population have patchy, weak oscillatory zoning, whereas the grains from the circa 165 Ma population are CL bright and finely oscillated. Both zircon populations have a similar range of \(\varepsilon_{Hf}\) values from +8 to +5 (Figure 3b).

Table 1
Summary of Sample Lithologies, Locations, and U-Pb Data

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<th>Sample name</th>
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<th>Location</th>
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<th>UTM N</th>
<th>No. of analyses</th>
<th>In situ zircon crystallization age(s)</th>
<th>Maximum depositional age</th>
<th>U-Pb zircon peaks (Ma)</th>
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<td>134 ± 8</td>
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<td>126</td>
<td>50 ± 1, 65 ± 1</td>
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Mineral abbreviations: bt, biotite; hbl, hornblende; grt, garnet; and sil, sillimanite. UTM zone 10 T. Weighted mean average of clusters of rim and core analyses interpreted to be from metamorphic zircon or zircon crystallized from partial melt and 2 sigma uncertainty. Weighted mean average of youngest cluster of >3 overlapping zircon core analyses with U/Th < 10 for metasedimentary samples and 2 sigma uncertainty.
4.3. Skagit Gneiss

Samples from the Skagit Gneiss are all characterized by the peak mineral assemblage of quartz + plagioclase + biotite ± garnet ± hornblende ± sillimanite. Cathodoluminescence images of Skagit Gneiss zircons reveal mostly oscillatory-zoned cores with lesser flat, ghost-zoned, and sector-zoned grains (Figures 4–6). Most zircons from the Skagit Gneiss samples have thin (~1–10 μm), unzoned rims that correspond to latest Cretaceous to Paleocene dates. Dates from zircon cores differentiate the Skagit Gneiss samples into three groups. Group 1 includes three samples that have dates with Paleocene to Proterozoic ages (NC-772, NC-774, and NC-775) (Figure 4). These samples all have large Late Cretaceous-Paleocene peaks between circa 72 and 65 Ma that correspond to both rim and core analyses; these analyses have higher U/Th ratios (>10) in comparison to most of the older analyses. Biotite paragneiss NC-772 also has circa 82 and 90 Ma peaks with low U/Th (Figure 4). The Group 1 samples also contain lesser amounts of Early Cretaceous (circa 140–120 Ma) and Late Jurassic (circa 170–150 Ma) zircons. Metapelite NC-775 and biotite paragneiss NC-774 have scattered dates older than circa 300 Ma that do not form distinct populations, whereas biotite paragneiss NC-772 has two Proterozoic populations around circa 1380 and 1800–1600 Ma. In all Group 1 samples, the Hf-isotope compositions for zircon grains older than circa 100 Ma have εHf values between those of depleted mantle and CHUR and Late Cretaceous zircons have a wide spread of εHf values from +10 to −30 (Figure 4).

Group 2 samples lack Proterozoic zircons and only have Middle Triassic to Paleocene dates. This group includes samples SK15-10B, SK13-34, NC-792, NC-777, and NC-778 (Figure 5). Three of five samples...
(SK13-34, NC-792, and NC-777) have peaks between circa 74 and 65 Ma that correspond to rim and core analyses and a spike in U/Th ratios. Group 2 samples have variable amounts of circa 130–110 Ma grains, but all have peaks between circa 175 and 140 Ma and smaller clusters of Late Triassic populations around circa 230 and 200 Ma. All analyses from Group 2 samples have $\epsilon_{Hf}$ values between +14 and +4 (Figure 5).

Group 3 samples are characterized by Late Cretaceous-Paleocene peaks and scattered Early Jurassic-Early Cretaceous analyses (NC-776, SK14-11A, SK14-11B, and SK14-05A) (Figure 6). Three of the samples have circa 68–65 Ma populations that have a range of U/Th ratios. Garnet amphibolite SK14-11A has a much larger circa 90 Ma population, with four zircons revealing circa 68 Ma dates. The $\epsilon_{Hf}$ values for zircons older than circa 75 Ma are dominantly between the depleted mantle and +8, with near-CHUR values observed for two circa 96 Ma analyses. Zircons younger than circa 75 Ma from biotite gneiss SK14-05A and siliceous gneiss SK14-11B are more variable and cover a wide range of $\epsilon_{Hf}$ values (+13 to +1 and +11 to $-3$, respectively) (Figure 6). In comparison, the circa 65 Ma zircons from metapelite NC-776 have a small range of $\epsilon_{Hf}$ values from +10 to +6, whereas the small circa 68 Ma population from sample SK14-11A has radiogenic $\epsilon_{Hf}$ values between +11 and +9.

5. Discussion

5.1. Interpretation of Protolith Ages

For sediment deposited in active arc settings, the youngest detrital zircon population, defined by $>3$ concordant analyses that overlap within 2 sigma uncertainty, is interpreted to be close to the age of deposition (the maximum depositional age (MDA)) (Dickinson & Gehrels, 2009). However, zircons in high-grade metamorphic rocks are commonly complicated and may contain both an inherited (detrital origin) core and younger rim growth related to anatexis, metamorphism, and/or the influx of fluids (in situ origin) (Chen et al., 2010; Fraser et al., 1997; Hoskin & Black, 2000; Roberts & Finger, 1997). Given these potential complications, we used the following criteria to separate zircons of detrital versus in situ origin: (1) U/Th ratios $>10$ are suggestive of zircon crystallized under metamorphic conditions as Th is likely taken up by other accessory phases such as...
monazite that also grew during metamorphism (e.g., Schaltegger et al., 1999); (2) rim growth is likely related to a younger thermal event, and cores are detrital; and (3) the dates are in situ if they are within error or younger than melt crystallization ages from the same outcrop. The analyzed migmatitic samples from the Skagit Gneiss and Napeequa Schist all show significant populations of Late Cretaceous to Paleocene zircons. Within the Skagit Gneiss migmatites, the circa 74–65 Ma zircons generally have elevated U/Th ratios and the majority are rim analyses. Gordon, Bowring, et al. (2010) showed that melt crystallization occurred by circa 69 Ma at the Gorge Lake locality (same outcrop as metapelite NC-776), by circa 66 Ma in the Sourdough Mountain locality (same outcrop as metapelite NC-792), and by circa 54 Ma at John Pierce Falls (same outcrop as metapelite NC-777 and biotite gneiss SK14-05A). These melt crystallization results are either younger or are within error of the major Late Cretaceous zircon age peaks that correspond to U/Th > 10 and that are rim analyses. Metamorphism likely immediately proceeded or was coeval with melt crystallization within the crystalline core; therefore, these new results suggest that the Skagit metasedimentary rocks reached depth by circa 74–65 Ma within the northern Chelan block. Within the Napeequa Schist, there is also evidence for metamorphism and/or melt crystallization during the Late Cretaceous. Migmatitic amphibolite SK13-112 revealed a cluster of dates from circa 77 to 67 Ma (Figure 3a), which are thus likely related to crystallization of leucocratic material within the amphibolite or minor metamorphic growth.

Figure 6. U-Pb and Hf-isotope results from the Skagit Gneiss Group 3 samples with representative CL-images.
Excluding the metamorphic and melt crystallization ages, the youngest three overlapping U-Pb analyses that defined the MDAs typically had U/Th < 10, were concordant, and were analyses of zircon cores. The MDA estimates for the Skagit Gneiss metasedimentary rocks are dominantly Early to Late Cretaceous (circa 134–96 Ma); however, one sample has a younger Late Cretaceous (circa 79 Ma) MDA (Figures 4 and 5 and Table 1). Samples NC-792, NC-777, NC-775, and NC-774 have several circa 100 Ma analyses that do not overlap within error; however, these results may suggest these samples have younger (mid-Cretaceous) MDAs. For the Napeequa samples, the protolith basalts of the amphibolites have a mid-Triassic (circa 240–230 Ma) age.

Schist SK13-27 from the Cascade River Schist does not contain zircon interpreted to be of in situ origin and likely has a sedimentary protolith that was deposited in the middle Cretaceous at circa 97 Ma. The protolith of siliceous schist SK16-05A is enigmatic. It contains ~50% quartz and ~50% K-feldspar; K-feldspar is rarely observed in the crystalline and accreted rocks of the North Cascades. In addition, the observed narrow age peaks likely reflect either an igneous age distribution or detrital zircons derived from localized sources (Figure 3b). Based on the lithology and zircon ages, the protolith can be interpreted as either a rhyolite or a fine-grained sedimentary rock. A rhyolitic protolith does not fit with regional Late Cretaceous volcanism (i.e., Tabor et al., 2003). Alternatively, the K-feldspar could be related to metasomatic replacement of plagioclase feldspar in a fine-grained sedimentary rock. Regardless of protolith lithology, the youngest ages in the sample correspond to a formation (either volcanic crystallization or depositional) age of circa 91 Ma.

5.2. Detrital Zircon Signatures of the Metasedimentary Rocks

Two Skagit Gneiss samples from Group 1 (NC-774 and NC-775) and one Cascade River Schist phyllite (SK13-27) reveal similar detrital zircon results, with several Mesozoic age peaks, scattered grains older than circa 300 Ma, and similar Hf-isotope patterns (Figures 3b and 4). The MDAs for the Skagit samples are older (circa 134 and 124 Ma) in comparison to the Cascade River Schist sample (circa 97 Ma); however, as mentioned above, the Skagit samples have concordant circa 100 Ma analyses with low U/Th, which may correspond to a younger (mid-Cretaceous) MDA. In comparison, samples from the Skagit Gneiss Group 2 were all deposited within a narrow window from circa 121 to 108 Ma and do not contain grains older than circa 250 Ma or zircons with unradiogenic Hf-isotope compositions (Figure 5).

All of the Skagit and Cascade River Schist samples have similar Mesozoic peaks. The circa 165–160 Ma peaks are common in all Cordilleran arc batholiths, such as the Coast Plutonic Complex and Sierra Nevada batholith (Chapman et al., 2012; Gehrels et al., 2009); however, the circa 130–120 Ma, 195 Ma, and 230 Ma peaks are rarer within Cordilleran arc belts (Figure 7). A lull in magmatism in Cordilleran arc systems occurred from circa 140 to 120 Ma (Gehrels et al., 2009; Paterson & Ducea, 2015), but magmatism occurred during this time in the central Sierra Nevada batholith (i.e., Fine Gold Intrusive Suite) (Bateman, 1992; Lackey et al., 2012). In addition, the Cascade River Schist and some of the Skagit Group 2 samples have older Mesozoic peaks at circa 205–195 and 230 Ma. Potential sources of the circa 205–195 Ma peak are scattered along the North American western margin and include the Wrangellia terrane of Vancouver Island (DeBari et al., 1999), the Black Rock terrane of northwestern Nevada (Quinn et al., 1997), and the Mojave terrane of southwestern Laurentia (Needy et al., 2009). For the circa 230 Ma peak, Triassic sediment sources are present in the Sierra Nevada and Mojave regions (Chapman et al., 2012; Needy et al., 2009), but they predate magmatism in the Coast Plutonic Complex (Gehrels et al., 2009). Moreover, the Triassic Marblemount-Dumbell plutonic belt is adjacent to the Cascade River Schist and may have been a source for the circa 230 Ma zircon population.

Despite the similarity in Mesozoic ages within the samples, there are differences in the εHf values for Mesozoic zircons between the groups of metasedimentary samples. The εHf values from the Skagit Group 1 and Cascade River Schist samples are mostly intermediate and plot between CHUR and the depleted mantle but have lower and/or negative values at circa 200, 150, and 100 Ma (Figures 3b and 4). The excursions to less radiogenic εHf values around circa 150 and 100 Ma correspond with lower whole-rock εNd values in coeval plutonic rocks of the Sierra Nevada; the lower whole-rock εNd values are interpreted to be related to assimilation of supracrustal rock (DeCelles et al., 2009). These similarities in the detrital zircon U-Pb and Hf-isotope signature indicate similar sediment provenances for at least parts of the Cascade River Schist and Skagit Group 1 metasediments. In comparison, the εHf values of the Mesozoic zircons from the Group 2 samples are more radiogenic: an εHf signature of ≥+9, with the exception of three analyses (εHf = +7 – +4) from sample SK13-34 (Figure 5). This radiogenic-isotope signature likely reflects an arc source that did not incorporate significant amounts of older, continental material and is thus distinctly different from the less radiogenic
zircons of the same age range observed in the Skagit Group 1 and Cascade River Schist samples. In all Skagit samples, the range of Hf-isotope signatures for Late Cretaceous in situ zircons is interpreted to be a result of dissolution and reprecipitation within the samples and likely reflects the variable Hf-isotope composition of the detrital zircons (Chen et al., 2010).

The other Skagit Gneiss Group 1 sample, biotite paragneiss NC-772, has a MDA, detrital zircon signature, and Hf-isotope compositions that distinguish it from all other samples. It has the youngest MDA (circa 79 Ma), two Late Cretaceous peaks (circa 90 and 82 Ma), smaller Jurassic populations, and Proterozoic peaks centered between circa 1.8 and 1.6 Ga and at 1.38 Ga (Figure 4). The Late Cretaceous populations correspond to pulses of magmatism observed all along the continental margin from the Mojave to the Coast Plutonic Complex (Figure 7) and have a large range of $\varepsilon_{Hf}$ values (+10 to −22) (Figure 4). These results are between values expected for Late Cretaceous arc magmas and reworked Proterozoic crust. There are two potential localities where Late Cretaceous plutons intrude Proterozoic crust: southwestern Laurentia, where “anorogenic granites” intruded Proterozoic basement in the Mojave desert, and northwestern Laurentia, where the southern Idaho batholith intruded the Lemhi Subbasin of the Belt Supergroup (Garver & Davidson, 2015; Gaschnig et al., 2011; Sauer et al., 2017) (Figure 7). For the Proterozoic zircons, the Hf-isotope data from both northwestern and southwestern Laurentia cover a similar range and do not differentiate between the two sources (cf. Goodge & Vervoort, 2006; Stewart et al., 2010; Wooden et al., 2012; Gaschnig et al., 2013). Thus, the U-Pb and Hf-isotope signature of the Skagit NC-772 sample can be connected to either northwestern or southwestern Laurentian provenances.

### 5.3. Potential Protoliths for Metasedimentary Rocks

The U-Pb and Hf results demonstrate variation in detrital zircon signature for metasedimentary units across the northern North Cascades crystalline core. Potential source affinities of these metasedimentary rocks can be deduced through comparison with Cretaceous potential protoliths preserved in the forearc (NWCS, Nanaimo Group), backarc (Methow terrane), and the clastic portions of the accretionary wedge (western mélangé belt) adjacent to the North Cascades. Detrital zircon data from the western mélangé belt (Brown, 2012; Dragovich et al., 2014, 2009, 2015, 2016; Sauer et al., 2017), NWCS (Brown & Gehrels, 2007), Nanaimo

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**Figure 7.** Plot of age and Hf-isotope data for major Cordilleran arc segments modified from Sauer et al. (2017). Age data sources: Coast Plutonic Complex, Gehrels et al. (2009); North Cascades, Miller, Paterson, et al., 2009; Idaho Batholith, Gaschnig et al. (2009); Sierra Nevada, Chapman et al. (2012); Mojave, Needy et al. (2009). Hafnium-isotope data sources: Coast Plutonic Complex, Cecil et al. (2011); North Cascades, Matzel et al. (2008) (calculated from whole-rock Nd data using the formula $\varepsilon_{Hf} = 1.36 \cdot \varepsilon_{Nd} + 2.95$); Idaho Batholith, Gaschnig et al. (2011); Sierra Nevada, Lackey et al. (2012) and Shaw et al. (2014); and Transverse Ranges, Barth et al. (2016).
Group (Brown, 2012; Mahoney et al., 1999; Matthews et al., 2017), and Methow terrane (DeGraaff-Surpless et al., 2003; Surpless et al., 2014) were compiled and statistically compared to the Skagit Gneiss and Cascade River Schist metasediments by multidimensional scaling (MDS) using the R package provenance (Vermeesch et al., 2016). Multidimensional scaling graphically ranks the Kolgrov-Smirnov dissimilarities in the age distribution of each sample to all other samples on a dimensionless Shephard plot (Borg & Groenen, 2005; Kruskal & Wish, 1978; Vermeesch, 2013) (Figure 8). Zircon analyses interpreted to be metamorphic or crystallized in a melt are not included.

The Skagit Gneiss and Cascade River Schist metasedimentary samples plot among the individual clusters for different potential sources found adjacent to the North Cascades arc. The samples are most similar to the WMB, parts of the Nanaimo Group, and the southern Methow terrane (Figure 8). They are the least similar to the NWCS, which is dominantly characterized by Late Jurassic and earliest Cretaceous sediments, and the northern Methow terrane, which has a higher proportion of mid-Cretaceous (circa 115 Ma) to Late Jurassic (circa 160 Ma) zircon in comparison to the southern Methow terrane (Surpless et al., 2014).

Southern Methow Cretaceous sediments are dominated by a distinct bimodal detrital zircon distribution with peaks at circa 160 and 115 Ma and MDAs less than circa 115 Ma (DeGraaff-Surpless et al., 2003; Surpless et al., 2014). The Skagit Gneiss samples do not have this typical bimodal Methow detrital zircon signature (Figure 5), and the Hf signature of Jurassic Methow detrital zircons covers a larger range in comparison to the Skagit samples (Figure 9a). Thus, despite the overlap on the MDS plot, the Skagit Group 2 samples likely do not correlate with a Methow terrane protolith.

Pre-Campanian Nanaimo Group and WMB samples are characterized by a detrital zircon signature with two to three Mesozoic peaks and no significant pre-Mesozoic age populations (Matthews et al., 2017; Sauer et al., 2017); this pattern is similar to that observed in Skagit Group 2 samples. In comparison, significant circa 1.7 and 1.4 Ga Proterozoic peaks appear in younger (less than circa 80–72 Ma) Nanaimo Group and WMB strata (Mahoney et al., 2014; Matthews et al., 2017; Sauer et al., 2017). The detrital zircon pattern of the post-
Campanian Nanaimo and WMB sediments correlate with the signature observed in the circa 79 Ma Skagit Gneiss sample (NC-772, Figure 4). However, most of the Skagit Gneiss metasediments have older MDAs than the Nanaimo Group strata (Mustard, 1994). If the Nanaimo Group was the source for the Skagit metasedimentary rocks, it would have to be coupled with an Early Cretaceous source, which is not preserved adjacent to the North Cascades.

In comparison, the WMB contains sedimentary components with MDAs between circa 152 and 72 Ma (Dragovich et al., 2016; Sauer et al., 2017). A sandstone from the WMB with a circa 109 Ma MDA has an Hf-isotope signature that aligns generally with paragneisses NC-774 and NC-775 from the Skagit Gneiss (Sauer et al., 2017) (Figure 9b). In comparison, the circa 200 Ma and Precambrian zircons from the Cascade River Schist schist have a less radiogenic composition than the WMB zircons of similar ages. Comparison between the circa 79 Ma Skagit biotite paragneiss (NC-772) and the circa 72 Ma arkosic sandstone of the WMB reveals similar Hf-isotope compositions for all zircon populations (Figure 9c).

Based on the similarities in the detrital zircon age and Hf-isotope data, the protolith of the Skagit Gneiss metasedimentary rocks and the Cascade River Schist likely originated in a forearc basin and/or accretionary complex, similar to the Nanaimo Group and/or the WMB. The Nanaimo Group and WMB, along with the North Cascades arc, are interpreted to have formed between ~700 and 2,300 km to the south (Jett & Heller, 1988; Matthews et al., 2017; Sauer et al., 2017; Wyld et al., 2006); thus, potential protoliths of the Skagit Gneiss metasediments also include sediments in analogous accretionary wedge and forearc rocks between the latitudes of Southern California and Oregon.

5.4. Incorporation Into the Crystalline Core

The North Cascades magmatic arc was built upon an amalgamation of accreted terranes, including the Napeequa Schist. This is reflected by the lack of prearc rocks with a continental affinity (Miller et al., 1993; Tabor et al., 1989). Based on in situ age peaks (circa 74–65 Ma), the protolith of the Skagit metasedimentary units reached depth by the latest Cretaceous or Paleocene, immediately following or coeval with the burial of
the Napeequa and Cascade River Schist in the study area. As described above, the metasedimentary rocks exposed in the northern Chelan block are correlated with accretionary wedge (WMB) and forearc (Nanaimo Group) deposits that formed during Cretaceous arc activity. Thus, supracrustal rocks were likely incorporated by (1) relamination, (2) underplating, or (3) underthrusting of forearc rocks.

In a relamination scenario for the Skagit metasedimentary rocks, subducted sediment rises off of the subducting plate, undergoes partial melting, and is emplaced at the base of the crust (Behn et al., 2011; Hacker et al., 2011) (Figure 1d). The pattern of protolith age with depth associated with this process would be chaotic due to the nature of accretionary wedge sediments; however, melt crystallization and metamorphic ages should show a younging pattern with depth as sediment diapirs were potentially progressively emplaced. The Skagit Gneiss samples in the north-central Chelan block represent dominantly the same crustal level (e.g., Whitney, 1992a) and preserve a range of melt crystallization/metamorphic ages (circa 74–65 Ma) (Figure 10).

Furthermore, as the North Cascades magmatic arc crust is postulated to have been >55 km thick by circa 90 Ma (DeBari et al., 1998; Miller & Paterson, 2001), relaminated metasupracrustal rocks should have reached high-pressure (>16 kbars) conditions at the base of the arc crust. Skagit Gneiss metasedimentary rocks record peak pressures of 8–10 kbars, with no evidence of an earlier higher-pressure signature (Gordon, Whitney, et al., 2010; Whitney, 1992a). It is possible that an earlier higher-pressure assemblage was erased as these metasedimentary rocks resided in the midcrust during a period of extensive metamorphism, migmatization, and magmatism from circa 74 to 45 Ma (Gordon, Bowring, et al., 2010; this study), but many high-pressure terranes that have undergone significant retrogression still typically retain some evidence for their earlier high-pressure history (e.g., Ernst, 2001). There may be deeper, higher-pressure metasedimentary rocks that are currently not exposed; however, for the samples studied here, a relamination incorporation scenario is unlikely.

In contrast, sediment may have been assembled in the accretionary wedge and underplated as a thick package at the base of the arc crust (Figure 1c). This has been proposed for the Pelona-Orocopia-Rand schists of Southern California (Chapman et al., 2013; Grove et al., 2003; Jacobson et al., 2011) and for the Swakane Gneiss (Matzel et al., 2004). Matzel et al. (2004) argued, however, that an underplating scenario is unlikely for the Swakane Gneiss as this process usually involves a shallowly dipping slab and a high-P and low-T...
metamorphic signature. Evidence for this is lacking in the regional structural history of the northwestern Cordillera (Miller et al., 1992); however, the components of North Cascades arc may have been located much farther south during the time of sediment incorporation based on paleomagnetic, paleofloral, and detrital zircon data (i.e., Miller et al., 2006; Rusmore et al., 2013; Sauer et al., 2017). In addition, the protracted metamorphic and partial melting history of the North Cascades core may have erased the low-T metamorphic signature. However, similar to the relamination model, the metasedimentary rocks should record a high-pressure signature due to the estimated ~55 km thickness of the North Cascades crust; therefore, underplating is also not a likely mechanism for the 8–10 kbar metasedimentary rocks exposed in the Skagit Gneiss.

Another potential mechanism for incorporation of sediment is the underthrusting and imbrication of forearc and/or accretionary wedge sediments along reverse faults in the upper (i.e., continental) plate of the subduction system (Figures 1a and 11). This scenario is consistent with both Cretaceous regional transpression and observed contractional structures (Brown, 1987; Paterson et al., 2004; Umhoefer & Miller, 1996) and the detrital zircon similarities among the Nanaimo, the WMB, and the Skagit and Cascade River metasedimentary rocks. Furthermore, the peak-metamorphic assemblages of the Skagit Gneiss (Whitney, 1992a) are consistent with a geothermal gradient typical of an active continental magmatic arc (Matzel et al., 2004). Thus, underthrusting of interclated forearc and accretionary wedge sediments into the core of the arc system (Figure 11) is consistent with both the regional geologic history and peak metamorphic conditions observed in the Skagit Gneiss.

Incorporation of the youngest sample, biotite paragneiss NC-772, may provide an estimate of the maximum rate of sediment underthrusting. The circa 79 Ma MDA coupled with circa 72 Ma in situ zircon ages indicates that the sedimentary protolith was transferred from the surface to ~30 km depth in ~7 Ma (i.e., ~4.3 mm/yr). This vertical displacement rate is within reason based on shortening rates in modern forearc regions (Mazzotti et al., 2002).

5.4.1. Relationship Between Sediment Incorporation and Magmatic Pulses

The circa 96–84 Ma main pulse of magmatism in the Chelan block coincided with the incorporation of the Cascade River and Napeequa samples from this study in the north central Chelan block (Figure 11). Plutons associated with this magmatic event are characterized by whole-rock εNd(t) values between +6.3 and +4.6 (n = 4; Matzel et al., 2008). Zircon from garnet-hornblende gneiss SK14-11A with similar crystallization ages have more radiogenic, near-depleted mantle Hf-isotope compositions (i.e., εHf(t) = +14 to +10) (Figure 7).

Smaller pulses of magmatism occurred from circa 79 to 65 Ma (Miller, Paterson, et al., 2009). Plutons related to this magmatic pulse in the Chelan block are observed to have less radiogenic isotope compositions (εNd(t) = +4.9 to +3.8; n = 5) in comparison with the mid-Cretaceous pulse (Matzel et al., 2008). In addition, zircon grains with dates less than circa 75 Ma from samples interpreted to be of an igneous origin (i.e., SK14-11B, SK14-05A, NC-776, and NC-771) have intermediate Hf-isotope compositions (i.e., εHf(t) = +10 to +3) that are typically less radiogenic than circa 96–84 Ma analyses (Figure 8).

Overall, circa 74–65 Ma melt crystallization and metamorphism within the Skagit Gneiss and Napeequa Schist samples of this study overlapped with the Late Cretaceous magmatic pulse in the Chelan block. The observed shift in pluton- and zircon-isotope compositions toward less radiogenic values may indicate that partial melts...
of incorporated supracrustal material contributed to pluton bodies; however, more isotope and geochemical data from the circa 79–65 Ma plutons are needed to better understand the effects of the sediment incorporation on the plutonic history of the North Cascades.

5.5. Implications for Regional Geology

The new age data also help to refine the formational history of the Cascade River Schist and Napeequa Schist. Field relations between the Napeequa and the Cascade River Schist are complex—the units are locally observed to be extensively imbricated and interfolded with each other (Brown et al., 1994; Miller et al., 1994). The age of the Napeequa Schist is bracketed by correlation with the Paleozoic to Jurassic Bridge River-Hozomeen Complex (Monger, 1986) and the circa 96 Ma intrusion of the Sulphur Mountain pluton (Walker & Brown, 1991). Results from this study demonstrate that amphibolites likely have a circa 240–230 Ma protolith age, indicating that parts of the Napeequa in the northern Chelan block are Triassic in age. Zircons from the Cascade River Schist samples of this study record Late Cretaceous ages and conflict with the previous interpretation that the Cascade River Schist is entirely a Late Triassic forearc or intra-arc basin related to the Dumbell and Marblemount plutons (Tabor et al., 1989). These samples from this study are structurally above a circa 220 Ma Cascade River Schist metatuff (Cary, 1990) and suggest that parts of the Cascade River Schist were likely deposited unconformably and/or tectonically juxtaposed with the Triassic components of the Cascade River Schist and Napeequa Schist in the Late Cretaceous (Figure 11). The Late Cretaceous components of the Cascade River Schist formed close to or coeval with the circa 90–88 Ma intrusion of the Eldorado orthogneiss and subsequent crustal loading, due to thrusting and/or pluton emplacement, and upper-amphibolite facies metamorphism (Brown et al., 1994; Miller et al., 1993) (Figure 11).

6. Conclusions

The metasedimentary material of the northern North Cascades crystalline core was likely sourced from the accretionary wedge and/or forearc region based on detrital zircon age and HF-isotope signatures. The protoliths of these metasedimentary rocks were likely deposited during the Early Cretaceous to Late Cretaceous (circa 134–79 Ma) and were incorporated at depth within the arc by the Late Cretaceous to early Paleocene (circa 74–65 Ma). Correlations of the accretionary wedge and forearc units with the Skagit Gneiss and Cascade River Schist and the observed peak pressures of 8–10 kbars imply sediment incorporation by underthrusting of forearc and/or accretionary wedge sediments. Additionally, these new data connect the metasedimentary rocks of the crystalline core to distinct detrital zircon signatures found along the continental margin.

Inferred time scales from deposition to burial of sediment now exposed as the Skagit Gneiss (circa 134–79 to 74–65 Ma, respectively) and Cascade River Schist (circa 97–91 to 76 Ma, respectively) align with circa 96–45 Ma arc magmatism in the North Cascades crystalline core and, more specifically, a pulse of circa 79–65 Ma magmatism within the north central North Cascades (Gordon, Bowring, et al., 2010; Haugerud et al., 1991; Mattinson, 1972; Miller & Bowring, 1990). This correlation in timing suggests that incorporation of sediment immediately preceded the magmatic flare-up. The metasedimentary rocks of the crystalline core provide evidence supporting underthrusting of sediment that resulted in the transfer of supracrustal rocks from the surface to midcrustal depths at rates of up to ~4 mm/yr.

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