New geochemical and geochronological insights on forearc magmatism across the Sanak-Baranof belt, Southern Alaska: A tale of two belts

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ABSTRACT

The Sanak-Baranof belt (SBB) includes a series of near-trench plutons that intrude the outboard Chugach-Prince William (CPW) terrane over ~2200 km along the southern Alaskan margin. We present new petrological, geochronological, and geochemical data for co-magmatic microgranitoid enclaves and granitoid rocks from the Crawfish Inlet (~53-47 Ma) and Krestof Island (~52 Ma) plutons on Baranof and Krestof Islands, as well as the Mt. Stamy (~51 Ma) and Mt. Draper (~54-53 Ma) plutons and associated mafic rocks that intrude the Boundary block at Nunatak Fiord near Yakutat. These data suggest that intrusion of the SBB plutons is actually a tale of two distinct belts: a western belt with crystallization ages that young systematically from west to east (63 to 56 Ma), and an eastern belt with crystallization ages ranging from 55 to 47 Ma, but with no clear age progression along the margin. Hf isotope analyses of magmatic zircon from the western SBB become increasingly evolved towards the east with εHf_t = 9.3±0.7 on Sanak Island versus εHf_t = 5.1±0.5 for the Hive Island pluton in Resurrection Bay. The Hf isotope ratios of eastern SBB rocks also vary systematically with age but in reverse, with more evolved ratios in the oldest plutons (εHf_t = +4.7±0.7) and more primitive ratios in the youngest plutons (εHf_t = +13.7±0.7). We propose that these findings indicate distinct modes of origin and emplacement histories for the western and eastern SBB, and that the petrogenesis of eastern SBB plutons (post 55-57 Ma) are associated with an increasing mantle component supplied to the youngest eastern SBB magmas. These plutons undoubtedly reveal important information about offshore plate geometries and a dynamic period of plate reorganization at ~55-57 Ma, but a clearer picture of the tectonic setting that facilitated these SBB intrusions cannot be resolved until the amount and significance of lateral translation of the CPW terrane is better understood.

INTRODUCTION

Over the past ~200 Ma, the southern Alaskan continental framework has been incrementally constructed and modified by a complex history of accretion, strike-slip faulting, metamorphism, and plutonism (Hudson et al., 1979; Plafker et al., 1994; Colpron et al., 2007; Garver and Davidson, 2015). Accretion of the outboard Chugach-Prince William (CPW) terrane to the Wrangellia composite terrane (Wrangellia, Peninsular, and Alexander terranes) resulted in one of the largest accretionary complexes in the world (Fig. 1), with the majority of its growth occurring during Late Cretaceous and early Paleocene time (Plafker, 1990; Plafker et al., 1994). This intensive accretionary period was concomitant with dextral strike-slip translational displacement of the outboard CPW terrane along the ~2000 km long Border Ranges Fault system (MacKevett and Plafker, 1974; Pavlis et al., 1988, 2003; Little and Naeser, 1989; Pavlis and Roeske, 2007; Fig. 1), further complicating paleo-reconstructions. Resolving the dynamics of this accretionary episode—and constraining the paleogeography of the outboard CPW terrane in particular—remain outstanding questions in Cordilleran tectonics.

There are several competing hypotheses concerning the paleo-position and formation of the CPW terrane along the Cordilleran margin (see Fuston and Wu, 2021 for review). The first, termed the 'Resurrection plate hypothesis,' posits that the Sanak-Baranof belt (SBB) intruded the CPW terrane more or less *in situ* (Haeussler et al., 2003). In this scenario, the series of biotite tonalite, granodiorite, and granite plutons that intrude the CPW terrane over ~2200 km are explained by the eastward migration of the Kula-Resurrection spreading ridge, associated with the long-since subducted Resurrection plate, and the near-trench plutons in the Pacific Northwest were formed from interaction with the Resurrection-Farallon ridge (Haeussler et al., 2003). This hypothesis requires that ridge trench interactions occurred simultaneously in two different places, and it requires that paleomagnetic data from host rocks of the CPW terrane be rejected. In the alternative 'Baranof-Leech River' hypothesis (Cowan, 1982; 2003), the CPW terrane formed far to the south, making the schist and turbidites of the CPW terrane at Baranof Island contiguous with the Leech River schist exposed on southern Vancouver Island (Fig. 1). In this scenario, the anomalous near-trench plutons that intrude the CPW terrane were all generated by a single ridge to the south. Following intrusion, some of these plutons experienced northward transport along with the CPW terrane north of the Kula-Farallon ridge positioned at ~48 to 49 °N paleolatitude (Cowan, 1982, 2003). Other ridge-trench subduction models are similar in scope but differ in their proposed Kula-Farallon plate configurations, and in their possible involvement with the Yellowstone hotspot (Engebretson et al., 1985; Bradley et al., 2003; Clennett et al., 2020; Fuston and Wu, 2021; Geen and Canil, 2023).

Two important and influential paleomagnetic data sets emerged early on that bear directly on the paleo-position of the CPW terrane and, by implication, the SBB plutons intruding it. One shows that pillow basalts of the Paleocene Ghost Rocks Formation (part of CPW) on Kodiak Island experienced 25 ± 7° poleward displacement (Plumley et al., 1983; Moore et al., 1983), and another suggested pillows and sheeted dikes of the Prince William terrane exposed on the Resurrection Peninsula (Kenai Peninsula) had experienced 13 ± 9° poleward displacement (Bol et al.,1992). Thus, the ensuing ridge-trench intersection models that considered the paleomagnetic data suggested that SBB plutonism occurred well to the south of Alaska, followed by coastwise translation of the CPW terrane and SBB following pluton emplacement (e.g., Bradley et al., 1993; Sisson and Pavlis, 1993; Haeussler et al., 1995; Pavlis and Sisson, 1995).

Regardless of which hypothesis is favored for the CPW terrane, there are several key observations and assumptions embedded within essentially all previous studies considering the SBB and its tectonic implications. These include that: (1) the SBB plutons are time-transgressive and young systematically towards the east (e.g., Bradley et al., 2003; Farris and Paterson, 2009); (2) the same tectonic mechanism (crustal anatexis in a thickened accretionary wedge, and/or ridge-trench intersection and slab window development) was responsible for generating the SBB plutons (Marshak and Karig, 1977; Hudson et al., 1979); and (3) through these lines of reasoning, the SBB encompasses a coherent set of petrogenetically related rocks across the entire ~2200 km belt, but is petro-tectonically distinct from other near-trench intrusive rocks farther to the south (e.g., rocks intruding the Leech River Schist on southern Vancouver Island, see Groome et al., 2003; Seyler et al., 2022; Geen and Canil, 2023). These assumptions persist despite the near-complete absence of geochronological and/or geochemical data available for SBB intrusive rocks spanning >400 km between the Boundary block at Nunatak Fiord near

Yakutat and Baranof Island at the purported easternmost periphery of the belt. Another critical source of uncertainty is the amount of movement by strike-slip displacement *within* the CPW terrane itself, which would obscure the original distance between SBB plutons at the time of intrusion. For example, there are indications that this offset may be particularly pronounced for SBB plutons in the Boundary block, which is west of the Fairweather fault (Fig. 1; Schartman et al., 2019).

Here we present new petrological, geochemical, and geochronological data for magmatic enclaves and their host granitoids from the Crawfish Inlet and Krestof Island plutons on Baranof and Krestof Islands near Sitka, Alaska. We present this detailed characterization of Crawfish Inlet and Krestof Island intrusive rocks alongside a comparable dataset for the Mt. Stamy and Mt. Draper plutons and affiliated mafic rocks that intrude the Boundary block at Nunatak Fiord near the town of Yakutat, Alaska. We also report new U-Pb crystallization ages and εHf_t analyses of magmatic zircons from select SBB intrusive rocks west of the Boundary Block to facilitate comparisons on a belt-wide scale, as well as new εHf_t measurements on detrital zircons collected from the CPW sedimentary rocks that host the near trench SBB plutons across the belt.

REGIONAL GEOLOGIC SETTING

The CPW terrane and outboard Yakutat microplate make up the extensive and complexly deformed Mesozoic to early Cenozoic accreted terranes that are now situated along the southern margin of Alaska (Fig. 1; Plafker et al., 1989, 1994; Bradley et al., 2003; Colpron et al., 2007; Garver and Davidson, 2015). The CPW composite terrane encompasses both the Chugach and Prince William terranes and is composed largely (~90%) of Campanian-Maastrichtian to Eocene turbidites and oceanic metabasalts (Plafker et al., 1989, 1994; Farmer et al., 1993; Garver and

Davidson, 2015; Davidson and Garver, 2017). The primary turbidite facies[1] of the Chugach terrane (predominantly Campanian-Maastrichtian in age) stretch roughly 2200 km from Sanak Island in the west to Baranof Island in the east (Fig. 1; Plafker et al., 1994; Bradley et al., 2003; Gasser et al., 2012). The Paleocene-Eocene Prince William terrane, namely the Orca Group, has historically thought to have been exposed primarily in and around the Prince William Sound, but new U-Pb detrital zircon ages with Paleocene maximum depositional ages for metamorphosed turbidites extend the Prince William terrane farther east to southern Baranof Island (Fig. 1; Rick, 2014; Olson et al., 2017). Sandstone composition and zircon provenance is similar for turbidites of the Chugach and Orca Groups, and they are thus treated as one common unit (see discussion in Garver and Davidson, 2015). However, a primary difference between the two is that the Orca Group has significant packages of mafic volcanic rocks that appear to be locally associated with ophiolites (Lytwyn et al., 1997; Davidson and Garver, 2017). East and south of Prince William Sound, amphibolites (± garnet) are also common in the schists and gneisses of the Chugach Metamorphic Complex (CMC), which is the high-grade metamorphic equivalent of the CPW terrane (Sisson et al., 1989; Bruand et al., 2011, 2014).

The thick package of imbricated turbidites (structural thickness >30 km) that dominates the CPW terrane is thought to have formed in an accretionary complex adjacent to an active volcanic arc built on or adjacent to early Mesozoic basement rocks (Plafker et al., 1994; Haeussler et al., 2006; Garver and Davidson, 2015). Petrographic and geochemical evidence suggests the source of detritus for the turbidites was a progressively eroded magmatic arc (i.e., the inboard Coast Plutonic Complex), and that erosion and deep exhumation resulted in extensive sediment accumulation along the continental margin during the Late Cretaceous and early Paleocene

[1] In the literature this mainly includes the Shumagin Fm., Kodiak Fm., Valdez Group, and part of the Sitka Graywacke.

(Hollister, 1979; Dumoulin, 1988; Samson et al., 1991; Farmer et al., 1993; Plafker et al., 1994; Garver and Davidson, 2015). Analysis of sandstones from across the belt and ages of detrital zircon from those sandstones indicate broad homogeneity of the clastic materials (Zuffa et al., 1980; Dumoulin, 1988; Garver and Davidson, 2015). From a geochemical perspective, the turbidites of the CPW terrane are similar to the elemental and isotopic composition of its Coast Plutonic Complex granitic source (Samson et al., 1991; Farmer et al., 1993; Sample and Reid, 2003).

INTRUSIVE ROCKS OF THE EASTERN SBB

Our study focuses primarily on the Mt. Stamy, Mt. Draper, Krestof Island, and Crawfish Inlet plutons in the easternmost portion of the SBB in SE Alaska. We sampled the Crawfish Inlet pluton in particular detail (Fig. 2; Tables 1 and 2; Supplemental Table S1), with the goal of evaluating geochemical and geochronological characteristics within a single eastern SBB intrusive body. We also conducted investigations and sampling of various plutons from across the remainder of the SBB (mainly west of Yakutat), including the Sanak, Nagai, Aialik, Hive Island, Sheep Bay, McKinley Peak, and Novatak Glacier plutons (Fig. 1; Lempert et al., 2015; Arntson et al., 2017).

The Crawfish Inlet pluton intrudes the Cretaceous to Paleocene Sitka Graywacke and its metamorphic equivalent schist of Baranof Island ("Baranof schist;" Rick, 2014), and is exposed over 560 km^2 on southern Baranof Island (Fig. 2; Loney et al., 1975). The compositionally similar Redfish Bay pluton on the southern tip of Baranof Island is thought to be connected to the Crawfish at shallow depths, making this system one of the largest composite batholiths in the SBB (Loney et al., 1975; Zumsteg et al., 2003). In addition, there are several small sills and plugs (i.e., "satellites") that occur southwest of the main body of the Crawfish pluton (e.g., locations 12 and 13 in Fig. 2; Loney et al., 1975). The Krestof Island pluton is located ~40 km northwest of the Crawfish pluton and is exposed over ~80 km^2 (Fig. 2). Although the exposed area of the Krestof Island pluton is relatively small, the pluton may be only partially exposed; its unexposed body is believed to be more expansive and may connect to other Eocene plutons on nearby Kruzof Island to the southwest (see Figure 3 in Loney et al., 1975). In comparison to the Crawford and Krestof plutons, smaller exposures of the Mt. Stamy and Mt. Draper plutons (Hudson et al., 1977) intrude the Schist of Nunatak Fiord (informal name, see Richter et al., 2006) in the Boundary block (Fig. 3). Approximately 5 km east of the Mt. Draper pluton is a small (<10 km^2) exposure of mafic intrusions with complex crosscutting relationships, colloquially known as "the Nunatak" (Sisson et al., 2003b). The Schist of Nunatak Fiord is comprised of CPW rocks that are compositionally similar to turbidites elsewhere in the belt (Schartman et al., 2019), but here they are metamorphosed to greenschist and amphibolite grade (Sisson et al., 2003a, 2003b).

FIELD SAMPLING

Sampling sites were restricted to well-exposed and nearly continuous outcrops at sea level, with one exception. Due to difficulty accessing the pluton interior, large float blocks that are believed to have been derived from the nearby Mt. Stamy pluton were collected from a steep drainage that comes directly out of the pluton. Figures 2 and 3 show sample locations and Tables 1 and 2 provide geographic coordinates for each sample (see Supplemental Table S1 for a complete listing). Samples collected from the Crawfish Inlet pluton were designed to capture a transect from the pluton periphery to its interior, which penetrates farthest into the pluton center along the south arm of Whale Bay (Fig. 2).

Field relationships offer evidence of co-mingling between granitoids and more mafic magmas in many of the eastern SBB intrusive suites. Magmatic enclaves are present within the Crawfish, Krestof, and Mt. Draper plutons. These magmatic enclaves generally occur in swarms of relatively smaller, roundish masses that possess aphanitic to fine-grained textures with their host granitoids (Figs. 4A-4D). A mafic dike that was sampled from within the Mt. Draper pluton exhibits a cuspate-lobate contact, suggesting a co-magmatic relationship between the dike and host granitoid (Fig. 4E-4F).

PETROGRAPHY

Granitoids of the Krestof, Crawfish, Mt. Stamy and Mt. Draper plutons are all medium- to coarse-grained assemblages of plagioclase, K-feldspar, quartz and lesser biotite. Minor phases in some samples include muscovite, hornblende, garnet, and rare clinopyroxene (Wackett, 2014; Arntson, 2018). Accessory minerals include apatite, zircon, titanite, and opaque oxides.

Enclaves within the Krestof, Crawfish, and Mt. Draper plutons are finer grained, appear enriched in ferromagnesian minerals relative to host granitoids (e.g., Figs. 5C-5D vs. 5A-5B), and exhibit crenulate to diffuse contacts with their hosts (Figs. 5G-5H). The occurrence of acicular apatite (Fig. 5E) in some enclaves indicates rapid magmatic quenching (e.g., Wyllie et al., 1962; Didier, 1973; Vernon, 1984; Webster and Piccoli, 2015). Acicular hornblende occurs in enclaves (Fig. 5C), whereas accessory hornblende in the host granitoid exhibits equant and coarser grains (Fig. 5A). Zoned plagioclase and poikilitic textures (Fig. 5F) further support a magmatic origin for the enclaves (Vernon, 1984).

Gabbros from ‘the Nunatak’, the large mafic intrusive body adjacent to the Mt. Draper pluton (Fig. 3), exhibit subophitic textures with hornblende replacing clinopyroxene in grains surrounding plagioclase. The co-magmatic mafic dike emplaced within the Mt. Draper pluton contains fine-grained hornblende, plagioclase, and biotite.

ANALYTICAL METHODS

A total of 60 samples from across the SBB were selected for major and trace element analysis by x-ray fluorescence and inductively coupled plasma mass spectrometry methods at the Washington State University GeoAnalytical Laboratory in Pullman, WA (Supplemental Table S1). Details of sample preparation, analytical procedures, and precision/accuracy estimates are available at https://environment.wsu.edu/facilities/geoanalytical-lab/technical-notes/.

Fourteen samples (eight enclaves, six host granitoids; Table 1) from the Crawfish and Krestof plutons were selected for analysis by Thermal Ionization Mass Spectrometry for Sr and Nd isotopic compositions at the Jackson School of Geosciences Isotope Geochemistry laboratory, University of Texas-Austin. Details of the analytical procedures used at this lab can be found at: www.geo.utexas.edu/isochem/tech_notes/pdf/Sr-Nd-Pb-techniques.pdf. Details of decay constants, analytical errors, age and fractionation corrections, and general isotopic parameters are reported in Table 1.

This study also presents new U-Pb zircon crystallization ages of 23 samples collected from 11 different plutons spanning the entire length of the SBB (Table 2). U-Pb and Hf isotope data were collected by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) at the Arizona Laserchron Center following the methods of Gehrels et al. (2008) and Gehrels and Pecha (2014). Details of the analytical methods are provided in Supplemental Tables S2 and S3 for U-Pb and Hf isotopes, respectively. All Hf isotope compositions referred to in the text are corrected for age (εHf_t).

The results for five SBB pluton samples reported here were previously published in Davidson and Garver (2017). The complete geochronological data set for SBB plutons is available in Supplemental Table S2. Weighted mean U-Pb dates and concordia diagrams are presented in Supplemental Fig. S1. BSE and CL images (Supplemental Fig. S2) were used to screen for inclusions and inherited cores. Inherited grains were not included when calculating the weighted mean ages reported in Table 2. Weighted mean Hf isotope compositions of zircon from 17 of these samples are also shown in Table 2, with the complete Hf isotope data set provided in Supplemental Table S3.

We also report detrital zircon Hf isotope data for detrital zircons collected from across the CPW terrane (Supplemental Table S3 workbook) at localities from the Shumagin Islands (4 samples), Seward area (4 samples), Prince William Sound (6 samples), Boundary block in the Yakutat area (2 samples), and Baranof Island (3 samples) (see Fig. 1). Because we are interested in the $^{176}Hf/^{177}Hf$ ratio of the sedimentary rocks at the time of intrusion of the SBB plutons, the measured $^{176}Hf/^{177}Hf$ ratios in zircon for a given region were recalculated to obtain the ratio at 50 Ma (εHf_{50Ma}), which is the approximate time for the intrusion of the SBB plutons. We note that a change of ±10 Ma has a negligible effect on εHf_{50Ma}. For each region (i.e., Shumagin, Seward, PWS, etc.), there are 84 to 184 Hf analyses taken from the main peaks of the zircon U-Pb age probability distribution of the sedimentary rocks for that region. Because the number of U-Pb analyses is considerably greater than the number of Hf analyses, we created “synthetic” Hf data for the entire U-Pb data set for the region by using the constrained random number generator in Microsoft Excel. This was accomplished by binning the U-Pb dates based on the U-Pb probability distribution plots and then having Excel assign a random Hf ratio between the measured minimum and maximum Hf values for the range of dates in that bin. For Precambrian zircons, we use an empirical linear relationship between U-Pb age and εHf_{50Ma}. An example spreadsheet demonstrating our calculations for the Shumagin Islands region is included in the Supplemental Table S3 workbook.

The synthetic Hf isotope data is necessary because most samples from the CPW terrane have a dominant Late Cretaceous to Paleocene U-Pb population (or "peak") on a probability distribution plot, with subordinate Jurassic, Paleozoic and Precambrian populations (see Garver and Davidson, 2015; Davidson and Garver 2017). However, we typically collect 10 Hf analyses from each of the prominent peaks, regardless of the number of zircons that make up the peak. Therefore, the synthetic εHf_{50Ma} values were used to obtain a better estimate of the volume of zircon with a given εHf_{50Ma} signature that could potentially be assimilated from CPW sedimentary rocks.

Any additional statistical modeling was conducted using R version 4.2.2 in the R statistical computing environment (R Core Team, 2022). All figures were initially constructed in either R or the IgPet geochemical software (Carr and Gazel, 2017), and final aesthetic modifications were completed in Adobe Illustrator. Thorough details on the statistical methods and full model results are available in Supplemental File 1.

WHOLE-ROCK MAJOR AND TRACE ELEMENT GEOCHEMISTRY

The Sanak-Baranof belt intrusive rocks include gabbro, gabbroic diorite, diorite, granodiorite and granite (Fig. 6). For rocks with >60 wt % SiO_2, Barker's (1979) normative anorthite-albite-orthoclase classification scheme suggests most SBB rocks are tonalites, granodiorites, or granites. Two samples from the Crawfish satellitic bodies are leucogranites due to their low color indices. To simplify discussions, we hereafter refer to all medium- and coarse-grained rocks that host magmatic enclaves and mafic dikes as "granitoids," regardless of whether they classify as tonalites or granodiorites.

Among the plutons studied here, the Mt. Draper pluton (n = 11 samples) exhibits the largest range in silica content, with values ranging between ~49 and 74 wt % SiO_2. Samples from the Crawfish pluton (n = 22) exhibit SiO_2 contents ranging from 56.5 to 75.3 wt %. Excluding the high-silica Crawfish satellite leucogranites (~75 wt % SiO_2), eastern SBB granitoids generally exhibit higher CaO, higher Na_2O, and lower K_2O relative to granitoids from the western SBB. Mafic samples from the Mt. Draper pluton are metaluminous and broadly similar in elemental composition to Alaskan metabasalts and ophiolites of the Prince William terrane (i.e., Orca Group; Fig. 6). Magmatic enclaves from the Krestof pluton (open squares) are distinct from their host granitoids (pink filled squares), with SiO_2 contents ranging between ~54 and 56 wt %, compared to ~62-63 wt % for their hosts (Fig. 6). Crawfish enclaves exhibit a much wider range in SiO_2 contents (~56 to ~72 wt %), overlapping with the host granitoids that are between ~66-70 wt % SiO_2. Krestof (open squares) and Crawfish (open red triangles) least evolved enclaves (<63 wt % SiO_2) exhibit distinct TiO_2 and P_2O_5 signatures (Fig. 6).

Geochemical distinctions between eastern and western SBB granitoids are more clearly defined using trace elements (Figs. 7-9, Supplemental Table S1). Eastern SBB granitoids are generally lower in Sc, La, Th, Zr, and especially Y (as well as Yb, which is not shown here), and are enriched in Sr relative to granitoids from the western SBB (Fig. 7). With respect to Th, Sr, La, and Zr, the least evolved (<63 wt % SiO_2) Crawfish enclaves (red open triangles) again plot as outliers (Fig. 7). Sr/Y and Ba/Nb ratios generally increase in eastern SBB rocks with increasing silica, whereas ratios in western SBB rocks remain flat or decrease (Fig. 7).

N-MORB normalized trace element patterns (Fig. 8) illustrate that both western and eastern SBB granitoids exhibit Nb depletions and Pb enrichments. Ratios of Sr/Y in most western SBB rocks and Cordova granitoids are relatively low and overlap with typical values for N-MORB (Fig. 9). However, a suite of near-trench dikes that intrude the accretionary prism near Seldovia, AK (Lytwyn et al., 2000; Bradley et al., 2003; Figs. 9A and Supplemental Item 1, SI Figure 1) have highly variable Sr/Y ratios with some approaching 175 (plotting off scale in Fig. 9A). The Cordova area plutons (i.e., Sheep Bay, McKinley Peak, Rude River) typically define a small range in Sr/Y from ~4 to 10, with the exception of a late-stage dike that cross-cuts the McKinley Peak pluton, which has Sr/Y = 85 (Fig. 9B; Barker et al., 1992). Granitoids from the Western CMC exhibit a considerable range in Sr/Y that overlaps with adakites (Fig. 9B), with the highest ratio again exhibited by a late-stage dike. The largest range in Sr/Y ratios is observed for the Mt. Draper and Mt. Stamy plutons in the Boundary Block (Fig. 9B; Sisson et al., 2003b), which have Sr/Y values up to ~200-225 (plotting off-scale in Fig. 9B). Crawfish Inlet samples exhibit a moderate range in Sr/Y from ~9 to 55, with many classifying as adakites (Fig. 9C), whereas Krestof samples do not classify as adakites. Four eastern SBB rocks that plot at low Sr/Y (<22) and anomalously low Y values (<4 ppm) are particularly high in silica (≥ 74 wt %). This group includes two Mt. Draper leucogranite samples (Fig. 9B) and two Crawfish micaceous garnet-bearing leucogranites (red diamonds; Fig. 9C).

STRONTIUM AND NEODYMIUM ISOTOPE GEOCHEMISTRY

Most eastern SBB granitoid rocks and their co-magmatic enclaves or affiliated mafic rocks have $\varepsilon_{Nd(t)}$ and $^{87}Sr/^{86}Sr_{initial}$ compositions (Table 1) that closely track endmember mixing curves between N-MORB and average CPW sediments (Figs. 10B-10D). Exceptions are two mafic Nunatak samples (one amphibolite and a gabbro) that were contaminated by crust and/or seawater (Sisson et al., 2003b; Fig. 10C). The coherence of eastern SBB rocks to the MORB-sediment mixing curve differs substantially from Sr-Nd isotopic data for the more westerly Kodiak batholith, which largely departs from this mixing curve (Fig. 10A). A Crawfish enclave with <63 wt % SiO_2 is an outlier among the Baranof Island suite but is isotopically similar to a late-stage felsic dike from Cordova (Fig. 10B) and unaltered rocks from Nunatak Fiord (Fig. 10C). Krestof Island enclaves and granitoids are more isotopically evolved than all Crawfish samples (Fig. 10D), despite having lower silica contents (Fig. 6). The Cordova and western CMC plutonic complexes include late-stage dikes (stars, Fig. 10B) that are isotopically more primitive than rocks from the main plutonic bodies (fields, Fig. 10B)

U-PB ZIRCON GEOCHRONOLOGY AND HF ISOTOPE GEOCHEMISTRY

Pluton Crystallization Ages and Hf Isotope Compositions

One sample from the Sanak pluton at the westernmost edge of the SBB (Fig. 1) yields a crystallization age of 63.1 ± 0.9 Ma and a weighted mean εHf_t composition of +9.3 ± 0.7 (Table 2; Fig. 11). Two samples from the Nagai Island pluton (in the Shumagin Islands) record statistically indistinguishable ages of 62.6 ± 0.7 and 61.7 ± 0.7 Ma, respectively, and a weighted εHf_t composition of +8.8 ± 0.7. The Aialik and Hive Island plutons near Seward have nearly identical ages of 56.5 ± 1.0 Ma and 56.4 ± 1.5 Ma, respectively, and εHf_t compositions of +5.9 ± 0.5 and +5.1 ± 0.5 (Fig. 11). The Hive Island pluton contains xenocrysts of kyanite (Kusky et al., 2003; Davidson and Garver, 2017) and yielded seven inherited grains that range in age from 60 – 361 Ma (Supplemental Fig. S1, Supplemental Table S2). Two samples from the Sheep Bay pluton in eastern Prince William Sound northwest of Cordova, Alaska, yield overlapping ages of 54.8 ± 0.7 and 53.9 ± 0.8 Ma, and identical εHf_t of +4.8 ± 0.5. One sample from the McKinley

Peak pluton east of Cordova records an age of 54.5 ± 1.7 Ma and an εHf_t composition of +7.4 ± 0.5 (Table 2, Fig. 11).

More extensive U-Pb age and εHf_t compositional data are available for several plutonic bodies between Yakutat and Baranof Island in the far eastern SBB. Four samples from the Mt. Draper pluton at Nunatak Fiord yield closely clustered ages of 54.0 ± 0.6, 53.9 ± 0.8, 53.1 ± 0.7, and 52.8 ± 0.6 Ma with εHf_t compositions ranging from +5.1 ± 0.6 to +7.6 ± 0.3 (Table 2; locations 1, 5, 30 and 32 on Fig. 3). These crystallization ages overlap with each other as well as with those obtained for the Sheep Bay and McKinley Peak plutons located ~400 km away (Fig. 11A). Mt. Draper sample RF16-32A yielded 13 inherited zircons that range in age from 65 to 1737 Ma. One sample obtained from the Mt. Stamy pluton north of Nunatak Fiord records a younger age of 51.4 ± 0.7 Ma, and an εHf_t composition of +6.8 ± 0.5 (Fig. 3, location 19). We also dated a sample (HL19-20) from the Novatak Glacier pluton that intrudes the CMC in the Fairweather Range southeast of Nunatak Fiord, which yields a crystallization age of 52.0 ± 0.5 Ma. This new concordant age (see Supplemental Fig. S1) refines the 49 ± 7.3 Ma lower-intercept discordant age reported by Sisson et al. (2003b).

One sample from the Krestof Island pluton north of Sitka records an age of 52.5 ± 1.0 Ma and has an εHf_t composition of +10.5 ± 0.5 (Fig. 2). Magmatic zircon for seven samples from across the Crawfish Inlet pluton yield crystallization ages spanning ~6 Myr, from 53.1 ± 0.8 to 47.3 ± 1.2 Ma (Table 2). These Crawfish samples also display a broad range of εHf_t compositions ranging from +4.7 ± 0.7 to +13.7 ± 0.7 (Fig. 11, Table 2). A muscovite + garnet-bearing leucogranite (CP13-08D) satellite pluton that intrudes the CPW schist adjacent to the composite Crawfish Inlet pluton yields an age of 52.7 ± 0.8 Ma (Fig. 2). Our data also suggest that the Crawfish Inlet pluton becomes progressively younger towards its interior. Samples adjacent to intrusive contacts with surrounding country rock record ages of 53.1 ± 0.8 (CP13-13) and 52.2 ± 0.9 Ma (CP13-01), respectively. Alternatively, samples collected from the innermost portions of the pluton accessible along the arms of Whale Bay yield ages of 48.6 ± 1.2 (CP13-03), 48.0 ± 1.0 (CP13-04), and 47.3 ± 1.2 Ma (CP13-09), respectively (Table 2, Fig. 2). This range of ages from the Crawfish pluton brackets the 51.4 Ma U-Pb age from the Redfish Bay pluton at the southernmost tip of Baranof Island (see Zumsteg et al., 2003).

Detrital Zircon Hf Isotope Compositions

Measured and synthetic Hf isotope data for detrital zircons in CPW turbidites from the Shumagin Islands, Seward, Prince William Sound, Boundary block near Yakutat, and Baranof Island are reported in Supplemental Table S3. In the Shumagin Islands, the measured εHf_t values range from +13.4 to –11.9 (n = 88 zircons) and the probability density plot for the εHf_{50Ma} synthetic data (n=471) derived from the measured values has a prominent peak at +8 on a probability density plot, with an average εHf_{50Ma} value of +2.7 (Fig. 11A). In the Seward area, detrital zircon εHf_t ranges from +15.6 to –12.0 (n = 84) with pronounced peaks at +10 and –5 on a εHf_{50Ma} probability density plot and an average of +0.6 (n = 725). In Prince William Sound, detrital εHf_t spans a range from +13.5 to –24.4 (n = 184), with a broad εHf_{50Ma} probability density distribution with bookending maxima at +5 and –17 and an average of –5.7 (n=1484) (Fig. 11A). In the Boundary Block, detrital zircon εHf_t values from the Schist of Nunatak Fiord range from +14.6 to –6.6 (n = 122), with a broad εHf_{50Ma} sawtooth peak from +8 to –4 and an average of +1.8 (n=590). On Baranof Island, detrital zircon εHf_t values range from +9.9 to –15.2 (n = 57), with a broad Hf_{50Ma} peak from +5 to –5 and an average of –1.8 (n=965) (Fig. 11A).

GEOCHEMICAL TRENDS THROUGH TIME

At the local-scale, trace element and isotopic compositions of the Crawfish Inlet and Krestof Island plutons in the far eastern SBB change systematically with crystallization age (Fig. 12, Tables 1 and 2, Supplemental Table S1). Krestof and Crawfish granitoids and evolved (>63 wt % SiO_2) enclaves that are older than 52 Ma have lower Sr/Y ratios and are not adakitic (Fig. 9C). With one exception (sample CP13-07A that was dated at 51.2 Ma), younger (<52 Ma) Crawfish samples have Sr/Y characteristics resembling adakites (Fig. 9C). This trend appears to be primarily driven by statistically significant ($P < 0.05$) time-transgressive variations in Y contents (Fig. 12D), which decrease linearly through time ($F_{1,12} = 16.56$; $R^2 = 0.58$; $P = 0.002$). Whole-rock Sr-Nd isotopic compositions of Krestof and Crawfish granitoids also vary through time, becoming more isotopically primitive with decreasing $^{87}Sr/^{86}Sr_{initial}$ ($F_{1,5} = 13.9$; $R^2 = 0.74$; $P = 0.014$; Fig. 12C) and increasing $\varepsilon_{Nd(t)}$ ($F_{1,5} = 24.72$; $R^2 = 0.83$; $P = 0.004$; Fig. 12B) values as crystallization age decreases. The time-transgressive variations in bulk-rock elemental and isotopic compositions mirror changes in the average εHf_t values of Crawfish and Krestof magmatic zircon ($F_{1,5} = 21.05$; $R^2 = 0.81$; $P = 0.006$), which also increase with decreasing age (Fig. 12A; Table 2). Full model outputs assessing the geochemical variations in Krestof and Crawfish magmas through time are available in Supplemental Item 1.

Time-transgressive compositional trends in εHf_t are also present at the regional scale across the SBB. Whereas differences in analytical methodologies preclude any direct assessment of the relationship between whole-rock geochemical metrics and U-Pb age using previously published data, our systematic collection and analysis of magmatic zircons for both U-Pb age and εHf_t collected from the same sample(s) permit a robust belt-wide comparative analysis of composition as a function of age across the belt (Fig. 11). During the first period of magmatism, from 63-56 Ma, εHf_t values for western SBB igneous rocks decrease with decreasing age, reflecting the decline in average εHf_{50Ma} values for the CPW sediments that they intrude (Fig. 11). During the ensuing 55-47 Ma period, this trend reverses and there is a systematic increase in εHf_t values for SBB igneous rocks that deviates sharply from the detrital zircon εHf_{50Ma} values for CPW sediments, which are most evolved in the sedimentary rocks exposed in Prince William Sound and on Baranof Island (Fig. 11). Granitoids from the Crawfish Inlet pluton exhibit a linear increase in εHf_t with decreasing age (Fig. 12A) and span a broad compositional range (εHf_t = +4.7 to +13.7).

DISCUSSION

Geochronological evidence for the 'tale of two belts'

Early workers recognized that near-trench igneous rocks of the SBB record a general time-transgression from west to east, which they ascribed to the migration of a trench-ridge-trench (TRT) triple junction being subducted obliquely beneath the continental framework (Karig et al., 1976; Marshak and Karig, 1977). Others later refined this trend by expanding the number of dates available for near-trench intrusive rocks across the entire ~2200 km belt, which were found to range from ~61 Ma on Sanak Island in the west to ~50 Ma on Baranof Island at the belt's eastern edge (Bradley et al., 1993, 2000, 2003; Zumsteg et al., 2003; Farris and Paterson, 2009). On the basis of variably reliable ages for SBB intrusive bodies obtained through K/Ar dating of muscovite or biotite (low reliability), $^{40}Ar/^{39}Ar$ dating of muscovite, hornblende, and biotite (intermediate reliability), and U-Pb dating of monazite and magmatic zircon (high reliability), these studies strengthened the case for systematic younging of SBB igneous rocks towards the east (Bradley et al., 1993, 2000, 2003). The repeatedly referenced 61-50 Ma age range and systematic younging of SBB intrusive suites towards the east has featured prominently in most tectonic reconstructions of the Cordilleran margin – even when the hypothesized tectonic framework models have been at odds. Specific examples of competing tectonic reconstructions that invoke this same systematic temporal trend for SBB plutons include the Resurrection Plate hypothesis of Haeussler et al. (2003), the Baranof-Leech River hypothesis of Cowan (Cowan, 1982, 2003), and several other Kula and/or Farallon ridge-trench configurations highlighted by Fuston and Wu (2021).

Farris and Paterson (2009) expanded on these previous approaches by applying a linear regression analysis of age as a function of distance from Sanak Island to derive an average estimate for the TRT triple junction migration rate along the margin, which they placed at 19.6 cm yr^{-1} and leveraged in support of the Resurrection Plate hypothesis (Haeussler et al., 2003). However, this presumed linear relationship between SBB intrusive age and position along the margin has until now been based on only 12 concordant U-Pb monazite and zircon dates that span the entire ~2200 km of the belt (Bradley et al., 2003; Farris and Paterson, 2009), with half of those available ages sourcing from the 59-58 Ma Kodiak batholith in the western SBB (Farris and Paterson, 2009). Of the remaining six concordant U-Pb ages, only two robust ages had been obtained from the entire eastern half of the belt – a distance of >800 km stretching from the eastern PWS to Baranof Island (Fig. 1).

We emphasize that given the sizeable estimates of northward translation of outboard terranes along the southern Alaskan margin (e.g., Plumley et al., 1983; Bol et al, 1992; Haeuessler et al., 2003; Cowan, 2003), it is challenging to reconcile trends in age and composition as a function of position along the modern margin. Nonetheless, we elected to consider belt-wide trends in this context to allow for direct comparisons with these previous studies of SBB rocks. Integrating our new U-Pb crystallization ages (n = 23) with existing U-Pb ages from across the belt (n = 12, Farris and Paterson, 2009) highlights divergent behavior in eastern SBB rocks that deviates from the systematic linear belt-wide relationship reported previously. Running separate linear mixed effects models (see Supplemental Item 1 for additional discussion and model outputs) for the western and eastern SBB highlights that distance from Sanak Island explains >97% of the variability in U-Pb crystallization ages for >56 Ma rocks in the western SBB, but only ~51% of the variability in observed U-Pb ages for <55 Ma eastern SBB intrusive rocks (Fig. 13B). These data collectively suggest that a strong relationship between crystallization age and position along the margin is maintained prior to 55-57 Ma, but this relationship unravels after ~56 Ma.

Our expansion of the available U-Pb age data for igneous rocks across the entire near-trench plutonic belt – and especially within the eastern SBB – reveals several key points. First, our new U-Pb zircon ages extend the duration of SBB magmatism by almost ~5 Ma (63-47 Ma) relative to the most commonly cited 61-50 Ma age range, although we note that some studies have alternatively referenced a ~61-48 Ma age range for the belt (e.g., Madsen et al., 2006). More importantly, our expanded dataset dispels the longstanding assumption that the age of SBB plutons decreases systematically from west to east in relation to position along the modern Alaskan margin, although we also note that Sisson et al. (2003b) did begin to outline the nonlinear age-position relations for SBB intrusive rocks within the western CMC and Boundary Block (i.e., Mt. Draper/Stamy plutons).

Our work builds upon their preliminary hypothesis and provides a wealth of new geochronological data that portrays a more nuanced picture of the timing of early Tertiary near-trench magmatism along the Cordilleran margin, which supports the notion that the SBB is better represented as two distinct (i.e., western and eastern) belts (Fig. 13B). Near-trench intrusive rocks emplaced during the first ~7 Ma years of magmatism (from 63-56 Ma) record a systematic spatial and temporal relationship, wherein position along the modern-day southern Alaska margin remains a strong predictor of intrusive age. During the second ~9 Ma of forearc magmatic activity (from 56-47 Ma), widespread and long-lived magmatism generated coeval and compositionally heterogeneous near-trench intrusive rocks that are now separated by ~800 km (from Prince William Sound to Baranof Island) along the modern-day margin.

Geochemical evidence for the 'tale of two belts'

Trace element geochemistry and the role of adakites

Adakite is the term broadly applied to a class of sodium-rich intrusive and/or extrusive igneous rocks with high Sr/Y ratios, which are compositionally distinct from 'normal' mantle wedge-derived arc rocks (Kay, 1978; Drummond and Defant, 1990; Martin, 1999; Martin et al., 2005; Hastie, 2021). Early studies on adakites linked their origin to slab melting (e.g., Drummond and Defant, 1990), but recent work has proposed alternative petrogenetic models for adakite formation (see Hastie, 2021 and references therein). It is now generally recognized that any tectonic environment that involves partial melting of basalt and/or amphibolite at sufficient crustal thicknesses to stabilize garnet and/or amphibole in the residuum can generate adakitic melts (e.g., Beard and Lofgren, 1991; Atherton and Petford, 1993). For example, adakitic melts have been found in intraplate environments stemming from partial melting of delaminated mafic lower crust (Xu et al., 2002). Others have noted that ridge subduction events and the ensuing generation of a 'slab window' (Defant et al., 1992; Thorkelson, 1996; Thorkelson and Breitsprecher, 2005) and/or potential for tearing around the edge of the down-going slab (Yogodzinski et al., 2001; Thorkelson and Breitsprecher, 2005) constitute tectonic settings commonly associated with adakite formation.

Previous petrogenetic models invoked adakite genesis in the SBB by either slab melting (e.g., Haeussler et al., 2003, Sisson et al., 2003b; Farris and Paterson, 2009) and/or partial melting of underplated mafic lower crust (e.g., Harris et al., 1996). Some of these studies also proposed that the SBB records systematic differences in Sr/Y ratios across the belt, with lower Sr/Y (non-adakitic) melts in the west that grade towards systematically higher Sr/Y ratios in the eastern SBB (e.g., Haeussler et al., 2003; Farris and Paterson, 2009). Farris and Patterson (2009) proposed that higher Sr/Y ratios in the eastern SBB are due to the onset of slab melting in this portion of the belt, and used this line of reasoning to support the Resurrection plate hypothesis of Hauessler et al. (2003).

Our compilation demonstrates that Sr/Y ratios exhibit no clear and consistent trends across the SBB (Figs. 9; Supplemental Item 1). For example, some western SBB magmatic systems – namely the suite of near-trench dikes that intrude the CPW terrane near Seldovia (Kenai Peninsula) – show strongly adakitic Sr/Y ratios (Lytwyn et al., 2000; Bradley et al., 2003; Fig. 9A). These compositionally heterogeneous dikes have been dated to 57.0 ± 0.2 Ma by $^{39}Ar/^{40}Ar$ methods (Bradley et al., 2000), consistent with interpretations that they form part of the SBB (Lytwyn et al., 2000; Bradley et al., 2003). The Seldovia dikes have high Sr/Y ratios (Lytwyn et al., 2000; Bradley et al., 2003; Fig. 9A and Supplemental Item 1) with values up to 175 (plotting off scale in Fig. 9A), despite lying ~300-400 km west of the definitively non-adakitic ~55 Ma Sheep Bay, Rude River, and McKinley Peak plutons exposed near Cordova (Barker et al., 1992; this study; Fig. 9B).

Many eastern SBB suites also show extremely variable Sr/Y ratios and Y contents. The largest range is observed for granitoids from the Mt. Draper and Mt. Stamy plutons, with Sr/Y values approaching ~200-225 (plotting off-scale in Fig. 9B). The sparse U/Pb ages we obtained for these rocks do not reveal any temporal trends in Sr/Y. The Crawfish Inlet rocks exhibit a moderate range of Sr/Y ratios (~9 to 55), some of which overlap with the adakite field (Fig. 9C). Our detailed geochronology for this pluton highlights a trend towards increasing Sr/Y through time (Fig. 12). This trend of increasing Sr/Y through time appears to be consistent for both the Crawfish and several other eastern SBB suites, as late-stage dikes in both the Cordova area (Fig. 9B; Barker et al., 1992) and western CMC (Fig. 9B; Harris et al., 1996; Sisson et al., 2003b) are notably more adakitic than earlier intrusives within these suites. However, more detailed age dating is needed to confirm this trend more reliably within other eastern SBB suites.

The lack of systematic variations in Sr/Y ratios across the SBB (Fig. 9 and Supplemental Item 1) challenges the notion that adakitic ‘slab melts’ are largely confined to younger rocks in the eastern SBB (e.g., Haeuessler et al., 2003; Farris and Paterson, 2009). Besides slab melting and/or melting of mafic crust, there are several other possible explanations for the development of highly variable Sr/Y ratios within individual SBB intrusive suites. One recent review (Luffi and Ducea, 2021, and references therein) considers the use of whole-rock geochemical parameters that correlate with crustal thickness (i.e., “mohometers”). They propose Sr/Y ratios as one of the metrics that best serves as a qualitative proxy of paleo-Moho depths. In line with this work, one possible explanation for the observed increase in Sr/Y through time in the Crawfish suite could be increasing crustal thickness during petrogenesis, leading to melting at greater depths and pressures that stabilize garnet and/or hornblende in the residuum. Although the Crawfish pluton could be anomalous, this mechanism for adakite genesis seems somewhat unlikely given the wealth of evidence for extensive plutonism and transtension in other portions of the eastern SBB circa ~55–50 Ma (e.g., Sisson and Pavlis, 1993; Pavlis and Sisson, 2003; Gasser et al., 2011).

Another mechanism capable of generating high Sr/Y ratios while lowering Y contents is fractionation of minerals with high distribution coefficients for Y but low coefficients for Sr. Examples of such phases include hornblende, garnet, zircon, and titanite (Sisson and Bacon, 1992; Ewart and Griffin, 1994; Bachmann et al., 2005; Ackerson, 2011; Padilla and Gualda, 2016). Both zircon and garnet have high distribution coefficients for Y (~130-180) and very low distribution coefficients for Sr (<0.02). Thus, removal of ~2-3% garnet and/or zircon results in rapid depletion of Y and a concomitant increase in Sr/Y ratios (>20-fold). The Sr distribution coefficients are similar for hornblende and titanite (average ~0.5-0.6), but the Y distribution coefficient for titanite (~720) is enormous compared to that for hornblende (~14). Removal of as little as 0.02% titanite can drastically deplete Y and increase Sr/Y ratios to >10,000. In contrast, fractionation of ~15% hornblende increases initial values of Sr/Y from ~10 up to ~95 and decreases initial values of Y from ~25 to <5, consistent with the variations observed for Crawfish granitoids (Fig. 9C). In other words, increases in Sr/Y in younger Crawfish magmas (and potentially other eastern SBB suites) could also stem from fractionation processes rather than deeper melting and/or variable involvement of partially melted mafic crust.

Although our belt-wide Sr/Y compilation challenges previous assertions that the western and eastern SBB can be distinguished by the presence (or absence) of adakites, we do build upon the premise originally introduced by Farris and Paterson (2009) that intrusive rocks from the western and eastern belts are systematically different. We propose instead that this tale of two belts is best illuminated by whole-rock Sr/Nd isotopes and particularly by εHf_t analyses of magmatic zircon, rather than through Sr/Y or other trace element characteristics. The increasing εHf_t and Sr/Nd isotopic signatures through time across much of the eastern SBB may reflect a greater involvement of isotopically primitive source endmembers, which could also contribute to the temporal trends in Sr/Y we observe within many of the eastern SBB suites.

Sr and Nd isotopic constraints

Our dataset from the Crawfish Inlet pluton documents systematic, time-transgressive compositional Sr-Nd isotopic variations recorded through time (~6 Ma) within an individual pluton (Fig. 12; Supplemental Item 1). There are many other well-studied examples of systematic age and geochemical variations within individual intrusive suites. For example, significant age ranges (from ~3 to 19 Ma) have been documented in temporally and chemically zoned plutons of the Sierra Nevada batholith (e.g., Bateman 1992; Coleman et al., 2004; Davis et al., 2012; Lackey et al., 2012; Putnam et al., 2015), as well as plutons of the Aleutian (e.g., Kay et al., 2019) and Andean arcs (Guillot et al., 2018; Rodriguez et al., 2019).

We suggest that this local signature of increasing mantle-derived proportions through time may comprise a characteristic signature across much of the eastern SBB intrusive belt (Boundary block notwithstanding), and this time-transgressive signature may in turn be used to distinguish between the western and eastern belts. Future studies may aim to better constrain the temporal and compositional relations at local levels within the Cordova, western CMC, and Yakutat area (Boundary block) intrusive suites to further test this assumption. Furthermore, higher resolution sampling and detailed characterization of near-trench igneous activity at local scales (i.e., within individual plutons and/or plutonic suites) across other tectonic environments that have recorded ridge-trench encounters such as in Japan (Maeda and Kagami, 1996; Shinjoe et al., 2021) and/or Patagonia (e.g., Forsythe et al., 1986; D'Orazio et al., 2000; Lagabrielle et al., 2000) may illuminate whether this trend is a recurring pattern associated with forearc slab window magmatism more generally, or is unique to the eastern portions of the SBB.

Hf isotopic constraints

Arguably the clearest case for partitioning the SBB into two separate belts is illustrated by our belt-wide compilation of εHf_t values versus U/Pb age (Ma) for the SBB plutons (Fig. 11). In the western belt, εHf_t of the plutons become systematically more evolved from west to east, and appear to track with the εHf_{50Ma} signatures of the sedimentary rocks they intrude (Fig. 11A). This finding supports a model of petrogenesis via mixing between depleted mantle melts and assimilation of CPW sedimentary rocks (e.g., Hill et al., 1981; Barker et al., 1992; Ayuso et al., 2009). In contrast, the εHf_t of the oldest plutons in the eastern belt (54 Ma) are the most evolved and become systematically more primitive with decreasing age (Fig. 11).

The consistent lowering of εHf_t values in western SBB rocks from Sanak Island to Prince William Sound could reflect an increase in the amount of assimilation of sedimentary rocks by N-MORB mantle melts towards the east. Barker et al. (1992) suggested CPW sedimentary proportions may be as high as ~90% in some Cordova area plutons, and the presence of kyanite xenocrysts in some western SBB granitoids like the Aialik and Nuka plutons (e.g., Kusky et al., 2003) further implicates a substantial metasedimentary contribution to SBB melts near the western-eastern transition zone. However, we also highlight that the lower εHf_t of Cordova area plutons could alternatively reflect the compositional shift towards a lower εHf_{50Ma} signature for the CPW sedimentary rocks around Prince William Sound (Fig. 11). On Baranof Island, the average εHf_{50Ma} of the Sitka Graywacke and Baranof schist is –1.8, and the εHf_t of the oldest sample of the Crawfish Inlet pluton (53 Ma) is +4.7 (Fig. 11, Table 2). Therefore, the increase in εHf_t towards more primitive values with age in the Crawfish pluton (as high as +13.7 at 47 Ma) likely reflects greater proportions of mantle-derived melts with time, consistent with the time-transgressive trends in Sr-Nd isotopic and trace elemental compositions (Fig. 12).

One possible explanation for the increasing mantle component over the ~6 Ma of magmatism in the Crawfish pluton is that there was a “clearing out” of the magmatic plumbing system during this long-lived magmatic episode, with a concomitant decrease in sediment assimilation through time. Within this framework, shorter lived magmatism (~1-2 Ma; see Farris and Paterson, 2009) within the western SBB does not record this transition, causing the εHf_t isotopic signatures of the western SBB plutons to track more closely with those of the sediments they intrude. Potential tectonic frameworks that explicitly link to the increasing mantle contributions in eastern SBB rocks could include: (1) an increasing mantle endmember component that was supplemented by interactions between the more southerly paleo-CPW terrane and ancestral Yellowstone hot spot (Wells et al., 2014), which would also help explain the additional heat source necessary to generate the observed metamorphic assemblages on southern Baranof Island (see Zumsteg et al., 2003); and/or (2) protracted transtensional activity in the ancient forearc during plate reorganization, which in turn facilitated partial melting of the mafic rocks that are interbedded with younger CPW sediments (Sisson and Pavlis, 1993; Pavlis and Sisson, 2003; Gasser et al., 2011).

SUMMARY AND CONCLUSIONS

The time-transgressive Sanak Baranof belt (SBB) exposed over ~2200 km along the southern margin of Alaska may be a tale of two belts: (1) a western belt with crystallization ages that young systematically from 63 Ma in the west (Sanak Island) to 56 Ma in the east (Resurrection Bay); and (2) an eastern belt with broadly coeval crystallization ages ranging from 55 to 47 Ma that spans >800 km from eastern Prince William Sound to Baranof Island (Table 2, Fig. 1). Major and trace element geochemistry and petrography of SBB intrusive rocks show that they vary widely in composition and classification from gabbros to garnet+muscovite-bearing leucogranites. Whole-rock elemental and isotopic observations fail to clearly elucidate systematic differences between the western and eastern belts, including Sr/Y ratios and Sr-Nd isotopic values (Figs. 9 and 10). In the western belt, εHf_t of magmatic zircon from the SBB plutons varies from +9.3 ± 0.7 on Sanak Island to +5.1 ± 0.5 at Resurrection Bay, which tracks the decreasing εHf_{50Ma} signature of detrital zircons from the CPW turbidites they intrude (Fig. 11). In the eastern belt, there is a distinct and systematic departure of εHf_t values for the plutons compared to the εHf_{50Ma} values recorded by the surrounding CPW turbidites. This is particularly pronounced at the easternmost edge of the belt on Baranof Island, where the CPW turbidites have an average $\varepsilon Hf_{50Ma} = -1.8$, while the oldest phases of the Crawfish Inlet pluton (~53 Ma) have $\varepsilon Hf_t = +4.7$ and the youngest phases (47 Ma) have $\varepsilon Hf_t = +13.7$, which approaches the εHf_t value for depleted mantle (Fig. 11).

These new observations and syntheses spanning the entire ~2200 km of the SBB suggest this is a tale of two belts comprised of a wide variety of granitoid rocks, which precludes a simple time-transgressive emplacement of plutons along the Paleocene-Eocene Alaskan margin due to sweeping subduction of a migrating ridge. Most plate reconstructions for the NE Pacific Basin indicate that emplacement of the SBB plutons occurred in a strike-slip environment that resulted in northward translation along the Cordilleran margin following intrusion, but the relationship to offshore plate geometries remains unclear because offshore marine magnetic anomalies of that age have long since been subducted (Engebretson et al., 1985; Shephard et al., 2013; Müller et al., 2019; Clennett et al., 2020; Fuston and Wu, 2021). Several observations highlight the tectonic complexity and unique attributes of the eastern SBB, which distinguishes this portion of the belt from those >55-56 Ma SBB plutons situated to the west.

First, intrusion of eastern SBB rocks likely occurred in a dextral strike-slip environment that was in part manifested by significant slip on the Border Ranges fault system (BRFS). For example, the Tarr Inlet Suture of the BRFS appears to have hundreds of kilometers of dextral slip (up to ~700 km) that occurred between 58 and 42 Ma (Smart et al., 1996; Sisson et al., 2003b). Strike-slip faults are also common within rocks of the CPW terrane and are especially apparent across the eastern SBB, where several structures appear to have accommodated particularly significant movement between the late Paleocene and early to middle Eocene (Bol and Roeske, 1993).

Second, wholesale crustal stretching and extension likely accompanied eastern SBB plutonism, and extension-derived 'bimodal' igneous products offers an intriguing explanation for the apparent compositional gap in SiO_2 contents for (eastern) SBB intrusive rocks (see Figures 6 and 7). The CMC in the eastern Chugach Range records a remarkable sequence of synchronous plutonism and transtension between ~55 and 50 Ma (see Sisson and Pavlis, 1993; Pavlis and Sisson, 2003; Gasser et al., 2011). The 57 Ma Resurrection ophiolite and its allied fragments may have also resulted from extreme transtension of the upper plate (Davidson and Garver, 2017). These observations suggest crustal thickening is likely not responsible for the observed increase in Sr/Y ratios through time for many (but not all) eastern SBB suites.

Third, although the offshore plate setting remains poorly understood, many tectonic models call upon interactions with an offshore ridge at a triple junction. To explain the geologic complexity of the (eastern) SBB, Sisson and Pavlis (1993) proposed that the subduction of transform offsets from a spreading ridge may have allowed certain areas along the margin to experience prolonged heating and/or repeated reheating (see Sisson and Pavlis, 1993; Pavlis and Sisson, 2003). Ridge segments and transforms may have therefore been juxtaposed at steep angles relative to the margin, with some segments subducting obliquely or nearly parallel to the margin (Sisson et al., 2003b). Eastern SBB magmas were thus likely affected by complexities in the nature of the offshore spreading ridge, which may have assumed enigmatic orientations and/or behavior during the dynamic period of plate reconfiguration between 56 and 52 Ma (Sisson and Pavlis, 1993).

Lastly, paleomagnetic results from rocks of the CPW terrane – host to the SBB – raise the possibility that intrusion occurred far to the south, and the CPW terrane and SBB were subsequently translated northwards to Alaska. The available paleomagnetic data indicate ~1400 to 2500 km of margin-parallel translation of the 57 Ma Resurrection Peninsula ophiolite and slightly older rocks on Kodiak Island (see Garver and Davidson, 2015 for further discussion). Published models suggest the age distribution of SBB plutons may be related to either movement of offshore plate geometries (see Clennett et al., 2020; Fuston and Wu, 2021) and/or movement of the CPW terrane as a strike-slip bound forearc sliver (or possibly both). In any case, the enigmatic nature of the eastern SBB is almost certainly related to the complexity of the dynamic Pacific plate reorganizations that occurred around Chron 24 to 23 (between ~56 to 52 Ma) (Pavlis and Sisson, 1995; Wells et al., 2014; Clennett et al., 2020; Fuston and Wu, 2021).

The original tectonic setting of the SBB and coeval plutonism in the Pacific Northwest (e.g., Madsen et al., 2006; Wells et al., 2014) is a Cordilleran conundrum. On the one hand, the timing and spatial distribution of the SBB has been used to infer an *in situ* setting wherein near trench plutonism was driven by subduction and spreading of the now vanished hypothetical Resurrection plate. This tectonic framework requires rejection of numerous paleomagnetic data sets that show the host rocks to the SBB have shallow inclinations and thus were formed much further south along the Cordilleran margin. On the other hand, an *ex situ* or far-traveling scenario

– which honors the paleomagnetic data – requires a complex petro-tectonic scenario where intrusion and concurrent strike-slip faulting carried the SBB plutons and CPW terrane over a thousand kilometers northward.

This latter hypothesis is further complicated by the fact that the original position of intrusion may have also overlapped with the ancestral Yellowstone hotspot (Wells et al., 2014), which could have generated additional melting in an oblique subduction setting wherein endmember OIB chemistry would likely be substantially modified by subduction zone processes. Regardless, excision of these rocks and translation along the margin would have left a truncation scar, which some have recognized (i.e., Johnson, 1984). These two hypotheses—*in situ* and *ex situ*—are mutually exclusive and we are left with two separate options: either the SBB intruded the CPW terrane more or less in place (i.e., Alaska), or they were intruded far to the south and subsequently translated northward. There is no middle ground. The conundrum is that although these near-trench plutons should be ideal contenders to help constrain the offshore plate setting, they cannot help clarify Cordilleran tectonic reconstructions until their original site of intrusion is resolved. One thing seems clear – the SBB belt records a transition at ~55-57 Ma, which likely reflects a dynamic period of plate reorganization in the North Pacific.

Parsing between potential mechanisms and tectonic scenarios that comprehensively address all the available geochemical, geochronological, structural, and paleomagnetic data are beyond the scope of this study. However, some viable possibilities seem to include a combination of oblique ridge subduction interacting with a dynamic transpressional to transtensional margin, which was simultaneously undergoing rapid sedimentation and tectonic thickening in the forearc stemming from exhumation and erosion of the Coast Plutonic Complex (Hollister, 1979; Haeussler et al., 2006; Davidson and Garver, 2017). In the easternmost SBB, these events may have also been facilitated and/or followed by interactions with the ancestral Yellowstone hotspot (e.g., Wells et al., 2014) and ensuing dextral strike slip transport along the margin, which carried both the CPW and Yakutat terranes northward to their modern-day position in southern Alaska. Regardless of what tectonic mechanism(s) are invoked, our findings clarify (at local scales) and complicate (at regional scales) the current picture of geochemical and geochronological relations across the SBB, and these results must be accounted for in future tectonic reconstructions of the Paleocene-Eocene Cordilleran margin.

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FIGURE CAPTIONS

Figure 1. Schematic tectonic map of the modern-day Cordilleran margin stretching from the southwestern Alaskan margin at Sanak Island to northern Washington state (modified after Cowan, 2003). Abbreviations are as follows: PWS = Prince William Sound; ESP = Eshamy Suite plutons; CMC = Chugach Metamorphic Complex; SNF BB = Schist of Nunatak Fiord in the Boundary block. Inset boxes identify locations of the maps illustrated in Figures 2 and 3.

Figure 2. Detailed geologic map of Baranof Island near Sitka, Alaska. Location is depicted by an inset box in Figure 1. Sample locations are shown as small labeled dots with the adjacent numbers corresponding to the sample names listed in Supplemental Table S1. Samples K1 and K2 (KP13-01 and -02) were collected from the Krestof Island pluton located north of Sitka, Alaska. The base map is modified after Wilson et al. (2015).

Figure 3. Detailed geologic map of the Nunatak Fiord region near the town of Yakutat, Alaska. The map location is shown by an inset box in Figure 1. The Boundary block is a fault-bounded block comprising the schist of Nunatak Fiord and the Mt. Stamy and Mt. Draper plutons. The Nunatak is a mafic and highly heterogeneous portion of the Mt. Draper pluton (location #5). Sample locations are shown as labeled dots with the numbers corresponding to samples listed in Supplemental Table S1. Sample 19 (RF16-19) was collected from a large debris flow in a

drainage that incises the Mt. Stamy pluton. Areas in gray (unlabeled geologic units) are ice-covered. The base map is modified from Wilson et al. (2015).

Figure 4. Field photos of select plutons from the eastern SBB (Boundary block and Baranof Island area). (A) Mafic enclave swarm in the Crawfish pluton. Note the cuspate-lobate boundaries between the mafic and felsic rocks; quarter (~2.4 cm diameter) for scale. (B) Mafic enclave swarm emplaced in the Krestof pluton; note the rock hammer (~0.4 m in length) for scale. (C) Typical Krestof Island magmatic enclave exhibiting roundish shape, higher color index and aphanitic texture relative to its host. (D) Mafic enclave in the Mt. Draper host granite. (E) Mutually cross-cutting relationships between a mafic dike (sample RF 16-30B) and the Mt. Draper pluton. (F) Zoomed image of the panel E inset. Upper red arrow shows an isolated xenolith of the mafic dike in the host granite, and the lower arrow highlights a cuspate-lobate texture between the dike and host granite, which indicates a comagmatic relationship.

Figure 5. Photomicrographs of selected samples from this study. Unlabeled yellow scale bars are equal to 1 mm. Mineral abbreviations are: Hbl = hornblende; Bt = biotite; Qz = quartz; Pl = plagioclase, Cpx = clinopyroxene. (A) Crawfish host granitoid (CP13-07A) under PPL and (B) XPL. (C) Associated magmatic enclave (CP13-07D) under PPL and (D) XPL. (E) Enclave CP13-07D under high magnification to highlight the presence of acicular apatite crystals (circled in red). (F) Crawfish tonalitic enclave (sample CP13-06B) with a poikilitic texture. (G) Contact between Krestof host granitoid (sample KP13-02A) and enclave (sample KP13-02B) shown under PPL and (H) XPL. The mafic enclave is dominated by finer grained plagioclase and clinopyroxene.

Figure 6. Major and minor element Harker diagrams for SBB intrusive rocks from this study and one sample (S69a) from Hill et al. (1981). The latter sample is geographically proximal to our

Sanak Island sample (SI12-02, see Supplemental Table S1 for details), which was collected for zircon analyses but lacks whole-rock elemental geochemistry. The gray fields outline the compositional range of Paleocene-Eocene Alaskan metabasalts and ophiolites (Lull and Plafker, 1990; Lytwyn et al., 1997; Sisson et al., 2003b) for comparison with SBB intrusive suites. The total alkalis vs. silica classification is from Middlemost (1994). ASI (Aluminum Saturation Index) is the molecular ratio of Al_2O_3/[CaO + Na_2O + K_2O] (Shand, 1951). The peraluminous-metaluminous boundary (solid line) at ASI = 1.0 is after Shand (1951) and the I-type/S-type boundary (dashed line) at ASI = 1.1 (with S-type >1.1) is after White et al. (1986). MALI is the modified alkali-lime index (Na2O + K2O - CaO; Frost and Frost, 2008). The boundary between calcalkaline and tholeiitic suites on the FeO*/MgO diagram is after Miyashiro (1974).

Figure 7. Trace element (in ppm) Harker diagrams for all new SBB intrusive rock samples reported in this study. Symbols are as in Figure 6.

Figure 8. N-MORB normalized (after Sun and McDonough, 1989) spider diagrams for new SBB samples reported from this study. Symbols are as in Figures 6, with two exceptions. In panel (F), red diamonds are used to distinguish the Crawfish micaceous leucogranite satellites, and the red shaded field represents all Crawfish samples with >63 wt % SiO_2 (both enclaves and host granitoids). Numbers in parentheses adjacent to the sample labels denote wt % SiO_2 values. (A) Spider diagrams for ~63-56 Ma western SBB rocks stretching from Sanak Island to the Hive Island pluton in Resurrection Bay. (B) One sample from the Novatak Glacier pluton in the Fairweather block plotted alongside mafic compositions from the mafic dike and gabbro that intrude the Boundary Block at Nunatak Fiord. (C) Krestof pluton (52 Ma) samples. (D) Granitoids from the 55-54 Ma Sheep Bay and McKinley Peak plutons near Cordova. Lines are missing where elemental analyses are not available (see Supplemental Table S1 for details). (E)

Evolved enclaves and host granitoids (54-51 Ma; >63 wt % SiO_2) from the Mt. Stamy and Mt. Draper plutons in the Boundary block. (F) Crawfish pluton samples (53-47 Ma). Figure 9. Sr/Y vs. Y (ppm) diagrams for samples with >54 wt% SiO_2 occurring in the SBB. (A) Rocks of the western SBB (63-56 Ma). The shaded fields represent previously reported datasets for >56 Ma rocks from the western SBB. Data sources for these fields are: Kodiak, Ayuso et al. (2009); Sanak-Shumagin, Hill et al. (1981); Seldovia, Lytwyn et al. (2000) and Bradley et al. (2003). Also illustrated are eclogite and garnet amphibolite partial melting curves labeled 1 and 2, respectively, after Drummond and Defant (1990), which assume an N-MORB source (264 ppm Sr, 38 ppm Y). The numbers adjacent to the tick marks indicate degrees of partial melting. (B) Sr/Y ratios for rocks of the eastern SBB (55-51 Ma) excluding the Crawfish Inlet and Krestof Island plutons. The aqua field represents Cordova samples from the Sheep Bay, McKinley, and Rude River plutons; the aqua star represents a late stage dacitic dike (Barker et al., 1992). The light-yellow field denotes early-stage intrusions from the CMC, while the yellow stars represent late-stage (Ti_4) post-deformational intrusive dikes established by cross-cutting relations (see Harris et al., 1996; Sisson et al., 2003b for details). The light orange field represents the Mt. Draper and Mt. Stamy plutons in the Boundary block. The orange star represents a leucogranite that plots off-field (Sisson et al., 2003b). (C) Sr/Y ratios for rocks in the far eastern SBB (53-47 Ma). The gray field represents adakites (e.g., Drummond and Defant, 1990, Martin, 1999), the blue rectangle represents N-MORB (Gale et al., 2013), and the brown circle represents CPW sediments (Barker et al., 1992; Hill et al., 1981). Symbols are enlarged for samples for which U-Pb ages are available (this study); the smaller symbols lack age data. All enclaves are assumed to be the same age as the host rocks they intrude based on field evidence of comagmatic relationships. Note that the Krestof host granitoid has an age of 52.1 Ma. The dashed field encompasses younger Crawfish samples with ages ranging from 51.2 to 47.3 Ma. The gray arrows and tick marks depict the same melting models shown in panel (A).

Figure 10. $\varepsilon_{Nd(t)}$ versus $^{87}Sr/^{86}Sr_{initial}$ diagrams for whole-rock samples from this study and other previously published Sr-Nd isotopic datasets for SBB intrusive rocks. Mixing curves (after Harris et al., 1996) between N-MORB and an average CPW sedimentary composition are shown in each panel. The numbers next to the tick marks in panel (A) denote the weight fraction of MORB that was added to sediment in each mixing model. (A) Kodiak batholith samples (data from Ayuso et al., 2009). Also shown are compositions of CPW sedimentary rocks (whole-rock compositions from Farmer et al., 1993, plus one sample from Harris et al., 1996). (B) Intrusive rocks from the Cordova area (Barker et al., 1992) and western CMC (Sisson et al., 2003b). Stars denote late-stage intrusions. (C) Nunatak Fiord and Mt. Draper/Stamy samples (Sisson et al., 2003b). Blue dashed arrow is a trend associated with seawater contamination and/or crustal assimilation (Sisson et al., 2003b). (D) Crawfish Inlet and Krestof Island samples (this study). The pink field represents oceanic island basalts (OIB) after Zindler and Hart (1986), Hofmann (1988; 1997), Sun and McDonough (1989), and Salters and Stracke (2004).

Figure 11. (A) εHf_t of magmatic zircon from the SBB plutons (plotted as symbols) compared with εHf_{50Ma} values for detrital zircon from various CPW turbidite groups (plotted as shaded areas of various colors). Color shaded fields are bubble plots that were constructed from probability density plots of the detrital zircon εHf_{50Ma} data (see Methods and Supplemental Table 3) and are centered near the U/Pb ages of the plutons that intrude them. Black stars are the average εHf_{50Ma} of the detrital zircons. Vertical error bars are $\pm 1\sigma$. (B) Weighted means of the εHf_t data from the SBB plutons. Vertical error bars are $\pm 2\sigma$. Blue arrows highlight the ‘U-shaped’ time-transgressive trend in εHf_t values for the SBB plutons through time.

Figure 12. Geochemical trends through time within the Crawfish Inlet and Krestof Island intrusive suites in the far eastern SBB. Multiple samples of the same age represent compositions from co-magmatic enclaves associated with the host granitoid sample that was U-Pb dated, as in Figure 9. Linear regression fits are shown in black and the 95% confidence intervals are depicted with light gray dashed lines. Model goodness-of-fit metrics (i.e., R^2 values) and levels of significance ($P < 0.05$) are also denoted in each panel. (A) Weighted means of the εHf_t data from magmatic zircon plotted versus U/Pb age (in Ma). Vertical error bars represent $\pm$ 2σ; some errors are within the symbol size. The line for chondritic uniform reservoir (CHUR) is after Bouvier et al. (2008). (B) Whole-rock $\varepsilon_{Nd(t)}$ isotopic compositions versus U/Pb age (Ma) for Crawfish and Krestof granitoids and evolved (>63 wt %) enclave samples for which both of these metrics are available. The line for CHUR is after Jacobsen and Wasserburg (1980). (C) $^{87}Sr/^{86}Sr_{initial}$ whole-rock compositions versus U/Pb age (Ma) for Crawfish and Krestof granitoids and evolved (>63 wt %) enclave samples. The line for bulk silicate earth (BSE) at $^{87}Sr/^{86}Sr_{initial} = 0.7045$ is after Salters and Stracke (2004). (D) Chondrite-normalized Y concentrations (Sun and McDonough, 1989) plotted versus U-Pb age (Ma) for all Crawfish/Krestof granitoids and enclaves with >63 wt % SiO_2.

Figure 13. (A) All U/Pb, Ar/Ar, and K/Ar ages from across the SBB including data from Bradley et al. (1993, 2000, 2003), Haeussler et al. (1995), Sisson et al. (2003b), Zumsteg et al. (2003), and Farris et al. (2006) plotted alongside new concordant U/Pb ages reported here (n = 23). White crosses denote previously obtained ages (n = 54) from across the belt while other symbols represent new U/Pb analyses (n = 23) from this study with symbols as shown in Figure 6. The vertical error bars denote standard errors (± 2σ) around the mean age. (B) Concordant U/Pb ages for SBB intrusive rocks versus distance (along strike) from Sanak Island (in km). White crosses

represent previously obtained ages (n = 12, data compiled from Farris and Paterson, 2009). Other symbols represent new analyses (n = 23) reported in this study, with symbols as in Figure 6. Vertical error bars denote standard errors (± 2σ) around the U/Pb weighted mean ages (see Table 2 for complete U-Pb results from this study).

SUPPLEMENTAL MATERIAL

Supplemental Item 1. Detailed statistical methods and statistical model outputs.

Supplemental Figure S1. U-Pb ages and Concordia diagrams for Sanak-Baranof belt plutons.

Supplemental Figure S2. Point maps of zircon analyses.

Supplemental Table S1. Major and trace element compositions for SBB samples.

Supplemental Table S2. U-Pb geochronologic analyses from the Sanak-Baranof belt, Alaska.

Supplemental Table S3. Hf isotope data from the Sanak-Baranof belt, Alaska.

Please visit https://doi.org/10.1130/XXXX to access all of the supplemental material, and contact editing@geosociety.org with any questions. The formatted raw data and R code are also available from the authors upon request.