Subduction of a segmented ridge along a curved continental margin:
Variations between the western and eastern Sanak–Baranof belt, southern Alaska

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Abstract

Between the western and the eastern parts of the southern Alaskan Sanak–Baranof belt there exist variations in pluton spacing, geochronology, geochemistry and metamorphism. All such characteristics can be explained by increase in heat flux towards the eastern parts of the belt. Despite such differences, the initiation of magmatism propagated eastward at a constant rate of 19 cm/year throughout the entire belt. The average spacing of magmatic centers changes from 165±88 km in the west to 67±41 km in the east. The duration of magmatism as measured by U/Pb zircon and monazite ages increases from 1–2 Ma in the west to 4–5 Ma in the east. The duration of Ar–Ar biotite cooling ages also increases to the east. In agreement with the extended cooling times, large regions of greenschist and amphibolite facies metamorphism are present in the eastern segments, whereas outside of narrow pluton aureoles high-temperature metamorphism is not present in the western Sanak–Baranof belt. Finally, intrusions with adakitic characteristics such as high Sr/Y ratios are present in the east, but not in the west suggesting that some degree of slab melting occurred in the eastern Sanak–Baranof belt. We suggest that the above east–west thermal and magmatic variations can be explained by a decreasing rate of subduction and a persistent slab window in the eastern Sanak–Baranof belt caused by the oblique subduction of a segmented spreading ridge along a curved continental margin, and that this model is compatible with the Resurrection plate hypothesis.

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1. Introduction

The Sanak–Baranof belt of southern Alaska has been recognized as a forearc plutonic belt resulting from the subduction of a spreading ridge for almost thirty years (Marshak and Karig, 1977; Bradley et al., 2003 and references therein). Most previous workers have examined parts of the belt in isolation without integrating the individual parts into a comprehensive tectonic model (e.g. Pavlis and Sisson, 1995; Harris et al., 1996; Farris et al., 2006), examined the entire belt in a more general sense (e.g. Bradley et al., 2003), or focus on the younger aspects of its evolution (after 53 Ma, Madsen et al., 2006). The goal of this paper is to use spatial variations in pluton spacing, geochronology, geochemistry and metamorphic grade to determine a tectonic model that can explain first-order observations throughout the entire Sanak–Baranof belt.

2. Sanak–Baranof belt magmatism and origins

The southern Alaskan margin contains one of the most studied examples of spreading-ridge subduction related magmatism in the world (Marshak and Karig, 1977; Hudson et al., 1979; Hill et al., 1981; Moore et al., 1983; Bradley et al., 1993; Hudson, 1994; Haeussler et al., 1995; Bradley et al., 2003; Haeussler et al., 2003a,b; Pavlis and Sisson, 2003; Kusky et al., 2003). It is composed of a 2100 km belt of granitic and granodioritic plutons, referred to as the Sanak–Baranof belt, 2006). The goal of this paper is to use spatial variations in pluton spacing, geochronology, geochemistry and metamorphic grade to determine a tectonic model that can explain first-order observations throughout the entire Sanak–Baranof belt.
which intruded into an active accretionary prism (Fig. 1). These plutons vary continuously in age from 61 Ma in the west (Sanak Island off of the Alaskan Peninsula) to 50 Ma at its eastern edge on Baranof Island in southeast Alaska (Bradley et al., 2003). A slab window is considered to have formed beneath the accretionary prism as the spreading ridge was obliquely subducted. The ridge and the slab window juxtaposed young oceanic crust (<1 Ma old) and hot aethenospheric mantle against the base of the accretionary prism (Thorkelson, 1996). This led locally to voluminous partial melting of the accretionary prism graywackes and argillites, which formed the Sanak–Baranof belt plutons that we observe today (Hill et al., 1981, Moore et al., 1983, Barker et al., 1994; Harris et al., 1996; Sisson et al., 2003a,b).

Three main data sets support the idea that the Sanak–Baranof belt plutons formed as a result of spreading-ridge subduction. First is their forearc location. The plutons are located in an accretionary complex that was active at the time of their emplacement, and at that time they were within several 10’s of kilometers of the trench (Fisher and Byrne, 1987). Second, the Sanak–Baranof belt plutons exhibit a continuous series of eastward decreasing crystallization ages (Bradley et al., 1993, 1998 and 2003). This time transgressive series has been interpreted to record the migration of a trench–ridge–trench triple junction along the continental margin. Third, chemical studies of the Sanak–Baranof plutons have consistently argued that they are composed of a combination of melted accretionary prism sediments and mid-ocean ridge basalt (Hill et al., 1981, Moore et al., 1983, Barker et al., 1994; Harris et al., 1996; Lytwyn et al., 1997, 2000; Sisson et al., 2003a,b).

3. Models of Sanak–Baranof evolution

As discussed in the previous section, numerous previous workers have agreed on the idea that the Sanak–Baranof belt formed by the progressive subduction of a spreading ridge. However, in detail there are disagreements between the various models. Probably the largest single disagreement is what ridge was actually subducted (Fig. 2). The standard candidate is that the ridge separated the Kula and Farallon plates (Engebretsen et al., 1985; Londsdale, 1988; Atwater, 1989). However, these models are plate circuit reconstructions based on magnetic linear anomalies and oceanic crust that would uniquely identify the location of the ridge has been subducted. Consequently, there is significant ambiguity in the location of the ridge, and it has been postulated to have intersected the North American margin anywhere from Mexico to Alaska, although the latitude of modern day Washington is cited most often (e.g. Moore et al., 1983; Haeussler et al., 2003a,b). Therefore, the use of onshore geology, in particular the Sanak–Baranof belt, provides the best evidence for the location of the ridge.

An alternative candidate for identity of the Sanak–Baranof ridge has been proposed by Haeussler et al. (2003a,b), and Bradley et al. (2003). In this model an additional small plate,
known as the Resurrection plate, is postulated to have existed between the Kula and Farallon (Fig. 2). This model explains the southward decreasing age of the forearc magmatic rocks in Alaska (Bradley et al., 1993, 2003), forearc magmatic rocks in Washington and the 50 Ma cessation of arc magmatism in the Coast plutonic complex of British Columbia followed by the birth of the transform Queen Charlotte fault system (Haeussler et al., 2003a,b). In addition to explaining geologic observations from Washington to Alaska, it is suggested here that the Resurrection plate model also provides an explanation for many of the east–west thermal and magmatic variations in the Sanak–Baranof belt. Madsen et al. (2006) also espouses the Resurrection Plate model, but suggests that it split into northern and southern sections previous to final subduction. The Resurrection plate hypothesis is the preferred model in this paper, but it is perhaps, not uniquely required.

One mechanism to gain additional information about the Sanak–Baranof system is to determine if its internal variations are indicative of a particular plate model. One of the most significant Sanak–Baranof belt characteristics is the occurrence of large regions of high-temperature, low-pressure metamorphic rocks only in the eastern parts of the belt such as the Chugach metamorphic complex and Baranof Island. In the western parts of the belt high-temperature metamorphic rocks only occur in narrow pluton aureoles. Sisson and Pavlis (1993) and Pavlis and Sisson (1995) suggested the high temperatures in the Chugach metamorphic complex were due to multiple passes of a slab window. However, in Pavlis and Sisson (2003) they later discounted that hypothesis because it was not supported by geochronologic data (Bradley et al., 2003). Instead they suggested that highly oblique ridge subduction coupled with some degree of northward terrane transport led to the high temperatures. However, that proposal does not indicate why the Chugach metamorphic complex is substantially hotter than the rest of the belt.

The primary goal of this paper is to use observations from both the eastern and western parts of the Sanak–Baranof belt to provide a comprehensive view of the southern Alaskan Paleocene/Eocene slab-window evolution. Using the spatial, temporal, and chemical distribution of plutons we argue that internal variations within the Sanak–Baranof belt can be most simply explained by the subduction of three or four major transform fault bounded spreading-ridge segments along a curved North American margin. This explanation is most compatible with the Resurrection plate model of Sanak–Baranof evolution because it requires margin parallel ridge subduction in the eastern parts of the belt and southeast Alaska. Margin parallel ridge subduction led to hot young oceanic crust and the slab window itself to be present for an extended period of time underneath the eastern parts of the belt which led to the generation of numerous thermal and magmatic effects.

4. Spatial patterns of Sanak–Baranof belt slab-window magmatism

4.1. Spatial analysis procedure/methods

Sanak–Baranof belt plutons between the age of 65 and 45 Ma were digitized to examine their spatial distribution. The chosen age distribution includes all near-trench plutons thought to be associated with triple-junction migration, but excludes a younger population of approximately 35 Ma plutons in the Prince William Sound region (Nelson et al., 1986). The primary maps from which pluton locations were digitized are Bradley et al. (2003) and Beikman (1980). Higher resolution maps were
4.2. Large-scale Sanak–Baranof belt spatial patterns

The first-order observation of Sanak–Baranof pluton spatial periodicity is that a uniform distribution of magmatism does not exist (Fig. 3). Instead plutons are grouped spatially together, and there are regions of high magmatic density separated by magmatic gaps that contain no plutons. In magmatic systems worldwide this is not an uncommon feature (e.g. Marsh, 1982; De Bremond d’Ars et al., 1995, Pelletier, 1999).

The broadest trend in the spatial distribution of Sanak–Baranof belt plutons is that they occur in three groups separated by regions that contain no exposed plutons and related magmatism (Figs. 1 and 3). We refer to each segment based on its geographic location: the Sanak–Kodiak segment, the Kenai–Prince William Sound segment and the Yakutat–Baranof segment. In addition to the spatial distribution, these three segments also contain metamorphic, geochronologic and geochemical commonalities that link the plutons together.

The spatial distribution of plutons in the Sanak–Kodiak segment is least well constrained because most of this region is under water. However, Sanak–Baranof granitic rocks are far more resistant to erosion than the surrounding accretionary prism sediments. For example, on Kodiak Island, the Kodiak batholith granitoids forms the high spine of the Island, and surrounding Kodiak Formation rocks are lower lying. Also near Seward, granitic islands extend far offshore, whereas their Valdez Group host rocks are exposed only to the coast.

Due to the erosional resistance of the plutons, even if they are not exposed on land, they should be exposed underwater, or at least have some type of geophysical signature. Using satellite seafloor altimetry (Smith and Sandwell, 1997), the only serious candidate for submerged plutons is between the Shumagin and Semidi Islands (Fig. 4). This region also contains a gravity anomaly suggestive of plutons. On the eastern side of Kodiak and Afognak Islands the EDGE seismic transect exists and does not indicate submerged granitic plutons (Ye et al., 1997). Therefore the plutonic gap between Kodiak and the Kenai Peninsula likely reflects reality. In the eastern Sanak–Baranof belt, a plutonic gap also exists, but the Malaspina and other large glaciers cover most of this area. Glaciers, combined with access difficulty due to extreme terrain, make the validity of the eastern gap uncertain.

4.3. Spacing of individual plutons

A common method of examining the spatial distribution of objects is the nearest-neighbor analysis. In this calculation, the distance from an initial pluton to the closest adjacent pluton is measured. The results are then plotted on a histogram, and compared to certain types of known distributions (i.e. a Rayleigh distribution). Using this type of analysis we find that the Sanak–Baranof belt plutons exhibit a nearest-neighbor spacing with a peak at 15–20 km followed by an asymmetric tail in the direction of increasing distance (Fig. 5). However, alteration of the bin spacing changes the histogram to some degree. With a bin spacing of 5 km a well-defined asymmetric pattern is observed (Fig. 5A). The bulk of the plutons occur within 50 km of each other, but there are some outliers up to 200 km away. Such outliers are individual plutons that occur on islands off of the Alaskan Peninsula. If the 50 km in which most of the plutons occur is analyzed at a narrower 2.5 km bin spacing (Fig. 5B), the histogram becomes almost symmetrical. However, it does have a small asymmetric tail composed of 5 plutons extending from 30–50 km. Symmetrical histograms are often modeled as normal or Gaussian distributions. Overall, we consider the Sanak–Baranof belt nearest-neighbor distributions asymmetric because a ‘tail’ is observed at several spatial scales. De Bremond d’Ars et al. (1995) equated this histogram shape to a Gamma distribution. However, the Sanak–Baranof data is better fit by Poisson or Rayleigh distributions, both of which are used to describe certain types of random phenomena.

Fig. 3. Histogram of Sanak–Baranof belt along strike pluton area with 50 km bins. Three 500–600 km long first-order segments between Sanak–Kodiak, Kenai–Prince William Sound, and Yakutat–Baranof are present. Pluton gap A may contain underwater plutons, but B and C are likely real (Fig. 4). Gap D suffers from glacier induced exposure problems. The average spacing of magmatic centers changes from 165±88 km in the western parts of the Sanak–Baranof belt to the 67±41 km in the Yakutat–Baranof segment.
5. East/West variations in the Sanak–Baranof belt

5.1. Spacing of magmatic centers

Histograms of pluton area per unit distance were used to analyze along strike pluton spatial variations within the Sanak–Baranof belt (Fig. 3). A 50 km along strike bin size was used because it provided the best balance between resolution and sample size. Overall, the histogram indicates that pluton area is not uniformly distributed along strike in the Sanak–Baranof belt. Instead, it is clustered. The three previously defined segments are visible (Sanak–Kodiak, Kenai–Prince William and the Yakutat–Baranof) as well as a change in the average spacing of pluton area peaks from the western to the eastern parts of the Sanak–Baranof belt. For the purpose of this analysis, a peak is arbitrarily defined as any 50 km bin that contains greater than 100 km² of pluton area. The Yakutat–Baranof segment in the east has an average peak spacing of 67 ± 41 km, whereas the western three segments have a larger peak spacing of 165 ± 88 km. To test the statistical reality of this difference an analysis of variance (ANOVA) was carried out between the two means. ANOVA tests compare within-group variability to between-group variability and give a probability of that result (P-value). The F-test is a ratio of between-group to within-group variability. High values of F indicate that the two groups are statistically different, and an F-value of one indicates that they are the same. The means of the peak spacing within the eastern and western portions of the Sanak–Baranof belt have an

Fig. 4. Geosat and ERS 1 seafloor topography and gravity. Seafloor topography and gravity data suggest that the region between the Shumagin and Semidii Islands may contain submerged Sanak–Baranof pluton, but the regions to the east and west of Kodiak and Afognak Islands do not. A. Seafloor topography (Smith and Sandwell, 1997). Rugged seafloor topography between the Shumagin and Semidii islands is suggestive of submerged plutons due to their erosional resistance. B. Shaded oceanic gravity data (Sandwell and Smith, 1997). The same region of rugged seafloor topography also contains gravity anomalies suggestive of intrusive bodies.
\(F\)-test value of 6.46, which indicates that they are different groups despite overlapping one-sigma uncertainties of peak spacing. The \(P\)-value of this result is 0.023, which indicates a 97.7% probability that the result is correct. \(P\)-values are considered ‘statistically valid’ if they are <0.05, and our result is well within that range.

The peak spacing in the eastern part of the Sanak–Baranof belt is very close to the bin size of the histogram, and therefore indicates that at the scale of this analysis, magmatism is essentially continuous within this zone. The >100 km\(^2\) peak spacing calculated in the rest of the Sanak–Baranof belt is approximately three times the bin size and demonstrates that the spacing is real. Also, even if some of the pluton distribution can be explained by exposure issues, the observed pattern is still robust enough to draw conclusions.

5.2. Geochronology

Over a distance of 2100 km the Sanak–Baranof belt plutons systematically decrease in age from Sanak Island on the west (61 Ma) to Baranof Island on the east (50 Ma). Bradley et al. (2003) and Farris et al. (2003) have argued that Sanak–Baranof belt plutons track the location of the triple junction. Therefore we can use the two end points to calculate a rate of triple-junction migration of approximately 19 cm/yr. Bradley et al. (2003) compiled existing radiometric dates for the Sanak–Baranof belt on to a series of plots that show age versus distance from Sanak Island with K/Ar ages on one diagram and U/Pb and Ar/Ar methods on another. The U/Pb and Ar/Ar dates exhibit a much more strongly defined trend than do the K/Ar ages. As the resolution of dating techniques has increased so has the clarity of the Sanak–Baranof belt age trends. The plots here (Fig. 6) build on those of Bradley et al. (2003) and incorporate newer data. The slope of a least squares regression curve through all of the age data on a plot of distance from Sanak Island versus time yields a more quantitative estimate of the rate of triple-junction migration than using the two end points alone. We have used a linear regression for two main reasons. First, the data appears linear and so a straight line is the simplest solution, secondly because in plate tectonics a TRT triple junction is likely to produce a linear age progression. We used several different groupings of Sanak–Baranof belt geochronologic data and all yielded rates varying between 16–20 cm/yr. The most selective group of data is from concordant U/Pb zircon and monazite ages. These ages also yield the best fit using a least squares linear regression. The linear regression indicates a
Fig. 6. Geochronologic data from the Sanak–Baranof belt. Data is from Bradley et al. (1993, 1998, and 2003), Haeussler et al. (1995), Sisson et al. (2003a,b) and Farris et al. (2006). A. Concordant U/Pb zircon ages. This is the most selective grouping of ages and yields the highest precision linear regression. It is our best estimate of the average triple-junction migration rate. B. High-temperature ages, including all U/Pb and Ar/Ar hornblende dates. At 1400 km from Sanak Island the duration of magmatism increases by several million years. C. All U/Pb and Ar/Ar dates; includes data from Fig. 6a and b plus Ar/Ar biotite and white mica ages. From the Kenai segment eastward cooling times increase. The increase is correlated with appearance of high Sr/Y ratio intrusions.
migration rate of 19.6 cm/yr, and has an $R^2$ value of 0.95 (Fig. 6A). The data fit well in the Sanak–Shumagin and Kodiak segments, but step below the line in the Kenai–Prince William sound segment. If a linear regression is performed separately on the Sanak–Kodiak and Kenai–Prince William Sound data a rate of 22 cm/yr is obtained for each segment. The age step between the two segments augments the spatial data indicating a magmatic gap, and strongly suggests a tectonic origin.

In the second data grouping, high-temperature Sanak–Baranof belt ages, including concordant and discordant U/Pb and Ar/Ar hornblende dates, have been plotted (Fig. 6B). There is more data, but the additional Ar/Ar hornblende dates record a temperature below the granite solidus. The concordant U/Pb age linear regression predicts the first onset of magmatism at any point along strike. Also of note is that towards the east side of the Sanak–Baranof belt, the duration of plutonic activity at any one point along strike increases significantly. For the first 1300 km from Sanak Island high-temperature ages indicate magmatic activity for $<1–1.5$ Ma at any point along strike, whereas east of that point magmatism persists for 2–4 Ma (Fig. 6B).

In the third Sanak–Baranof belt age grouping all “modern” ages (all U/Pb and Ar/Ar, after Bradley et al., 2003) have been plotted (Fig. 6C). The major change of this data set from the previous two is the addition of Ar/Ar biotite and sericite ages. The biotite ages record cooling through approximately 350 °C and not pluton crystallization. The sericite ages are mainly from gold-quartz veins thought to be associated with the sub-window event (Hausseler et al., 1996). Even with the increased variety of data the concordant U/Pb regression predicts the initiation of magmatism throughout the Sanak–Baranof belt. In the west part of the Sanak–Baranof belt cooling times are much shorter (1–2 Ma) than those in the east (up to 5 Ma). A sharp jump in cooling times occurs at the boundary between the Kodiak and Kenai–Prince William segments. The jump in cooling times also correlates with changes in pluton chemistry to be discussed in the subsequent section, but to preview, western segments with low cooling times have low Sr/Y ratios, whereas eastern segments with high Sr/Y ratios have long cooling times.

5.3. Pluton chemistry

The dominant interpretation of the geochemical origin of Sanak–Baranof belt plutons is that they are a combination of greywacke and argillite derived accretionary prism melts and a mantle derived component basaltic component, such as MORB (Hill et al., 1981; Moore et al., 1983; Barker et al., 1994; Harris et al., 1996; Sisson et al., 2003a,b; Ayuso et al., 2005; Farris, 2006; Farris and Paterson, 2007). Some variation in the relative amounts of mantle derived versus accretionary prism sediments exists from study to study, but the general conclusion as to the two main components does not. On a local scale there is more variability than suggested above, but the goal here is to examine large-scale change. Below we present data that indicate the Sr/Y ratio of near-trench intrusions increases from the western to eastern sides of the Sanak–Baranof belt. These data are a combination of XRF (Hill et al., 1981; Barker et al., 1992; Tangalos et al., 2003), ICP-MS (Sisson et al., 2003a,b; Kodiak data presented here), and ICP-AES (Bradley et al., 2003).

The chemistry of the Sanak–Baranof belt plutons systematically changes from west to east (Fig. 7). Plutons from the Chugach metamorphic complex (eastern Sanak–Baranof belt) exhibit high Sr/Y ratios (>50), high overall concentrations of Sr (>2–300 ppm), Al$_2$O$_3$ >15.0%, and flat to moderately LREE enriched REE patterns that do not contain a Eu anomaly (Sisson et al., 2003a,b; Harris et al., 1996). In contrast, intrusions from the western parts of the Sanak–Baranof belt (Sanak, Shumagin and Kodiak) contain low Sr/Y ratios (<25), LREE enriched REE curves with well developed Eu anomalies, and lower Sr (<300 ppm) (Hill et al., 1981; Moore et al., 1983).

The trends outlined above are generally valid, but locally the situation is more complex. For example, Sisson et al. (2003a,b) identified four different generations of near-trench intrusions in the Chugach metamorphic complex (eastern Sanak–Baranof belt). Their first generation ($T_1$) has similar geochemical characteristics to the plutons of the western Sanak–Baranof belt, whereas the later episodes ($T_{1–4}$) are as described previously. The later three pulses have a larger mantle derived component that is reflected in the radiogenic isotopes with $\varepsilon_{Nd}$ and $^{87}$Sr/$^{86}$Sr values of 1 to 8 and 0.703–0.7045, respectively (Sisson et al., 2003a,b). The first generation intrusions have isotopic values similar to that of Valdez Group metasediments ($\varepsilon_{Nd}$ and $^{87}$Sr/$^{86}$Sr values of 1 to 3 and 0.705–0.707, respectively). Geochemical modeling by Sisson et al. (2003a,b) has suggested that the first generation is composed of 50–80% meta-sedimentary melts and 50–20% mantle derived basalt, whereas in later generations of melt the percentages are reversed (50–80% mantle derived basalt).

The Kenai–Prince William segment appears to have intrusions that are transitory between the end members of the western and eastern Sanak–Baranof belt (Fig. 7B). Certain plutonic suites have chemistry similar to that of the Sanak–Shumagin–Kodiak regions. For example, the plutonic suite described by Barker et al. (1994) located near Cordova in the eastern Prince William sound has many chemical similarities with the western Sanak–Baranof belt plutons, including a low Sr/Y ratio (Fig. 7B). Barker et al. (1994) concluded that these plutons were derived from high percentage partial melts of accretionary prism sediments and MORB in an approximately 70/30 ratio. Hill et al. (1981 and 1982), Ayuso et al. (2005) and Farris (2006) concluded that the Shumagin and Kodiak batholiths formed from similarly high ratios of sediment and basalt.
Fig. 7. Sr/Y versus Y ratios for Sanak–Baranof plutons. Overall, high Sr/Y ratios suggest some degree of slab melting occurred in the eastern two Sanak–Baranof belt segments. A. Plutons in the Sanak–Kodiak segments have low Sr/Y ratios and do not have an adakitic signature. Data is from Hill et al. (1981), Tangalos et al. (2003) and this paper. B. In the Kenai–Prince William sound segment some dikes and plutons exhibit adakitic characteristics, however plutons near Cordova generally lack a high Sr/Y signature. The Cordova data is from Barker et al. (1992) and Seldovia data is from Bradley et al. (2003). C. In the Yakutat–Baranof segment certain intrusions also plot in the adakite field. Data is from Sisson et al. (2003a,b).
however Barker et al. (1994) also analyzed one felsic dike and it had a Sr/Y ratio similar to those found on the Kenai Peninsula.

The Kodiak region also contains magmatic complexities when examined in detail (Farris, 2006, 2007). Kodiak Island has two main belts of Paleocene magmatism: The granitic Kodiak batholith, which intruded into the center of the turbidite dominated Kodiak Formation, and the trenchward belt, which intruded into the Ghost Rocks Formation. Modeling of trace, REE and oxygen isotope data indicate that the Kodiak batholith formed by equilibrium crystallization of high melt fractions (F = 1.0–0.5) of garnet and graywacke, had garnet as a residual phase, and was derived from >80% sedimentary sources with only a small basaltic component. In comparison, the trenchward belt rocks formed by assimilation fractional crystallization of a MORB source with an garnet, and contained no garnet.

Despite the significant local complexity of Sanak–Baranof plutons, regional variations with tectonic significance do exist. Plutons on the east (Fig. 7B and C) and the west side (Fig. 7A) of the Sanak–Baranof belt each contain distinct geochemical signatures. The diagnostic features of the western Sanak–Baranof belt segments are low Sr/Y ratios, a large negative Eu anomaly on REE curves and a high percentage of assimilated sediments. In contrast, the eastern Sanak–Baranof belt plutons have high Sr/Y ratios, a greater mantle derived component and they lack a Eu anomaly. In the Kenai–Prince William sound segment, dikes tend to have the chemical characteristics of the eastern Sanak–Baranof belt, whereas some plutonic suites of the west.

These variations are important because high Sr/Y ratios are often indicative of an increased component of slab melting, suggesting that in the eastern Sanak–Baranof belt slab melting and the generation of adakitic melts was an important process (Harris et al., 1996), whereas in the western segments, it was not.

5.4. Host-rock metamorphic grade

Another variation between the eastern and western parts of the Sanak–Baranof belt is metamorphic grade. Along the entire Sanak–Baranof belt, plutons locally increase the metamorphic grade. However, the western Sanak–Baranof belt, from Sanak Island to the Prince William Sound, is characterized by a relatively low-grade prehnite–pumpellyite facies metamorphism (Sample and Moore, 1987). In contrast, the eastern Sanak–Baranof belt, extending from the Chugach Metamorphic Complex to Baranof Island, contains large regions with a much higher greenschist to amphibolite facies metamorphic grade (Hudson et al., 1979; Hudson and Plafker, 1982; Sisson et al., 1989; Pavlis and Sisson, 1995; Zumsteg et al., 2003). These observations correlate with the extended duration of plutonism and cooling times discussed in the previous section.

6. Discussion

6.1. Western versus eastern Sanak–Baranof belt

Overall, the Sanak–Baranof belt contains systematic spatial differences in pluton spacing, geochemical characteristics, geochronology and degree of regional metamorphism that all indicate a significantly greater input of heat into the eastern part of the system. This study has also shown that there is a statistically real difference in pluton spacing between the eastern (67±41 km) and western (165±88 km) portions of the belt (Fig. 3). Closer pluton spacing and a higher regional metamorphic grade are correlated with each other. The western portion of the belt is characterized by low prehinite–pumpellyite grade regional metamorphism (Sample and Moore, 1987), whereas large parts of eastern Sanak–Baranof belt, such as the Chugach metamorphic complex (Pavlis and Sisson, 1995) and Baranof Island (Zumsteg et al., 2003), are characterized by green schist and amphibolite facies metamorphism. Zumsteg et al. (2003) has shown that at least on Baranof Island the higher metamorphic grade cannot be related solely to the plutons. Whatever process caused the greenschist and amphibolite facies regional metamorphism in the eastern Sanak–Baranof belt probably also led to the higher density of plutons. In addition, the overall duration of magmatism (U/Pb ages) and the cooling times (Ar/Ar biotite) are longer in the eastern segments than in the west (Fig. 6C). All of these observations can be explained by a greater or longer lasting input of heat into the eastern Sanak–Baranof belt.

Geochemical data from the Kenai–Prince William Sound and Yakutat–Baranof segments indicate that some of the intrusions have adakitic characteristics, whereas plutons to the west in the Sanak through Kodiak segments do not. Harris et al. (1996), Lytwyn et al. (2000) and Sisson et al. (2003a,b) have all previously reported adakite-like intrusive rocks in the Seldovia region and the Chugach Metamorphic complex. Adakites are thought to be derived from slab melts (Drummond and Defant, 1990) and can be identified by high Al2O3 (>15%), high Sr/Y ratios (>50), high Sr (>300 ppm), low heavy REEs, lack of a pronounced Eu anomaly and low Y (<15 ppm). Also, the term adakite was defined for volcanic rocks, but some tonalite, trondhjemite, and granodiorite (TTG) suites have similar geochemical signatures and origin (Drummond and Defant, 1990). Therefore, the Sanak–Baranof intrusive rocks with this signature are termed adakite-like. Alternatively, intrusive rocks with adakite-like characteristics have been reported from thick crustal locations caused by eclogite melting at their base, including: the Tibetan Plateau (Gao et al., 2007) and the Andes (Stern and Kilian, 1996; Garrison and Davidson, 2003). However, a thick crustal origin for Sanak–Baranof adakite-like rocks is unlikely because they formed in a forearc <15 km thick. Young hot oceanic crust at this depth will contain metamorphic hornblende (Peacock, 1996); therefore partial melting of it could produce an adakite signature. Thorkelson, 2001, and Breitsprecher (2005) argued that adakitic melts should be common in slab-window systems, and in the eastern Sanak–Baranof belt some, but not all intrusive rocks contain these characteristics. However, in the western part of the belt (Sanak–Kodiak) a slab-melt signature is not present. One of the reasons that oceanic crust does not normally melt during subduction is that it is not hot enough (Drummond and Defant, 1990). A prolonged or greater intensity thermal event could explain the evidence for slab melting in the eastern Sanak–Baranof belt.
6.2. Slab-window thermal modeling

To place constraints on variables that influence metamorphic temperatures, cooling times and the volume of magma production in the Sanak–Baranof belt a one-dimensional thermal model of a slab window was constructed (Fig. 8). The model is of a similar nature to James et al. (1989) thermal modeling of the Chugach Metamorphic complex in which they examined the thermal effects of the subduction of very young oceanic crust. However, the model used here examines the thermal evolution above a stationary instantaneously emplaced slab window. The rationale behind the model is to provide first-order constraints on the thermal effects in this tectonic environment. The slab window and the region above it is modeled by the instantaneous heating of a semi-infinite half space (Turcotte and Schubert, 1982):

\[ T = \text{erfc}(y/(2*\kappa*t)) \times (T_m - T_o) + T_o. \]

The model tracks the temperature evolution of a point above the center of the slab window that is not affected by processes at the slab-window margin. \( T \) is the temperature at a distance \( y \) above the slab window, \( T_m \) is the temperature of the slab window, \( T_o \) is the initial temperature of the half space and \( t \) is amount of time the half space has been in contact with the slab window. In the models \( T_m=1400 \) °C, and \( T_o=227 \) °C. These values were chosen because 1400 °C is the average ambient temperature of the aesthenosphere (Wilson, 1989) and is therefore a likely slab-window temperature and 227 °C is the estimated Kodiak Formation temperature when it was part of the active accretionary prism (Sample et al., 1987). \( \kappa \) is the thermal diffusivity of the half space and \( \text{erfc} \) is the complimentary error function. This model treats the slab window as an infinite plane in which temperatures can be calculated at specific times and distances above the slab window. The slab window is a constant heat source, and therefore as \( t \to \infty \), \( T_o \to T_m \). All heat is transferred via conduction. Slab-window migration or advective and convective processes are not taken into account.

Thermal effects from the model indicate that rock within one kilometer of the slab window (at a depth of 15–20 km (Farris et al., 2006)) would be heated far above the 5 kbar 800 °C greywacke solidus (Stevens et al., 1995) in less than 100,000 years (Fig. 8). Over this same time period rocks located >5 km away would be heated <50 °C above ambient 514 accretionary prism temperatures, and there would be little metamorphic mineral growth in those rocks. By 200,000 years, rocks 5 km away would have reached temperatures >400 °C and should begin to grow recognizable metamorphic minerals. However, rocks located 10 km away would still show no thermal effects, and it would take almost 700,000 years for such rocks to intersect the approximately 350 °C biotite isograd. The implication of this model is that rocks close to the slab window will melt, whereas rocks located greater than 5 to 10 km away will feel little if any slab window related thermal effects over time scales of several hundred thousand years.

6.3. Slab-window thermal effects

The majority of existing data indicate that plutons in both the eastern and western parts of the Sanak–Baranof belt are related to slab-window processes (Hill et al., 1981; Moore et al., 1983; Bradley et al., 1993; Pavlis and Sisson, 1995; Bradley et al., 1998, 2003 and Sisson et al., 2003a,b; Kusky et al., 2003; Farris et al., 2006). Therefore some aspect of the slab-window evolution must differ from the eastern and western segments in order to explain the observed variation in regional heat.
budget. Our previously described thermal modeling provides some first-order constraints on how hot a given region will become due to slab-window passage. According to the model, the two dominant variables influencing final regional temperature are: 1) Depth to the slab window and 2) The length of time the slab window resides under a given location. Decreasing depth and increasing time will both lead to higher regional temperatures, whereas the reverse will leave little thermal signature of slab-window passage. There is evidence that both processes were operative in the eastern Sanak–Baranof belt.

Throughout the Chugach terrane, peak pressures are relatively constant at 2–3 kbar (Sample and Moore, 1987; Vrolijk, 1987; Sisson and Pavlis, 1993). However, on Baranof Island, Zumsteg et al. (2003) measured metamorphic pressures in the Sitka greywacke ranging from 3.4 to 6.9 kbar. They stated that the range in pressures reflect incomplete equilibration along a clockwise $P$–$T$ path. However, Brew et al. (1991) calculated pressures of 3 kbar from the Crawfish Inlet pluton (a Sanak–Baranof belt pluton on Baranof Island) using Al-in-hornblende barometry. Overall, data from Zumsteg et al. (2003) suggests that Baranof Island may have been exhumed to a deeper level than the rest of the belt. Therefore, the rocks currently exhumed on Baranof Island could have been much closer to the slab window than the rest of the Sanak–Baranof belt. This would account for part if not all, of its higher metamorphic grade, but such an explanation does not work for the high-temperature Chugach metamorphic complex in which the greatest reported pressures are around 3 kbar (Sisson and Pavlis, 1993).

Another way to increase heat input is to slow down the migration of the slab window/triple junction. Slowing down the slab window would cause hot young oceanic lithosphere and the slab window itself to reside underneath a given location for a longer time period. Based on thermal modeling, James et al. (1989) came to the conclusion that the high-temperature metamorphism in the eastern Chugach mountains could be explained by the subduction of oceanic crust of <1 Ma as well as a slab window. We suggest that the variety of high-temperature characteristics present in the eastern Sanak–Baranof belt resulted from a slab window that resided under the region for an extended duration coupled with locally greater exhumation.

### 6.4. Kinematic evolution of the Sanak–Baranof belt

Modeling and observational data suggests that increasing the time the slab window spent under the eastern Sanak–Baranof belt is one of the primary mechanisms by which it acquired its high-temperature characteristics. However, understanding why the slab window stalled under that region is primarily a kinematic and tectonic question.

In the previous examination of pluton spacing, three segments separated by gaps and also grouped by geochemical characteristics were identified. These were the Sanak–Kodiak, the Kenai–Prince William Sound and the Yakutat–Baranof segments. Each of these segments has a length that is similar to that of first-order mid-ocean ridge segmentation (MacDonald et al., 1991), and therefore we propose a working hypothesis that the large-scale segmentation of the Sanak–Baranof belt is the result of segmentation in the subducting ridge that led to its formation.

MacDonald et al. (1991) identified four levels of mid-ocean ridge segmentation: First-order segments are 600±300 km long and are bounded by large transform faults, second order segments are 140±90 km in length and are separated by discontinuities such as oblique shear zones and jogs in the axial rift valley, third order segments are 50±30 km long and are bounded by inter-volcano gaps and fourth order segments have spacing of 14±8 km and result from offsets of axial summit caladeras. The different length scales of magmatism are due to the periodicity of mantle upwelling along a mid-ocean ridge (Le Mée et al., 2004). In addition to the large-scale segmentation, the Sanak–Baranof belt also contains magmatic centers with spacing of 200 km in the western segments, third (Yakutat–Baranof segment) 200 km and forth order (individual plutons) mid-ocean ridge segmentation. While not uniquely identifying mid-ocean ridge segmentation as responsible for Sanak–Baranof magmatic periodicity, the similarity at multiple length scales is strongly suggestive.

The two-dimensional distribution of pluton can also yield information about how the local kinematics of plate motion changed throughout the Sanak–Baranof belt. This section is placed in the discussion because it is somewhat speculative, but potentially quite informative.

In the Kodiak portion of the Kenai–Kodiak segment and the Kenai–Prince William Sound and Yakutat–Baranof segments there exist wedge shaped distributions of plutons when their map view locations are plotted with respect to the Border Ranges fault and their distance from Sanak Island (Fig. 9). Pluton locations are plotted with respect to the Border Ranges fault because it forms the backstop to the Chugach accretionary complex and is present throughout the entire belt. These wedge shaped pluton distributions are potentially related to the progressive subduction of an individual ridge segment, and could form as the resulting slab window penetrated further into the accretionary prism.

Throughout the Sanak–Baranof belt, the rate of along strike migration of the plutons allows a migration rate for the triple junction to be calculated (Fig. 6). This rate, if based on the initiation of forearc magmatism, is constant throughout the entire belt at a rate of 19 cm/yr ($v_m$). This rate, when combined with length ($L$) and widest point of each pluton wedge ($W$) allows a rate of trench perpendicular convergence ($v_c$) to be calculated.

$$v_c = W/(L/v_m).$$

With the rate of trench perpendicular convergence, the angle between the ridge and the trench ($A_r$) can also be calculated using:

$$A_r = \tan^{-1}(v_c/v_m).$$

These calculations indicate that the rate of trench perpendicular convergence decreased from 11 cm/yr in the vicinity of the Kodiak Island (a second order ridge segment) to approximately 2 cm/yr in the Yakutak–Baranof segment, and also that the
angle between the ridge and trench decreases from $30^\circ$ to $5^\circ$–$10^\circ$, respectively (Table 1).

An independent check on the above convergence rates can be obtained by comparing them to rates calculated from the different plate models. Haeussler et al. (2003a,b) derived plate velocity triangles for the Kula, Resurrection and Farallon plates based on the plate circuit reconstructions of Stock and Molnar (1988). According to those estimates the Kula–North America and the Resurrection–North America velocities range from 11.6 to 10.2 cm/year. Those values are similar to reconstructions...
6.5. Oroclinal rotation, northward transport and tectonic models

The next question is why did the rate of subduction apparently slow only in the eastern part of the belt? One viable explanation is that the southern margin of Alaska was still curved at 60 Ma (Plafker et al., 1989, 1994). Cae et al. (1989) estimated that approximately 44 ± 11° of oroclinal rotation occurred since that time period. Cole et al. (2006) states, based on volcanism in the Talkeetna Mountains, that oroclinal rotation initiated in the time interval 57–52 Ma after the spreading ridge had passed. However, prior to oroclinal rotation an angle of approximately 120° still existed between southern and southeast Alaska. Some or all of the two eastern Sanak–Baranof segments would have been located on the northwest trending side of the bend, and these are the two segments that indicate decreased rates of convergence. These two segments also suggest a very shallow angle between the ridge and trench (5°–10°). Therefore, as the spreading ridge approached the bend in the continental margin the angle between the ridge and the trench would have decreased leading to a situation in which only young hot buoyant oceanic crust was being subducted for a great distance along strike. As subduction continued, the trailing edge of the plate would have gone down the trench and exposed a large long lasting slab window.

One potential criticism of this model is that paleomagnetic evidence indicates significant northward transport of the Chugach accretionary terrane (Plumley et al., 1983; Bol et al., 1992). For example, Bol et al. (1992), in a study of the Resurrection Peninsula ophiolite (Nelson et al., 1989), reported northward translation of 13 ± 9°. In comparison, paleomagnetic data from the inboard Wrangelia terrane suggests no northward translation in rocks as old as 55–65 Ma (Hallis and Coe, 1994). Bradley et al. (2003) contains a more detailed discussion of these issues, but overall geologic displacement on faults does not support such large northward displacements.

One study that explicitly focuses on northward translation of Sanak–Baranof rocks is Roeseke et al. (2003) who proposed that upwards of 1000 km of northward dextral slip occurred on the Border Ranges/Hanagita fault systems (Fig. 1) between the Late Cretaceous and Middle Eocene. However, geologic evidence from multiple locations in southern Alaska indicates that motion on the Border Ranges fault system largely ended by the time of triple-junction passage. On Kodiak Island, dikes the same age as the Kodiak batholith (58 Ma) are present north of the Border Ranges fault (Davies and Moore, 1985; Clendenen et al., 2003).

Little and Naeser (1989) identified similar sedimentary units across the fault in south central Alaska, and Johnson and Karl (1985) have shown that the 51 Ma Lake Eldendale pluton plugs the fault in southeast Alaska. Due to these across fault linkages large displacements (>10°–100 km) on the Border Ranges fault since 50–60 Ma are unlikely, however prior to triple-junction passage, significant movement, on the order described by Roeseke et al. (2003), could have occurred. Subsequent northward translation is likely to have occurred on more inboard faults such as the Denali and Tintina (Bradley et al., 2003).

Another model of Sanak–Baranof evolution that depends on significant northward terrane transport is that of Cowan (2003). In this study Cowan (2003) proposed that the subducting ridge was located at the present day latitude of Washington State and orientated at a high angle with respect to Alaska. Due to this orientation the ridge was therefore near stationary. The age progression of Sanak–Baranof intrusions was derived by the northward migration of the Chugach terrane past the ridge. An advantage of this model is that it explains similarities between the Leech River schist on Vancouver Island and rocks on southern Baranof Island located 1100 km to the north. In the Cowan (2003) model, the Leech River schist is simply a fragment that got left behind. However, a large problem with this model is that it requires slip rates on forearc faults of 19 cm/yr over a 10+ million year period. Such rates are extremely high. In general fault movement typically takes up a fraction of...
plate motion, not a multiple of it, and whatever the plate model, convergence rates between North America and the outboard plates were on the order of 10–12 cm (Stock and Molnar, 1988). Data sets presented in this paper strongly argue for oblique ridge subduction to obtain the high rates of age migration in the Sanak–Baranof belt.

The most detailed work on the Chugach metamorphic complex has been done by Pavlis and Sisson (2003), Pavlis et al. (2003) and Sisson et al. (2003a,b). This region is important because it contains the highest grade of regional metamorphism in the Sanak–Baranof belt. Pavlis et al. (2003) and Pavlis and Sisson (2003) have identified multiple deformation episodes that record a complex history of transtensional ductile deformation that occurred simultaneously with high-temperature Sanak–Baranof metamorphism. This contrasts with syn-triple-junction structures observed on the western parts of the belt. For example, tectonically formed magmatic fabrics in the Kodiak batholith are interpreted by Farris et al. (2006) to record little or no shear, but instead formed near perpendicular to the direction of subduction. Overall, Pavlis and Sisson (2003) indicate that the combination of northward terrane transport, southward triple-junction migration, oblique ridge subduction coupled with a 54 Ma plate reorganization involving a ridge-transform boundary (Sisson et al., 2003a,b) led to the anomalously high regional metamorphic temperatures observed in the Chugach metamorphic complex. In general, the Pavlis and Sisson (2003) model fits into what is being espoused in this paper, but there are some caveats. First, as previously mentioned, the degree of northward terrane transport must be <10′s–100 km. Second, the ridge segment subducted at 54 Ma must be a second order or smaller ridge segment (MacDonald et al., 1991). Third, the degree of oblique subduction in the eastern part of the belt must be greater than in the west. However, one incompatibility between the Pavlis and Sisson (2003) model and this paper is that they argue for Kula, Farallon and North America plate configuration.

The Resurrection plate model best fits the geological data presented in this paper, and provides a simple coherent explanation for east directed systematic increase in the Sanak–Baranof thermal and magmatic budget. The Sanak–Kodiak segment has a low regional metamorphic grade, widely spaced magmatic centers, no evidence of slab-melt component in the forearc intrusions, moderate ridge–trench obliquity and a fast rate of trench perpendicular convergence. The Kenai–Prince William segment is transitional in that it has Sanak–Kodiak like plutons in the Kenai (Kusky et al., 2003), high-temperature metamorphism on its eastern edge, overall moderate cooling times, some evidence of slab melting, widely space magmatic centers, but has kinematic evidence for more oblique subduction and slower rates of convergence. In comparison the Yakutat–Baranof segment exhibits primarily higher temperature characteristics with longer time scales of cooling and magmatic intrusion, high grades of regional metamorphism, closely spaced magmatic centers, slab melting, and the most oblique ridge subduction and the slowest.

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Fig. 10. Theorized Sanak–Baranof spreading-ridge segmentation and characteristic differences between the eastern and western parts of the belt. These observations can be explained by oblique subduction of a segmented spreading ridge along a curved continental margin such that final ridge convergence slowed significantly due to margin parallel subduction.

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rates of convergence. All of this evidence together can be simply explained by oblique ridge subduction along a curved North American margin in which final ridge subduction in southeast Alaska and southward is near margin parallel (Fig. 10). Therefore the ridge and the slab window remained in contact with the continental margin for an extended period of time, consequently causing the numerous thermal effects discussed above. At approximately 50 Ma the trailing edge of the plate was subducted which in turn ended arc magmatism in the Coast plutonic complex of British Columbia and gave birth to the transform Queen Charlotte fault system (Haeussler et al., 2003a,b).

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.tecto.2007.10.008.

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