Emplacement of the Kodiak Batholith: A consequence of slab-window migration

David W. Farris1, Peter Haeussler2, Richard Friedman3, Scott R. Paterson1, R. W. Saltus4, and Robert Ayuso5

1. University of Southern California, 3651 Trousdale Ave., Los Angeles, California, 90089, USA
2. U.S. Geological Survey, 4200 University Drive, Anchorage, Alaska, 99508, USA
3. University of British Columbia, 6339 Stores Road, Vancouver, British Columbia, CAN
4. U.S. Geological Survey, P.O. Box 25046, MS 964, Denver, CO 80225, USA
5. U.S. Geological Survey, Reston, VA 201921, USA

ABSTRACT

The Kodiak batholith is one of the largest, most elongate intrusive bodies in the forearc Sanak-Baranof plutonic belt located along the southern margin of Alaska. These plutons are interpreted to have formed during the subduction of an oceanic spreading-center and the associated migration of a slab-window. Individual plutons of the Kodiak batholith track the location and evolution of the underlying slab-window. Six U-Pb zircon ages from the axis of the batholith show a northeastward decreasing age progression of 59.2±0.2 Ma at the southwest end to 58.4±0.2 Ma at the northeast tip. The trench-parallel rate of age progression is within error of the average slab-window migration rate for the entire Sanak-Baranof belt (ca. 19 cm/yr).

Structural relationships, U-Pb ages and a model of new gravity data indicate magma from the Kodiak batholith ascended 5-10 km as a northeastward younging series of 1-8 km diameter visco-elastic diapirs. Individual plutons ascended by multiple emplacement mechanisms including downward flow, collapse of wall rock, stoping and diking. Stokes flow xenolith calculations suggest ascent rates of 50-100 m/yr and an effective magmatic viscosity of ≈10^7 Pa s. Pre-existing structural or lithologic
heterogeneities did not dominantly control the location of the main batholith. Instead its location was determined by the location of the slab window at depth.

**INTRODUCTION**

Forearc magmatism is the hallmark of spreading-ridge subduction (Sisson et al, 2003, Bradley et al, 1993, 2003). Study of the physical processes involved in the evolution of such near-trench intrusions will yield insight into the evolution of spreading-ridge subduction and slab-window systems. The near trench Sanak-Baranof belt (Hudson et al., 1979) is one of the premier examples of magmatism interpreted to be related to a migrating slab window (Marshak and Karig, 1977; Moore et al., 1983; Bradley et al., 2003). Within this belt, the Kodiak Island region contains a diversity of different types of Paleocene magmatism, which range from mafic and felsic dikes to large granitic batholiths (Fig. 1). They were emplaced at shallow (1-2 km) to mid-crustal levels (>10 km) and their geometry is largely undisturbed by subsequent faulting. Each of these intrusions provides information at a distinct time and place in the spreading-ridge subduction process and taken in concert can provide a more complete picture of the evolution of the system (Kusky et al., 2003).

Magmas interact with crustal materials at a variety of spatial scales. Plutons of the Sanak-Baranof belt provide a unique opportunity to study these interactions because it has had a comparatively short and simple magmatic history. The Kodiak region experienced a single pulse of magmatism that has not been subsequently altered, reheated or modified by collision (Kusky et al. 2003). In contrast, silicic magmatic systems found in continental arcs are often active for tens to hundreds of millions of years and involve multiple pulses of magmatism and reheating (e.g., Paterson et al., 2003). Such a
protracted history will lead to a much more complicated structural and chemical
evolution that is more difficult to interpret.

In this paper we examine how the magmas of the Kodiak batholith interacted with
the accretionary prism on a local scale. These are near-field aspects of magmatic
interactions and are akin to more traditional pluton ascent and emplacement studies. On
Kodiak Island, forearc intrusions can be divided into two distinct belts (Fig. 1). The main
Kodiak batholith is comprised of a large (>700 km$^2$) elongate granitic batholith and
smaller but compositionally similar satellite plutons. The trenchward belt, located near
the Contact fault and farther south in the Ghost Rocks Formation, is composed of small
gabbro bodies, biotite-rich granitic plutons and pillow basalts. Within the main batholith,
plutons that were frozen at different points in their emplacement history help to constrain
the overall evolution of the granitic system. For example, the Anton Larson Bay pluton
solidified early in its emplacement history, whereas the northern tip of the main batholith
near Terror Lake had a more prolonged history at a slightly deeper crustal level. Our
goal is to use observations of the physical aspects of Kodiak batholith evolution to 1)
gain a better understanding of how granitic magmas interact with the crust in general, 2)
to test how well the slab-window concept explains observable features within the
batholith and 3) to use the Kodiak batholith as an example to better understand the
evolution of slab-window systems.

**Spreading-ridge subduction in southern Alaska**

Marshak and Karig (1977) first proposed that the Sanak-Baranof belt could have
formed by the subduction of an oceanic spreading-ridge (Fig. 2), and the concept has
been supported by many subsequent workers in the region (Hill et al., 1981; Moore et al.,
1983; Bradley et al., 1993; Sisson et al., 1989; Sisson and Pavlis, 1993; Plafker et al., 1994, Haeussler et al., 1995; Bradley et al., 1998; Kusky et al., 1999; Bradley et al., 2003, Haeussler et al., 2003; Kusky et al., 2003, Sisson et al., 2003). One exception is Hudson et al. (1979) and Hudson (1994) who argued that the forearc plutons formed as a crustal melting event resulting from the subduction of hot, young oceanic crust, but not necessarily the spreading-ridge.

Three main data sets support the concept of spreading-ridge subduction in southern Alaska (Bradley et al., 2003). The first is the near-trench location of the intrusions. Fisher and Byrne (1987) have argued that the melange zones along the southeast edge of the Ghost Rocks Formation were the Paleocene subduction zone mega-thrust. This indicates that all of the near-trench intrusions on Kodiak Island were within 70 km of the actual trench, which is too close for arc magmatism to occur. The second data set is the age progression of near-trench plutons (Bradley et al. 1993, 1998, 2003), which decrease from 61 Ma in the west at Sanak Island to 50 Ma in the east near Baranof Island. The subduction of a spreading-ridge and the eastward progression of the associated triple junction is the simplest way to explain the age progression over a 2100 km distance. Thirdly, chemistry of the near-trench plutons indicates that they formed from variable proportions of high percentage partial melts of accretionary prism sediments and mid-ocean ridge basalt (Hill et al., 1981; Barker et al., 1992; Harris et al., 1996; Bradley et al., 2003 Sisson et al., 2003). The explanation that best fits the above three data sets is that Sanak-Baranof belt plutons are the product of a migrating slab-window that resulted from the subduction of a spreading-ridge (Hill et al., 1981, Moore et al., 1983; Haeussler et al., 1995; Bradley et al., 1993, 1998, 2003; Kusky et al., 2003).
HOST ROCK FOR THE KODIAK ISLAND PALEOCENE PLUTONS

The main Kodiak batholith intruded into the Late Cretaceous Kodiak Formation, which outcrops over a 60 km wide belt across Kodiak Island (Fig. 1). The Kodiak Formation and was deposited on the trench slope, and shortly after deposition was underplated within an active accretionary prism (Fisher and Byrne, 1987; Sample and Moore, 1987; Nilsen and Moore, 1979). It is composed dominantly of thinly bedded (1-5 cm) sand and shale turbidites. Thinner beds tend to contain a higher percentage of shale, whereas beds greater than approximately 30 cm thick are almost entirely composed of greywacke. In thick greywacke sections individual bedding surfaces are difficult to observe and the strata appear almost massive. Shale rip-up clasts are also associated with such >1-5 m greywacke sections. At the scale of an individual outcrop the Kodiak formation is stratigraphically coherent, but over its entire width it is cross cut by a numerous strike parallel thrust faults along which sections were repeated (Sample and Moore, 1987). Nilsen and Moore (1978) estimated the depositional thickness of the Kodiak Formation was 3-5 kilometers.

Regionally the Kodiak Formation has a low metamorphic grade with maximum pressure and temperature conditions of 2-3 kbar and 200-250°C (Sample and Moore, 1987). Texturally the low-grade metamorphism led to pressure solution fabrics and slaty cleavage in argillaceous rocks, but greywacke rich sections exhibit virtually no fabric. Also, the Kodiak Formation is cut by extensive sets of quartz veins that likely formed under high fluid pressures within the accretionary prism (Vrolijk et al., 1988).

KODIAK PALEOCENE INTRUSIVE ROCKS

The Trenchward Belt
The Paleocene trenchward belt is composed of elongate granitoid bodies, basaltic dikes and small gabbroic plutons that lie along or to the south of the Contact fault (Fig. 1). These intrusions were emplaced at shallow crustal levels of <5 km, and likely <1-2 km, which is supported by the observation that some of the dikes grade into pillow basalts. However, intrusions become coarser grained and generally appear to deepen in emplacement depth towards the Contact fault (Fig. 1). On the southeast side of the Ghost Rocks Formation, pillow basalts also outcrop by themselves. Trenchward belt intrusions have K-Ar biotite ages ranging from 62-63 Ma at the southwestern end of Kodiak Island, and are potentially related to the Kodiak batholith (Moore et al., 1983) however, they appear to be several million years older.

**The Main Kodiak Batholith**

The main Kodiak batholith is a continuous, elongate body of granite and granodiorite with an aspect ratio >10:1 that extends for over 110 km along the axis of Kodiak Island and has a map exposure of >700 km² (Fig. 1). In addition, a number of compositionally similar satellite plutons are located within several kilometers of the main body. Detailed mapping was conducted at the northern tip (Fig. 3 and 4) of the batholith and at the Anton Larson Bay pluton (Fig. 5). Reconnaissance mapping was carried out over parts of the rest of the batholith. The description and interpretations below are primarily the product of observations in the Terror Lake region, but based on the reconnaissance observations elsewhere, we believe they are valid for the entire Kodiak batholith.

**Intrusive Units of the Main Kodiak Batholith**
The main batholith has been subdivided into three units based on the amount of included residual host rock (Fig. 3). They are qualitatively denoted as the low-, medium-, and high-inclusion units. All are composed of varying amounts of plagioclase, quartz, potassium feldspar, biotite and muscovite and range from granite to tonalite in composition. Biotite and ilmenite are the only observed mafic phases. Ilmenite typically occurs as euhedral to saphedral hexagonal crystals located at the center of larger biotite grains. Accessory phases include zircon and monazite. Pleochroic haloes surrounding zircons included in biotite are common. Some of the units contain biotite aggregates, quartz blobs, xenocrysts of sillimanite and garnet and xenoliths of highly metamorphosed host-rock blocks. The sillimanite xenocrysts occur as isolated crystals in the granite and also are found within the biotite aggregates. We interprete the biotite aggregates, quartz blobs, xenocrysts and xenoliths as products of varying degrees of host rock assimilation.

The low-inclusion unit contains almost no visible host rock material. It is homogeneous granite to granodiorite composed of plagioclase, quartz, potassium feldspar, biotite, ilmenite and muscovite. There are only small compositional variations within this unit based primarily on the relative proportions of quartz, biotite and alkali-feldspar. Magmatic muscovite is most common in this unit. Near the batholith margins the percentage of biotite decreases and the rock becomes more leucocratic.

The medium-inclusion unit is similar, but contains 5-10% partially digested host rock material. These fragments are distributed throughout exposures of this unit, and have several common elements including: 1-10 cm wide biotite aggregates, 1-10 cm wide blobs of pure quartz, large Al$_2$SiO$_5$ (sillimanite) xenocrysts (up to 5-10 cm) and highly metamorphosed blocks of host rock (Fig. 7).
The most diagnostic indicator of the medium-inclusion unit is the presence of large Al$_2$SiO$_5$ xenocrysts (Fig. 7). Petrography and crystal morphology indicate that such xenocrysts predominantly occur as sillimanite (Fig. 8). However, other xenocrysts such as kyanite, andalusite, garnet, cordierite and biotite are also present to lesser degrees (Hill et al., 1981; Kusky et al., 2003).

The blocks of host rock that are found in the medium- and high-inclusion intrusive units are qualitatively different than the blocks found adjacent to the margin of the batholith. Blocks found near the margin retain a very similar character to the rocks in the nearby metamorphic aureole. Marginal blocks contain porphyroblasts (garnet/cordierite/biotite) similar to those found in the aureole, and some sedimentary structures have been preserved. In contrast, blocks found in the interior of the batholith have lost all traces of their initial sedimentary character, have undergone extensive metamorphic segregation and are composed of gneissic bands of biotite and quartz.

The high-inclusion unit outcrops in roughly elliptical bodies located in the center of the batholith. These bodies range in diameter from 1-3 km and are separated from each other by 1-2 km (Fig. 3). They often have gradational boundaries but in certain locations they exhibit sharp contacts. Characteristically, the high-inclusion unit contains between 10-50 % partially assimilated host-rock material and has a greater percentage of distributed biotite (15-30%) than the low inclusion unit (5-15%). Many of the biotite aggregates contain large porphyroblasts such as garnet and sillimanite. Also, the high-inclusion units have a much higher percentage of large aplite dikes (often >1.0 m wide). Such aplite dikes are late and truncate the magmatic fabric. Overall, the general appearance of the high-inclusion unit is that of a solidified host-rock / granite slurry.
The Anton Larson Bay pluton

The Anton Larson Bay pluton is located 15 km to the northeast of the main batholith and is the northeastern-most Paleocene pluton on Kodiak Island (Fig. 1). The Anton Larson Bay Pluton is composed of two different types of granitic rock (Fig. 5). The northern half of the pluton is a homogeneous quartz, biotite, plagioclase, and potassium feldspar granodiorite that is compositionally similar to the low inclusion granodiorite in the main batholith. It is medium to fine grained, contains occasional biotite concentrations (generally less than 10 cm in diameter) and small aplite dikes, but is otherwise free of host rock inclusions.

The southern half of the pluton is composed of leucocratic, muscovite-bearing and biotite-poor granite. This unit contains many large, structurally intact host-rock blocks that range in length from hundred of meters to centimeters. Some of the smaller blocks have been partly disintegrated along bedding planes. Also present are biotite rich schlieren bands that are parallel to bedding planes in nearby host rock blocks. In addition, several quartz-filled miarolitic cavities were observed.

Magmatic Fabrics Within the Kodiak Batholith

Within the Kodiak batholith and its satellite intrusions the orientation of magmatic fabrics is overall quite uniform. In this paper, a magmatic fabric is defined as the preferential alignment of individual mineral grains that formed in the presence of melt (Paterson et al., 1998). The fabrics fall primarily in the flattening field (foliation dominated), cut through all internal boundaries and are not deflected by proximity to pluton margins. This is true even when the fabrics are at a high angle to the pluton / host rock interface. The average fabric has a strike and dip of 225° and 60-75° (Fig. 6A),
respectively (azimuth and right-hand rule). This orientation is similar to the dominant cleavage orientation in the Kodiak Formation (Sample and Moore, 1987). These observations indicate that the majority of the magmatic fabrics in the Kodiak Batholith formed late in its crystallization history and are due to tectonic regional strain fields.

In general, the intensity of the magmatic fabric is greatest in the high assimilation units and decreases in the low assimilation units. The variation in fabric intensity is likely due to the increased prevalence of biotite in the high inclusion granitic rocks because the alignment of biotite grains is more readily observable than alignment of quartz and plagioclase.

The magmatic fabric geometry outlined above is dominant throughout the Kodiak batholith, however there are some exceptions. The strike of the fabric is not deflected by proximity to internal or external boundaries, but the dip direction of the magmatic fabric commonly changes at internal boundaries within the pluton (Fig. 6A). Locally, there is a tendency for fabrics to be aligned with the nearest pluton margin. This is most common along irregular pluton margins and in regions with higher volumes of stoped blocks such as the southern portion of the Anton Larson Bay pluton.

**Kodiak Batholith Aureole**

**Aureole Metamorphism**

The main batholith has a recognizable high temperature thermal aureole with a map width of one to five kilometers. The thickness of the aureole, especially the high temperature zone (defined by the first appearance of cordierite) is strongly controlled by the local width of the batholith. On average the high temperature aureole width is approximately 0.15 body radii, but this value decreases where the batholith is thin (0.05-
0.10 at 1 km batholith width) and increases where it is thick (0.20-0.25 body radii at 7-8 km batholith width). The peak metamorphic assemblage contains cordierite, garnet, biotite ± fibrolite, indicating temperatures of \( \approx 650^\circ C \) at 2-3 kbar (Fig. 8) (Spear, 1995). Shale rich units tend to have higher proportions of cordierite and biotite, and units with a greywacke protolith tend to have more garnet. Andalusite is also present, but is not common. Adjacent to the batholith margin, some of the host rocks contain fibrolite, but sillimanite porphyroblasts as large as those in the interior of the batholith are not found in the thermal aureole. This suggests that the large \( \text{Al}_2\text{Si}_3\text{O}_9 \) xenocrysts in the batholith are not derived from the immediately adjoining host rock margin.

**Bedding Deflections**

Overall, the orientation of bedding planes throughout the Kodiak Formation is relatively invariant with an average strike and dip of 225° and 70°, respectively (Fig. 6B). However, the central belt rocks have more shallow dips of 15-30° (Sample and Moore, 1987). Throughout the unit there are zones of structural disruption related to low temperature (200-250°C) accretionary prism underplating, but these bound kilometer scale packages of stratigraphically coherent metasedimentary rocks (Sample and Moore, 1987). However, the zones of stratal disruption (typically thrust faults) and bedding all have a similar strike with some variation in dip (Sample and Moore, 1987). The regional homogeneity of bedding strike throughout the Kodiak Formation makes it an excellent marker for deformation in the pluton aureole.

Near the margins of the batholith, bedding planes within the Kodiak Formation are deflected towards the pluton margin so that they intersect the contact at a high angle (Fig. 3, 5, 6 and 12). Such geometry is observed on both the east and the west sides of
the batholith. However, it is most pronounced in the northeast/southwest tips of the pluton. In the tip regions, bedding planes are rotated from the regional orientation (225°/70°) to almost east/west (265°/50°). The deflection of bedding in this manner is observed in multiple intrusions that are not directly along strike of one another, such as the main Kodiak batholith near Terror Lake, the Anton Larson Bay pluton and the Whale Passage pluton (Fig. 1). In between these bodies the strike of Kodiak Formation bedding reverts to its regional orientation. This suggests that the deflection is not part of a continuous regional structure. Therefore we interpret the deflections to have formed during the emplacement process.

The Anton Larson Bay pluton has particularly well preserved bedding deflections at the northern and southern ends of the pluton (Fig. 5) in which bedding strike is rotated almost east-west. These are similar to the bedding deflection observed around the main batholith near Terror Lake. However, to the south of the Anton Larson pluton, along both sides of Kizhuyak Bay, bedding dips more shallowly than in other places in the Kodiak Formation (15-30° vs. 60° respectively). In the southern portion of the Anton Larson Bay pluton the bedding deflection is especially apparent, and can be tracked into the interior of the pluton via a kilometer scale host rock thumb (Fig. 5). Rafts of host rock with similar bedding orientations surround the host rock thumb, but some of the stoped blocks have clearly undergone rotation with respect to each other. However, in the northern part of the pluton, the bedding deflection is abruptly truncated at the pluton margin. We suggest that the southern section of the pluton represents an initial stage of intrusion, whereas the northern part is more evolved and that any host rock deflections...
that extended into the pluton have been transported vertically out of the plane of observation.

**Aureole Fabrics**

Throughout the Kodiak Formation cleavage is generally parallel to bedding and flattening fabrics are dominant (Sample and Moore, 1987). Within the batholith aureole cleavage is still generally parallel to bedding, however constrictional fabrics with a down dip lineation are present close to the pluton contact. The lineation is parallel to the pluton margin, has an average plunge of 30° (Fig. 3), tends to steepen with proximity to the pluton and is defined by aligned mineral grains and boudinaged greywacke beds. However, near the NE and SE ends of the batholith lineations are orientated at a high angle to the pluton margin.

**Aureole Strain**

We have attempted to quantify strain in the Kodiak batholith aureole by using quartz veins and bedding planes that were deformed during the emplacement of the batholith. Quartz veins are prevalent throughout the Kodiak Formation, and occur as sets of straight en-echelon veins. They are a consequence of high fluid pressure coupled with low temperature (200-250°C) accretionary prism deformation (Fisher and Byrne, 1987; Sample and Moore, 1987; Vrolijk et al, 1988), and therefore were pre-existing at the time of pluton emplacement. Near the contact, the veins are ptygmatically folded and boudinaged depending on their orientation with respect to the batholith margin. Folded quartz veins are observed in other locations within the Kodiak Formation, however the degree of the folding is much greater near the batholith margin. Therefore we interpret
the finite strain of the aureole rocks to be dominantly the result of pluton emplacement, although there is likely a lesser regional tectonic component.

Strains were quantified by measuring an initial length, a final length and then calculating stretch using the relation:

\[ s = \frac{L}{L_0} \]  

(1)

In which \( s \) is stretch, \( L_0 \) is the initial length and \( L \) is the final length. Initial and final lengths were quantified by measuring structures in photographs taken of outcrops in which the orientation of the outcrop surface was measured in the field. At each site (eight total) as many veins as possible (ranging from 1 to 45) were measured (Table 1), and veins of similar orientation were averaged together. Each set of folded veins or beds yields shortening or extension values along their axis. We observed that veins oriented perpendicular to the pluton margin were ptygmatically folded, whereas vertical margin parallel veins had been boudinaged. This method is intended to only provide a first order quantification of aureole strain, and at best produces a 2-D strain ellipse. However, the data suggests that the axis of maximum elongation was near vertical (stretch of 1.8 and 80% extension) and that the axis of maximum shortening was horizontal and oriented perpendicular to the pluton margin (stretch of 0.5 and 50% shortening).

Strain in the Kodiak batholith aureole is heterogeneous. How strain is partitioned depends on a number of factors such as proximity to the pluton margin, angular relationship of host-rock fabric to pluton margin, lithology type, and aureole width. The width of the structural aureole is approximately 0.10-0.15 pluton body radii, and in most locations the thermal aureole (defined by metamorphic biotite) is wider than the structural aureole. The highest strains (above 50 %) are only observed within approximately 0.05
body radii of the pluton margin and rapidly decrease to 10-30% strain by distances of 0.20 pluton body radii. One exception to the continual strain decrease away from the pluton margin is caused by 10-50m thick greywacke beds on the NW side of the batholith south of the Terror Lake Reservoir (Fig. 4). These beds appear to act as rigid struts and transmit strain away from the pluton margin. Argillite beds immediately to the NW of the greywacke have increased strain. Strain is also partitioned between argillite and greywacke beds on a smaller scale. This is best illustrated in sequences of thinly (2cm) bedded alternating greywacke and argillite. Quartz veins cut across all layers, but are deflected and sometimes boudinaged when they cross individual argillite beds (Fig. 7b).

**GRAVITY CONSTRAINTS ON KODIAK BATHOLITH GEOMETRY**

To constrain the three-dimensional geometry of the Kodiak batholith gravity was measured along a transect perpendicular to the long axis of the intrusion (Fig. 1 and 9). The transect was conducted just to the south of the Terror-Lake mapping area through one of the widest (7-8km) portions of the batholith. A LaCoste-Romberg gravimeter was used to make the measurements (see DR-Appendix 1 for gravity data and corrections). A number of stations from a previous gravity survey near the town of Kodiak were reoccupied to attempt to tie our new measurements into the existing database. We attempted to established stations atop hills with previously surveyed elevations. In practice, most locations did not have previously surveyed elevations, and altitudes from two barometric altimeters were averaged, after compensating for elevation drift during the day. These elevations were checked against hand-held GPS measurements. The absolute accuracy of the elevation at each station is estimated at approximately ±2 meters. This lowers the precision of the gravity data, but does not
preclude useful interpretations. We estimate the overall error of individual measurements at ±2.5 mgals (Fig. 9).

To reconstruct sub-surface geology, terrain corrections both for absolute elevation (bouguer) and slope were applied to each station. Also, the data exhibited a long period systematic northwestward tilt that is due to the underlying subducting slab. This tilt was removed by rotating the data so that stations in the Kodiak Formation on either side of the batholith had a similar gravity signature. This was done to emphasize the gravity anomaly of the Kodiak batholith.

Modeling of residual gravity anomalies was done using the program GM-SYS. Density values were constrained by measuring the density of 30 samples from the main batholith, various satellite intrusions (both granitic and gabbroic), metamorphic rocks in the thermal aureole, and from the Kodiak and Ghost Rocks Formations. Average values are shown in Table 2. Using that data we modeled the sediments and metamorphic rocks as having a 0.0 g/cm³ density anomaly, the granite as having a -0.10 g/cm³ density anomaly and the basalts and gabbro as having a +0.10 g/cm³.

The gravity modeling indicates that the main batholith extends downward for a minimum depth of 5-10 km and has relatively steep margins. Such thickness values for the batholith should be considered minima because they assume that the composition of the granitic rocks and the country rock density remains constant with depth. Large intrusions often become less siliceous (and therefore more dense) with increasing depth (Ducea, 2001), and elsewhere in the Chugach terrane deeper structural levels expose high-density gabbro and amphibolite (Sisson et al., 2003). Also, the gravity model indicates that in the center of the batholith rocks with the same density as the high
inclusion granites extend downward for 5-10 km. Satellite plutons on either side of the main batholith are also indicated by the data. Although not well resolved, the satellite plutons appear to have a similar geometry as the main body. The basalt/gabbro bodies of the trenchward magmatic belt show up approximately where the gravity transect crosses the Contact Fault. They are not exposed at the surface at this location, but crop out 15 km to the south along strike on Sitkalidak Island (Fig. 1). Overall, the gravity data show that the Kodiak batholith extends downward for at least 5-10 km, and that the high inclusion unit is present for its entire vertical extent.

**U/ Pb GEOCHRONOLOGY**

Seven samples collected along the axis of the Kodiak batholith have been analyzed for U/Pb geochronology using isotope dilution thermal ionization mass spectrometry on zircon and monazite. Six yielded resolvable ages (Fig. 10). The analyses were conducted at the University of British Columbia (see DR-appendix 2 for analytical methods). Within each sample a number of zircons and monazites were analyzed to determine the spread of possible crystallization ages for the Kodiak batholith, and to determine the extent of inheritance from assimilated sediments (Table 3).

02KD57 and 02KD56 were collected from the southwestern most part of the Kodiak batholith (Fig. 1). Zircons from 02KD57 yield an age of 59.1±0.2 Ma based on two overlapping and concordant zircon fractions (Fig. 10A). Whereas 02KD56 yielded an indistinguishable age of 59.2±0.2 Ma also based on two concordant and overlapping zircon fractions (Fig. 10B). Monazite fractions from both samples plot above concordia (Fig. 10A and B) with lower precision than the zircons. Despite the reverse discordance both monazite results are consistent with the zircon dates.
Sample 01KD81A from Three Saints Bay (Fig. 1) yielded two overlapping and concordant zircon fractions, the younger of which has an age of 59.0±0.3 Ma (Fig. 10C). Monazite grains yield the considerably less precise and reversely discordant age of 57.4±1.6 Ma. It is likely that the 59.0±0.3 Ma zircon age represents magmatic crystallization, whereas the monazite date may be a high temperature, potentially sub-solidus cooling age. The error bars on the zircon ages from this sample also overlap with 02KD56-57, and so does the upper age limit on the monazite grains.

Sample 01KD072 comes from the trenchward belt near the Contact fault on Sitkalidak Island (Fig. 1). It is characterized by considerable inheritance with zircon fractions plotting below concordia with ages ranging from 80 to 120 Ma (Fig. 10D). A chord can be fit (MSWD of 0.22) through fractions A-D, but it yields imprecise upper and lower intercepts of 183 +58/-40 Ma and 55.7 +20.8/-37.9 Ma, respectively. Also, a yellow scrappy monazite from the sample yielded an imprecise age of 64±9 Ma. The field relations in area suggest that considerable host rock assimilation has occurred, and the results from the U/Pb geochronology support this observation, but the data do not allow a precise age estimate.

In the Hidden Basin region zircon fractions from sample 01PH121A form a three-point regression with a lower intercept at 58.9±0.2 Ma and an upper concordia intercept of 1.9 Ga (Fig. 10E, F). Zircon fraction A has been excluded from the regression because its inherited component appears to have a different age than the roughly co-linear fractions B, C and D. Including fraction A in the regression yields a less precise age of 60.2 +2.9/-3.7 Ma and a high MSWD of 584.5, which indicates a poor fit to the data.
One of the zircon fractions in the regression is concordant at 58.9±0.2 Ma. Also, there are several imprecise monazite fractions with ages varying from 58 to 64 Ma.

Sample 02KD52 is from the Uganik pluton which is located approximately 25 km to the west of the northern tip of the main batholith (Fig. 1). It has an age of 58.5±0.2 Ma based two concordant zircons (Fig. 10G). Monazites ages concur, but have lower precision. This age is almost identical to that found 01KD57A (see below).

The northeastern-most sample (01KD57A) is from the tip of the Kodiak batholith near Kizhuyak Bay. The age of this sample is estimated from four concordant and overlapping zircon fractions that yield a date of 58.4±0.2 Ma (Fig. 10H). This is the most reliable crystallization age we have obtained from the Kodiak batholith. This result is not surprising in that the granite in the Terror Lake area is quite homogeneous and contains little in the way of macroscopic host rock material.

**DISCUSSION**

**General Magmatic Processes / Evolution of the Kodiak Batholith**

**Internal magma chamber processes**

On a regional scale, the main Kodiak batholith has a highly elongate overall geometry with an aspect ratio of >10:1 (Fig. 1). However, our detailed mapping has shown that the batholith is composed of a number of intermingled elliptical bodies with aspect ratios of closer to 3:1 (Fig. 1 and 3). Where these individual plutons overlapped a contiguous batholith was formed, but to the north and west of the main batholith the spatial density of the plutons decreases and isolated granite bodies were formed (e.g. the Anton Larson Bay and Uganik plutons).
The dominant compositional variation among all of the Kodiak plutons is the amount of partially assimilated host rock, which appears to be roughly correlated with the size of an individual pluton. For plutons with a diameter < 3-5 km the amount of partially assimilated material is very low (low-inclusion granite) and the plutons are internally homogeneous. However, larger plutons are compositionally zoned, and the amount of included host rock material increases towards their center.

In the Terror Lake region the high inclusion zones form a series of elliptical bodies in the center of the batholith. Such zones do not connect to the pluton margin and the xenoliths within them contain a metamorphic mineralogy that is different from the cordierite, garnet and biotite assemblage found in the aureole.

Previous workers have interpreted the existence of garnet and Al$_2$SiO$_5$ xenocrysts in the Kodiak, Kenai and Shumagin batholiths as evidence that the magmas originated at 5-10 km below current levels of exposure and ascended quickly (Kusky et al., 1997, 2003; Hill et al., 1981). In this explanation, magmas would have carried the xenocrysts up from absolute depths of 15-20 km (Kusky et al., 2003). Our observations corroborate this interpretation, however a key aspect of this theory is that the Al$_2$SiO$_5$ xenocrysts were predominantly kyanite, which requires high pressures (5-7 kbar) to form (Deer et al., 1992). Within the Kodiak batholith large 2-3 cm Al$_2$SiO$_5$ xenocrysts are common, and in the field have a bluish tint. However, petrographic analysis indicates that the aluminosilicate xenocrysts in the Kodiak batholith are dominantly sillimanite and not kyanite (Figure 8B). A wide variety of xenocrysts such as kyanite, andalusite, garnet, cordierite and biotite are present in the Kodiak batholith, as they are in the Shumagin and Kenai plutons (Hill et al., 1981; Kusky et al., 1997, 2003), but sillimanite is the principal
Al$_2$SiO$_5$ phase. The presence of sillimanite, as opposed to kyanite, does not preclude a magma origin depth of 15-20 km, but is not required. Our gravity model indicates that the batholith extends to similar depths as suggested by the initial interpretations of the xenoliths, and supports the interpretation that the xenoliths and xenocrysts of the high assimilation zones were carried up from considerable depth.

**Stokes Flow Calculations**

A problem with a model of upward vertical transport of the xenoliths is how to physically get them up through the magma column. The xenocrysts and the larger, but less dense, xenoliths were all denser than the granitic magmas of the Kodiak batholith. In a static magmatic system the xenoliths would sink. Therefore, the host rock material could not have undergone ascent via buoyancy alone, but instead must have been carried up by magma flow.

This idea can be tested using Stokes flow calculations and by determining a minimum magma ascent velocity needed to entrain the observed xenoliths. The relationship between magma ascent velocity and viscosity in determining the maximum size and density of entrained xenoliths can be modeled using the equation (Turcotte and Schubert, 1982):

$$
U=(2\times(\rho_r\rho_s)\times g\times r_s^2) / (9\mu)
$$

(2)

Where $U$ is the upward magma velocity needed to entrain a xenolith of density $\rho_s$ and radius $r_s$, the viscosity and density of the magma is $\mu$ and $\rho_r$, respectively, and $g$ is acceleration due to gravity. This equation assumes a Newtonian magma rheology and spherical xenoliths. Figure 11B shows that a xenolith of a given size and density can be entrained by magmas with a continuous range of velocities and viscosities. Viscosity and
velocity can be exchanged on a one to one basis, and therefore the equation provides a non-unique solution. However, with outside constraints on one of these parameters a unique solution can be obtained.

To place constraints on the ascent velocity and viscosity of the Kodiak batholith magmas, equation 2 has been rearranged so that observable quantities can be plotted against the calculated curves:

\[ r_s = \left( \frac{9^*U^*\mu}{2^*(\rho_f - \rho_s)^*g} \right)^{1/2} \]  

(3)

Figure 11A shows the size and density distribution for Kodiak batholith xenoliths from high inclusion regions plotted against calculated Stokes flow curves. The xenolith volumes were recalculated as spheres, and their densities were calculated from field measurements of modal mineralogy. The calculated densities are similar to those measured from Kodiak batholith rocks. Stokes flow curves approximate this distribution if the minimum xenolith density is close to the magma density, which we believe is a reasonable assumption given the geochemical estimates of high sediment assimilation for Sanak-Baranof belt plutons (Barker et al., 1992; Harris et al., 1996; Sisson et al., 2003).

Rubin (1995) stated that a realistic viscosity for crystal free high silica magmas ranges from $10^4$ to $10^8$ Pa s. If we take the end member values and put them into the above Stokes flow equations to determine a possible range of ascent rates for the Kodiak batholith magmas we get 5m / year at $10^8$ Pa s and 50,000m / year for $10^4$ Pa s. The xenolith metamorphic grade and the gravity model suggest that Kodiak magmas had to ascend a minimum of 5-10 km. Using the above rates the Kodiak magmas would have a range of ascent times varying from several thousand years to a few months.
The above stated range in magma viscosities is for nearly crystal-free melts, however the Kodiak batholith magmas have likely never been crystal free. If crystals or any type of entrained material are present in a magma, viscosities increase exponentially. In addition, as crystallization proceeds the magma will develop a yield strength that will influence the size and density of xenoliths it can lift (Sparks et al., 1977). The viscosity of a melt will vary continuously as it cools and undergoes crystallization. For example, Paterson and Miller (1998) have calculated viscosities of $10^{14-16}$ Pa s for granitic magmas with high crystallinity (>60-70%). The high inclusion zones within the Kodiak batholith contain between 10-50% partially assimilated host rock, which are minimum values of crystallinity during ascent. In addition plagioclase crystals exhibit complex zonation suggesting protracted magma residence times. Such evidence strongly indicates that during ascent the Kodiak batholith magmas were not crystal free and consequently had higher viscosities on the order of $10^7$-$10^8$ Pa s. Therefore, magma ascent would have occurred at a rate of less than 5-50 m/year over a period of thousands of years.

Another problem is that the majority of the high inclusion zones occur in the center of the batholith. An explanation for this observation could be that the batholith acted as a giant pipe though which magma was flowing. Pipe-flow analytical models show that the velocity of a fluid in the center of a pipe is greater than the flow velocity near the pipe wall (Turcotte and Schubert, 1982). If the Kodiak batholith acted as a large vertical magma pipe, then the magma in the center would ascend at a higher velocity than magma near the pluton margin. This would allow the magma in the center to entrain significant amounts of partially digested host rock that would otherwise sink due to its negative buoyancy. Such a model fits our observations of the Kodiak batholith in which
granite near the pluton margin contains little entrained host-rock material whereas the center portion is composed of high-inclusion granite (Fig. 3).

Larger pipes also allow greater overall fluid velocities over larger cross-sectional areas. Pipe flow would explain why high-inclusion zones are found only in plutons of large diameter. Under this scenario magma ascent velocities high enough to entrain substantial host rock material would only occur once a pluton reached a certain size.

**Emplacement / Ascent Processes**

The study of pluton emplacement mechanisms attempts to quantify the importance of individual processes responsible for the magmatic removal and redistribution of host rock. Paterson and Fowler (1993) have termed such processes material transfer processes. With respect to the Kodiak batholith system our goal is to determine how the Paleocene magmas interacted with and altered the overlying accretionary prism.

The classic end-member possibilities for magma movement through the crust are hot Stokes diapirs and elastic dikes (Paterson and Fowler, 1993; Miller and Paterson, 1999). In a pure hot Stokes diapir, magma ascends upward by the downward flow of host-rock with a Newtonian rheology. A characteristic structural feature of this ascent mechanism is the presence of rim synclines, steep lineations, and a wide structural aureole. Hot stokes diapirs ascend relatively slowly (m/yr) and are limited in how far they can ascend through the crust by thermal constraints (e.g. they crystallize; Marsh, 1982).

Conversely, magmatic dikes propagate as elastic magma filled cracks that can travel very quickly (up to m/s) through the crust. The space the magma occupies is
created by the elastic compression of the surrounding rock (Rubin, 1993). Proponents of
diking as a dominant emplacement mechanism argue that elliptical plutons form via
ballooning (Molyneux and Hutton, 2000; Paterson and Vernon, 1995) in which dikes
ascend upward through the crust and when they reach a certain depth they cease to
propagate upwards, but instead radially expand.

Paterson and Miller (1998) and Miller and Paterson (1999) proposed another
category of ascent mechanism, the visco-elastic diapir. Visco-elastic diapirs are thought
to ascend via multiple material transfer processes operating upon a power-law crust. In
this theory, a magma body would ascend via a combination of wall-rock flow, stoping,
diking and possibly many other mechanisms. Space for the ascending pluton is created
primarily by the downward transport of host rock through and around the magmatic
column. In most pluton emplacement studies, only 30-50 percent of the “missing” host
rock can be accounted for. Visco-elastic diapirs present a possible solution to the space
problem by providing a viable mechanism for transporting host rock out of the plane of
observation (Miller and Paterson, 1999).

We propose that visco-elastic diapirs provide the closest match to our
observational constraints on the Kodiak batholith. In the following section we will
discuss the relative importance of dikes vs. diapirs in the Kodiak batholith and place
constraints on the role of the underlying slab-window.

Both the Anton Larson Bay pluton and the northern tip of the Kodiak batholith
(Terror Lake) exhibit similar structural features. Bedding planes in the aureole tip
regions of each pluton are deflected away from regional trends and towards the margin of
the respective plutons (Figures 3, 5, 6 and 12). This is best observed in the southern
portion of the Anton Larsen Bay pluton where bedding deflection can be followed into
the interior of the pluton via a trail of host rock rafts and stoped blocks. In more
structurally evolved intrusions such bedding deflections are sharply truncated at the
pluton margin. This is the case in the main Kodiak batholith and the northern part of the
Anton Larson Bay pluton. Such bedding deflection is observed in multiple plutons and is
not observed in other locations in the Kodiak Formation. Therefore as noted above, we
interpret bedding deflections toward the pluton margin as emplacement related.

One mechanism to explain the observed geometry is that the Kodiak Formation
was pulled downward and rotated towards the pluton during the ascent of the granitic
magma (Fig. 12). Host rock above a pluton and away from its sides is going to be
significantly stronger and have a higher viscosity than rocks along the pluton margin due
to a pluton-induced temperature increase (Kohlstedt et al, 1995; Paterson and Vernon,
1995; McBirney and Murase, 1984). It is rheologically preferred for host rock to be
transported towards weaker materials, and therefore towards the pluton and downward
along the pluton margin during magma ascent. We interpret the observed bedding
deflection as either a wall rock collapse feature or related to downward flow in the
aureole. However, the difference between those two interpretations is not great, in that in
each case host rock material is transported downward with respect to the pluton.

Multiple lines of evidence indicate that the Kodiak batholith magmas ascended as
a series of visco-elastic diapirs such as described by Paterson and Vernon (1995). The
first line of evidence is the basic elliptical geometry of individual intrusions. This is
observed in isolated plutons (Fig. 1) and in the high inclusion bodies within the larger
batholith (Fig. 3). Low aspect ratio magmatic bodies tend to ascend by some type of
viscous mechanism (Rubin, 1993). The second line of evidence is that the aureole around each intrusion contains ductile structures that can be interpreted as evidence for downward flow. Both the Anton Larson Bay pluton and the main batholith have bedding deflected towards their margin in their tip regions, and the main batholith is surrounded by a ductile aureole that exhibits significant vertical extension (locally up to 80%). The third line of evidence comes from the estimated ascent rate and viscosity calculations. Based on Stokes flow calculations the ascent rate and viscosity of the Kodiak batholith was >50 m / year and $10^7$ Pa s, respectively. This empirical estimate is similar to Weinberg and Podladchikov's (1994) calculation that a diapir rising through a power-law crust needs to ascend at a minimum rate of 10 m / year to avoid freezing in the mid to lower crust. The upper viscosity estimate also supports diapiric ascent (Rubin, 1993). In addition to the ductile aureole processes, there is evidence that brittle processes such as diking and stoping were operative simultaneously. Overall, the evidence suggests that the Kodiak batholith ascended as a series of visco-elastic diapirs that operated via multiple material transfer processes.

**Relationship of the Kodiak batholith to regional structures**

Kusky et al. (2003) postulated that the near-trench plutons of the Kenai Peninsula (which are similar to the Kodiak batholith) were emplaced into a large extensional jog in the Contact fault, and that the orientation of individual plutons was controlled by P-shears (e.g. Tikoff and Teyssier, 1992). According to this theory, magmas generated at or near the slab-window ascended through the crustal discontinuity formed by the Contact Fault and other adjacent fault systems. Kusky et al. (2003) have also suggested that such a fault assisted emplacement model may work for the Kodiak batholith.
In the Kodiak accretionary complex, the two main crustal discontinuities are the Contact fault and the Border Ranges fault system (including the Uganik thrust, the Border Ranges fault itself, and the Shuyak thrust, Fig. 1). Many other small faults are present within the accretionary complex, but no others form significant crustal discontinuities. The Border Ranges fault separates Cretaceous and younger accretionary units from Late Jurassic and older rocks (Roeske et al., 1989). Except for a few isolated leucocratic dikes there is no slab window associated magmatism along or north of the Border Ranges fault on Kodiak Island. The Contact fault separates the Paleocene Ghost Rocks Formation from the Late Cretaceous Kodiak Formation. Small elongate granite and gabbro bodies of the trenchward belt are found in the hanging wall of the Contact fault along the length of the island. These magmas could have ascended along the boundary between the two units and have been subsequently exhumed by the Contact fault. However, the trenchward belt intrusions are volumetrically much smaller than the main batholith (<20 km² versus >700 km²). If major crustal discontinuities dominantly determined the location of the near-trench plutons then the bulk of the Kodiak batholith magmas would be found along one of the major pre-existing faults in the region. Instead the bulk of the Kodiak batholith granites are located in the middle of the Kodiak Formation.

**Inferences about the slab window**

Our analysis indicates that Kodiak batholith magma generated at or near the slab-window ascended as a series of visco-elastic diapers that decrease in age from southwest (59.2 Ma) to the northeast (58.4 Ma), and that the migration rate within the batholith is similar to the average age progression of the entire Sanak-Baranof belt (19 cm / yr (Bradley et al., 2003)). Therefore, we postulate that the location of a given pluton marks
the location of the slab window at a particular point in time, and that this remains so
down to a scale of 10-20 km. Such a relation suggests that the slab window itself was of
similar width at the depth of pluton generation. Also, the composition of the plutons
yields some information about processes within the slab-window itself (Bradley et al.,
2003; Lytwyn et al., 2000; Harris et al., 1996; Sisson et al., 1993, 2003). Geometry
(vertical thickness) and xenoliths contained within the plutons can provide information as
to the depth of the slab-window. From this information we can begin to describe the
evolution of the slab window as it migrated through the Kodiak Island region.

The elongate nature (with an aspect ratio of >12: 1) of the main Kodiak batholith
is one its most striking features (Kusky et al., 2003). However, within the Sanak-Baranof
belt the Kodiak batholith is not unique. Several granitic bodies in the Chugach
Mountains east of Prince William Sound have similar elongate geometries (Bradley et al.,
2003; Kusky et al., 2003). Individual granitic Paleocene plutons in the Kodiak region
have map view aspect ratios of between 1:1 and 1:3. We suggest that the high aspect
ratio of the main Kodiak batholith is an artifact of rapid slab-window migration and
consequent thermal softening of the overlying crust.

The main Kodiak batholith is composed of an eastward migrating series of
individual plutons that overlap with one another. In the southern part of the Terror Lake
area (Fig. 3) such co-mingled individual plutons can be identified by the sequence of high
inclusion zones. Adjacent plutons must have intruded one another while a significant
amount of melt was still present. This would account for the generally diffuse boundaries
between high inclusion bodies, although some sharp contacts do exist. In the low
inclusion granite it is difficult to distinguish individual pluton boundaries from internal
contacts due to the homogeneity of the unit. However, individual plutons can be inferred from their external oval shape. In Fig. 3, the tadpole head of the batholith, the Kizuyak Bay pluton and the Crown Peak Pluton all are individual plutons. By the time the northeast tip of the batholith formed (Terror Lake) the southwestern portion was almost certainly below its solidus given the 800,000-year crystallization age difference between the two ends.

One mechanism that could have lead to the formation of the elongate batholith and would fit with the observed field relations is a self-propagating thermal softening of the crust over the slab-window. Once an initial pluton penetrated through the accretionary complex the crust surrounding it would be thermally softened and therefore would form a minimum energy pathway for subsequent batches of magma (Paterson et al., 2003). In typical arc magmatic systems this mechanism can lead to concentrically zoned batholiths such as the Tuolumne in the Sierra Nevada (Paterson et al., 2003). However, in the Kodiak system the underlying site of magma generation (the slab-window) was migrating rapidly to the northeast. Therefore, subsequent batches of magma would ascend as close to the previous pluton as possible, but due to slab-window migration the source would be a little to the northeast. Once initiated, this process of magma localization would be self-sustaining as long as magma was being produced at depth and would lead to the observed elongate batholith composed of numerous small elliptical plutons.

One aspect of the Kodiak batholith the above explanation does not address is why such voluminous magma generation occurred at a specific distance from the paleotrench. Ultimately, such an explanation must include a large influx of heat and or a lowering of
the melting temperature of the accretionary prism metasediments. At depth, the location of the Kodiak batholith could mark the location in which hot asthenosphere first became juxtaposed against the base of the accretionary prism. This would induce partial melting and localize the ascent of subsequent magmas.

Gravity, xenolith and U/Pb age data indicate that the Kodiak batholith magmas formed at a depth of 15-20 km as a result of a northeastward migrating heat source. We argue that the best explanation for this heat source is an eastward migrating triple junction with an associated slab-window at depth (Hill, et al.; 1981; Moore et al., 1983; Bradley et al., 2003; Kusky et al., 2003). The slab-window juxtaposed hot aesthenospheric mantle (1400°C) or possibly a large volume of basaltic magma (1200°C) against the base of the accretionary prism (Harris et al., 1996) leading to high (50-75 %) percentage partial melting (Bradley et al., 2003; Lytwyn et al., 2000; Moore et al., 1983) and the formation of a gravitationally unstable melt layer immediately above the slab-window. Out of the melt layer individual plutons of the Kodiak batholith ascended as a series of buoyancy driven visco-elastic diapirs that tracked the migration of the slab window itself.

**CONCLUSIONS**

1. Kodiak batholith magmas ascended by multiple material transfer processes. Crack-related processes such as diking and stoping occurred early in its magmatic evolution, whereas downward flow and high strain of host rock in the aureole dominated the later history of the batholith. Structural heterogeneities such as faults or changes in rock type did not dominantly control the location of slab-window plutons. Instead the plutons penetrated the accretionary prism with little regard to pre-existing structure. The primary
control on the location of plutonic bodies within the Kodiak Formation was the location of the migrating slab window at depth.

2. Metamorphic grade of high-inclusion zone xenoliths and the gravity transect support the inference that there was 5-10 km of vertical transport of host-rock fragments and magma within the main batholith. Stokes flow calculations based on xenolith size and density suggest that the Kodiak batholith magmas ascended at a rate of 50-100 m/yr and had a viscosity of approximately $10^7$ Pa s. Such values are compatible with diapiric ascent through a power-law crust.

3. The dominant effect of far-field strains on the Kodiak batholith was the formation of its magmatic fabric. These fabrics formed late in its magmatic evolution and provide a snapshot of the regional contractional strain field at the time the batholith passed through its solidus.

4. TIMS U/Pb zircon ages indicate a consistent southwest to northeast age progression across Kodiak Island of 59.2±0.2 Ma to 58.4±0.2 Ma, respectively. The entire batholith was emplaced in just 0.8±0.4 Ma. Such ages are consistent with the overall eastward younging of the Sanak-Baranof belt of near-trench plutons, and moreover, the rate of migration as measured within the Kodiak batholith at a scale of 10's of kilometers is similar to the average rate for the entire Sanak-Baranof belt.

Acknowledgements
A special thanks goes out to Dwight Bradley and the Slab Windows project of the Minerals Program of the U.S.G.S. Without their exceptional financial and logistical support this research would not have been possible. My field assistants Michael Rieser, Buddy Tangalos and Clinton Colasanti deserve thanks for their invaluable help and for remaining good spirited through long, cold and wet field seasons. Finally, the warm and generous people of the Kodiak Islands contributed greatly, and particularly to Gary Carver for all those warm showers.
Figure Captions

Figure 1. Map of the Kodiak Island region with major geologic features overlain on a digital elevation model. Note the location and northeastward decreasing age progression of the U/Pb ages.

Figure 2. Schematic slab window formed landward of a trench-ridge-trench triple junction after Thorkelson (1996). Spreading continues after the creation of new oceanic crust ceases, leading to the juxtaposition of hot asthenospheric mantle against the base of the accretionary prism.

Figure 3. Detailed structural map of the northern tip of the Kodiak batholith. Note how Kodiak Formation bedding planes are deflected towards the pluton margin. Magmatic foliations within the batholith cut across all internal contacts, and high-inclusion zones are located in the center of the batholith.

Figure 4. Cross-sections A-A' and B to B' across the Kodiak batholith. See Fig. 3 for cross-section locations and the unit descriptions. Note the folds near the pluton contact. They are better developed along the western margin. Variation of dip-directions of the magmatic fabric within the batholith itself is most likely an artifact of rheological differences between internal units at the time the magmatic fabric formed.

Figure 5. Map of the Anton Larson Bay pluton. The southern portion of the pluton contains abundant dikes and large host-rock blocks, whereas the northern portion is nearly inclusion free. Also, note the deflection of bedding planes towards the pluton margin at the northern and southern ends of the pluton (see Fig. 3).

Figure 6. Structural data from the northern tip of the Kodiak batholith shown in Fig. 3. Data are plotted as poles to planes on an equal-area net and contoured using the 1% area method (2% contour interval). A. Magmatic foliation from the Terror Lake region. B. Kodiak Formation bedding orientations from Terror Lake.

Figure 7. Field photos. A. Voluminous stoped blocks in one of the trenchward belt Pasagshak Bay plutons. B. Quartz vein deflected across argillite bed indicating differential strain between layers of greywacke and argillite. C. Pylamatic quartz veins used to calculate ductile strains in the pluton aureole. D. Vertically boudinaged quartz veins used to quantify extension in the aureole. E. Typical xenolith found in the high-inclusion unit of the batholith. F. Homogeneous granite typical of the low-inclusion intrusive unit.

Figure 8. Photomicrographs from the Kodiak batholith. A. Peak metamorphic assemblage of cordierite (Cd), garnet (grt) and biotite (bt) found in the batholith aureole. B. Sillimanite (Sil) xenocryst found within the Kodiak batholith. Note how the larger grain is composed of slender columns with cleavage perpendicular fractures that are typical of sillimanite. C. Low inclusion zone granite. The plagioclase (pl) grain exhibits
well-developed concentric zoning. Most of the minerals are primarily magmatic, and have not undergone substantial sub-solidus strain.

Figure 9. Gravity transect across Kodiak Island (C-C'), the location of which is shown in Figure 1. The gravity data indicates that the batholith is steep sided, extends downward for a minimum of 5-10 km, and that the high inclusion zone near its center extends downward for an equivalent distance.

Figure 10. Concordia diagrams for U/Pb TIMS dates from different points along the length of the batholith. Light grey ellipses are zircon dates and dark grey are from monazite fractions. Ages range from 59.2±0.2 Ma at the southwestern end of the batholith to 58.4±0.2 at the northern end of the batholith near Kizhuyak Bay, and are interpreted to track the migration of the slab-window and triple junction.

Figure 11. A. Stokes flow curves for the maximum xenolith size that can be entrained by a magma with a given velocity and viscosity. The size and density of Kodiak batholith xenoliths are plotted on top of the Stokes flow curves, and allow the viscosity and velocity of the magmas to be estimated at 10^7 Pa s and 50 m/yr., respectively. B. This plot shows the range of magma viscosities and ascent rates that can entrain a xenolith of a given size and density.

Figure 12. 3-D view of bedding plane deflections surrounding the northern tip of the Kodiak batholith. The observed deflection of bedding planes is compatible with downward flow, rotation and collapse of the aureole into the rheologically weak pluton margin.

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oceanic lithosphere
upper mantle
660 km slab
window
lower mantle
A, B and C denote different plates

magmatism above slab window
arc volcanoes
continental crust

upper mantle
lower mantle
continental crust
Paleocene granite and granodiorite containing up to 5-10% included host rock material (pure quartz, biotite aggregates, sillimanite xenocrysts, and gneissic host rock xenoliths).

Paleocene granite and granodiorite containing 10-50% included host rock material including pure quartz, biotite aggregates, sillimanite xenocrysts, and gneissic host rock xenoliths.

Paleocene fine grained quartz and feldspar aplite dikes (1 cm to 10 m wide).

Kodiak Formation - Late Cretaceous greywacke/argillite turbidite sequences

Water

Glaciers

Map Symbols

- Fault
- Fault: Location inferred
- Strike of bedding
- Inferred strike of bedding
- Magmatic foliation
- Host rock foliation
- Host rock bedding
- Mountain summit elevation
- Mineral lineation
- Anticline
- Syncline

Kodiak Bay pluton

Crown Mountain

The Kodiak Batholith

Terror Lake region of the Kodiak Batholith
A. Dominant Kodiak batholith magmatic fabric orientation

B. Deflected Kodiak Formation bedding in pluton tip regions
   Regional Kodiak Formation bedding orientation

N=244

N=96
Near Deadman Bay
02KD57
59.1 ± 0.2 Ma

Three Saints Bay
01KD81A
59.0 ± 0.3 Ma

Hidden Basin
01PH121A
58.9 ± 0.2 Ma

Uganik pluton
02KD52
58.5 ± 0.2 Ma

Sitkalidak Island tonalite
01KD072C
~80 Ma

Terror Lake
01KD57
58.4 ± 0.2 Ma
Magma density = 2650 kg/m³

Minimum density and xenolith size estimates
Magma density = 2650 kg/m³

A.

B.

Xenolith density is 2750 kg/m³ unless otherwise noted.

Zone of realistic magma viscosities and velocities for granitic diapirs ascending through crust with a power law rheology.
Vertical magma ascent

Cold, rigid Kodiak Formation
Rheologically "pinned" in place

Downward flow in aureole drags bedding toward pluton margin

Northern end of the Kodiak batholith

Kodiak Bay pluton
### Table 1

Strain measurements in the Kodiak batholith aureole in the Terror Lake region

<table>
<thead>
<tr>
<th>Station</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Strain marker</th>
<th>Number of markers</th>
<th>Trend</th>
<th>Plunge</th>
<th>Angle to pluton margin</th>
<th>Stretch</th>
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<td>49</td>
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<td>57.73666</td>
<td>-152.96926</td>
<td>quartz veins</td>
<td>6</td>
<td>220</td>
<td>85</td>
<td>10</td>
<td>1.83</td>
<td>83</td>
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<tr>
<td>02-KD-101</td>
<td>57.74858</td>
<td>-152.9544</td>
<td>folded bedding</td>
<td>8</td>
<td>315</td>
<td>12</td>
<td>75</td>
<td>0.85</td>
<td>-15</td>
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<tr>
<td>02-KD-116</td>
<td>57.60283</td>
<td>-153.01195</td>
<td>quartz veins</td>
<td>22</td>
<td>180</td>
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<td>70</td>
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<td>01-KD-123</td>
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<td>23</td>
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<tr>
<td>02-KD-142</td>
<td>57.56378</td>
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<td>quartz veins</td>
<td>14</td>
<td>140</td>
<td>9</td>
<td>65</td>
<td>0.67</td>
<td>-33</td>
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</table>

*note: negative values indicate percent shortening positive values extension*

### Table 2

<table>
<thead>
<tr>
<th>Rock type</th>
<th>Density (g/cm³)</th>
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<tr>
<td>Kodiak batholith low inclusion granite and granodiorite</td>
<td>2.62-2.67</td>
</tr>
<tr>
<td>Kodiak batholith high inclusion unit</td>
<td>2.74-2.77</td>
</tr>
<tr>
<td>Kodiak and Ghost Rocks Formation sedimentary rocks</td>
<td>2.72-2.76</td>
</tr>
<tr>
<td>Pasagshak Bay Basalt</td>
<td>2.8</td>
</tr>
<tr>
<td>Pasagshak Bay Gabbro</td>
<td>2.9</td>
</tr>
</tbody>
</table>
The table presents TIMS age data for various locations. Each entry includes the fraction identifier, sample name, and age in Ma with uncertainties. The data includes isotopic ratios and apparent ages. The text also references additional information about the samples, such as colors and growth habits. The data is organized in a tabular format for easy reference and analysis.