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Geology of the Bering Shelf region of Alaska-Russia: Implications for extensional processes in continental crust

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ABSTRACT

The Bering Strait and surrounding regions of Alaska and Russia represent an excellent example of stretched and magmatically modified crust. A variety of data, from crustal-scale seismic reflection profiles to detailed studies of gneiss domes, and the history of deep crustal xenoliths provide unique insight into the lithospheric processes that accompany extension of continental crust.

The Bering Strait gneiss domes represent well-documented cases of crustal-scale flow at sillimanite to granulite facies conditions, rising rapidly from 12 kb to andalusite-stable conditions during crustal thinning at about 90 Ma. Seismic reflection and refraction document 30-35 km thick crust with subhorizontal reflectivity and a sharp Moho. Mid- to lower-crustal reflectivity coincides with the geographic limits of Cretaceous (120-80 Ma) syn-extensional magmatism, arguing that the locus of crustal extension was controlled by magmatic heating. A younger (75- 55 Ma) magmatic belt developed southward of the Cretaceous belt before subduction and arc magmatism jumped to the Aleutians in the Eocene.

Xenoliths from the deep crust within the Cretaceous magmatic belt have a history linked to gneiss dome rocks, yielding Cretaceous magmatic and/or Cretaceous and Paleocene metamorphic ages. Equilibration conditions represent the deeper part of the P-T array represented by gneiss dome rocks. The metamorphic gradients defined (30-50°C/km) are too hot to be explained by anything other than mantle-derived magmatic heat input to the crust. High-grade rocks in the gneiss domes preserve their earlier (protolith) histories as evidenced by U-Pb zircon ages (i.e., Cretaceous metamorphic rims on older cores). Xenoliths from the deep crust do not, recording only Cretaceous magmatic and Cretaceous-Paleocene metamorphic ages, providing compelling evidence for the complete reconstitution/re-equilibration of continental crust from the bottom up during mantle-driven magmatism.

Extension occurred at least in part during opening of the Arctic Basins and was likely driven by slab rollback which successively dragged fragments of the earlier accretionary collage of Alaska-Russia towards the modern subducting Pacific margin of Alaska. Similar processes may have affected the lower crust beneath the Basin and Range province. It is further suggested that metamorphic core complexes of the U.S. Cordillera may owe their unique differences (compared to each other) to how hot they were and how closely their genesis is tied to magmatism.

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INTRODUCTION

The tectonic and petrologic processes involved in the growth and modification of continental crust are topics of broad interest across many disciplines in the solid earth sciences (e.g., Rudnick and Gao, 2003; Brown and Rushmer, 2005; Levander et al., 2005). This paper provides a summary of new ideas about the origin of the Alaska portion of the Cordillera emerging from studies in the Bering Strait region of the circum-Pacific margin (Fig. 1). Along this portion of the Cordilleran orogen, a protracted series of extensional events, all accompanied by magmatism, severely modified and dispersed older accreted terranes.

One of the fundamental contributions to our understanding of deep crustal processes has been the acquisition of crustal-scale seismic reflection profiles. These rough snapshots of the structure of the deep crust and upper mantle have provided new data and insights that have revolutionized our thinking about what takes place at depth beneath both ancient and modern orogens (e.g., Klemperer et al., 1986; Allmendinger et al., 1987; Mooney and Meissner, 1992; Fuis et al., 1995; Nelson et al., 1996; Cook et al., 1999; Levander et al., 2005). In turn, these new data provide the following challenges: How do we integrate the complex structural and petrologic histories revealed by geologic studies to what often appears to be a simpler (and contemporary) structure of the deep crust? How can surface geologic studies be used to predict the nature, history and structure of the deep crust? The Bering Shelf region of Arctic Alaska and Russia (Fig.1) provides a unique opportunity to directly address these challenges: Neogene basalt fields entrain xenoliths of the lower crust and mantle, which have been seismically imaged (Klemperer et al., 2002) (Fig. 1). The evolving geologic and petrologic database for this region is discussed in detail by Akinin et al. (in press) and provides robust evidence for a much younger history of the lower crust than is apparent from Alaska's long-lived accretionary history. The extending Basin and Range province of the western U.S. Cordillera is underlain by mostly supracrustal rocks. Deeper structural levels exposed in metamorphic core complexes have been called "windows into the lower crust," providing us with just a glimpse of top of these deeper levels. Results from studies in the Bering Strait provide a broader context for understanding the lithospheric-scale driving processes during continental extension and for the development of extension-related gneiss domes and core complexes.

GEOLOGIC SETTING

The northern Cordillera (and particularly Alaska) is often cited as a classic example of an accretionary Phanerozoic orogenic belt which included orogenic thickening of Late Precambrian crust and its Paleozoic to early Mesozoic cover during arc collision and terrane accretion in the Mesozoic (e.g., Coney et al., 1980; Monger et al., 1991; Nokleberg et al., 1998). In Alaska and environs, however, Cretaceous to early Tertiary magmatism is widespread and mostly post-dates this accretionary history (Fig. 1). The role of this magmatism in the crustal evolution of the orogen at this latitude has been viewed as quite minor compared to its accretionary history. For instance, Nokleberg et al. (1998) as well as many other workers, classify Mesozoic intrusive and volcanic rocks as "overlap" and "stitching" units (using the terrane vocabulary) compared to the "allochthonous terranes" which are viewed as the major players in the crustal growth of the region. On the other hand, geologic studies in Alaska and Russia that focused on subhorizontal metamorphic tectonite fabrics and gneiss domes in the southern Brooks Range and Bering Strait region provided a very different view of the evolution of the orogen at this latitude. These studies suggested that the Cordilleran orogenic "collage" in Alaska was significantly extended during Cretaceous magmatism (e.g., Miller and Hudson, 1991; Miller et al., 1992; Hannula et al., 1995; Bering Strait Geologic Field Party, 1997; Calvert, 1999; Amato et al., 2002; Akinin and Calvert, 2002; Amato and Miller, 2004). Furthermore, deep crustal seismic reflection and refraction data indicate that the crust beneath western Alaska and the Bering Strait is only about 30-35 km thick and that the middle and lower crust is characterized by subhorizontal reflectivity and little Moho relief (Klemperer et al., 2002), now considered the hallmarks of extended continental crust world-wide (Mooney and Meisner, 1992).

The petrologic, geochemical, metamorphic, and geochronologic histories of crustal xenoliths from various basalt fields in the Bering Strait region in context with the seismic data represented in Figure 2 provide additional challenge to the existing view of accretionary crustal growth beneath the Bering Shelf region (Akinin et al., in press; Figs. 1, 2 and 3). High-precision U-Pb dating of individual zircon grains from extremely small, mostly mafic xenoliths, using the spatial and mass resolution of the SHRIMP-RG, provide a geochronologic data set with which to elucidate the temporal links between magmatism, metamorphism, and deformation. Pertinent data from gneiss domes together with seismic and xenolith data are summarized in Figures 2 and 3. Based on their petrology and geochemistry, the xenoliths represent mantle-derived magmas and cumulates, metamorphosed at granulite facies conditions during continued mantle-derived magma input into the crust (Akinin et al., in press). Ages of igneous and metamorphic zircons in the xenoliths match geologically documented ages of magmatism (Fig. 2, inset 3). Magmatic heating of the crust to granulite facies conditions provides the explanation for the extreme high-T metamorphic gradients seen in the Kigluaik and Koolen gneiss domes (Fig. 3). Magmatism was intimately associated with the observed large-scale flow of rocks in the gneiss domes, both predating and post-dating the main flow fabrics which took place during partial melting of the crust (e.g., Amato and Miller, 2004). Documentation of large-scale flow of crustal rocks in the gneiss domes provides a good explanation for pervasive sub-horizontal seismic reflectivity recorded in middle and lower crustal rocks beneath exten-

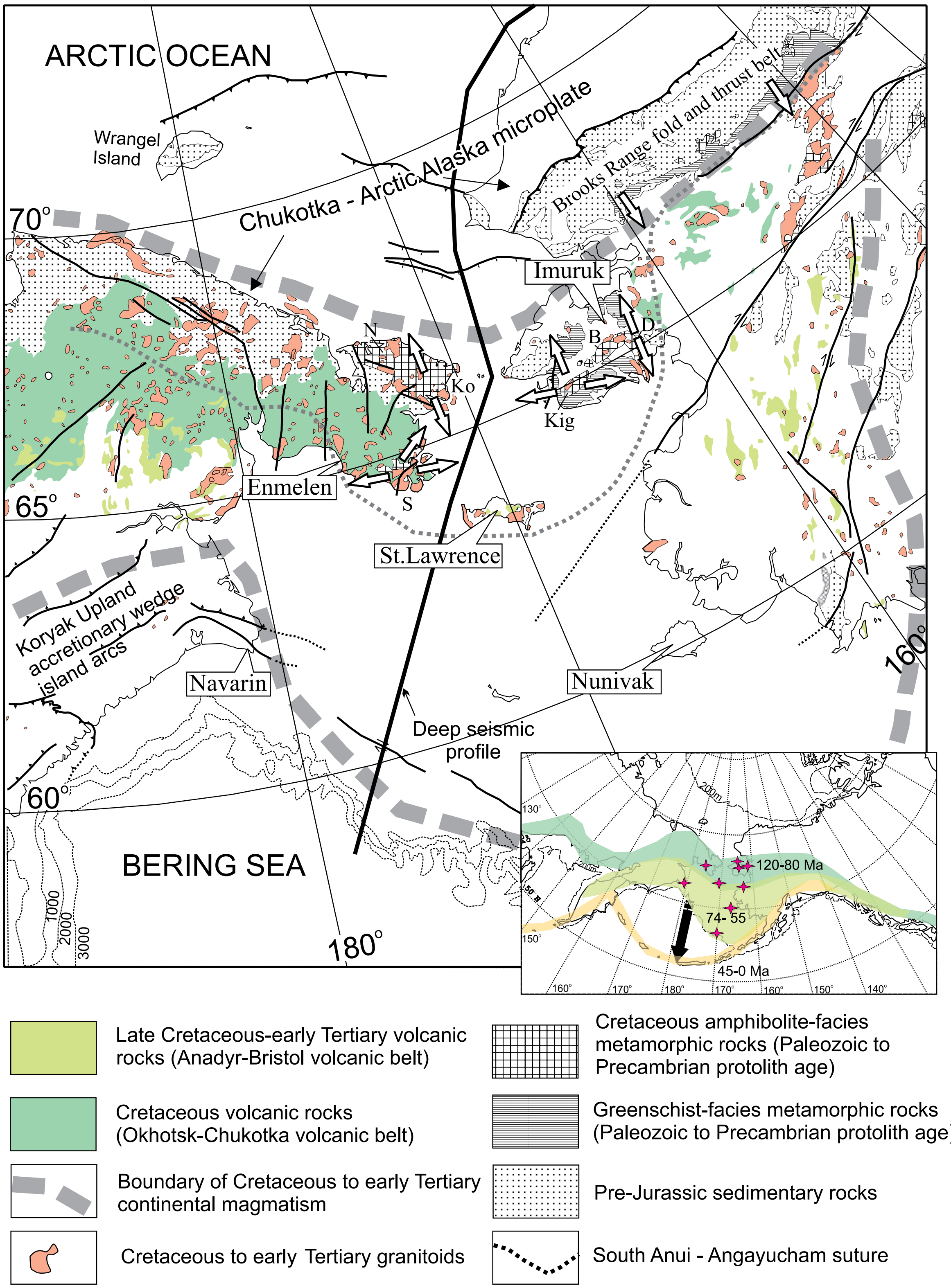


Figure 1. Index map of Alaska and adjacent Russia showing main geologic features discussed in text, modified after Akinin et al. (in press). The deep crustal seismic profile is shown with a black line (Klemperer et al., 2002). Approximate northern and southern limits of Cretaceous to early Tertiary continental calc-alkaline magmatism are shown by light-gray dashed lines. The localities of crustal xenoliths studied are labeled with square boxes. Inset shows the general observed pattern of southward migrating, syn-extensional arc magmatism which occurred in the Bering Strait region following crustal thickening and accretion. Metamorphic culminations are labelled: Kig – Kigluaik Mountains; B – Bendeleben Mountains; D – Darby Mountains; Ko – Koolen dome, N – Neshkan dome; S – Senyavin uplift. Stretching directions in metamorphic rocks are shown by white arrows (Till and Dumoulin, 1994; Dumitru et al., 1995; Bering Strait Geologic Field Party, 1997; Miller et al., 2002). White regions on continents correspond to Cretaceous, Tertiary and Quaternary sediments.

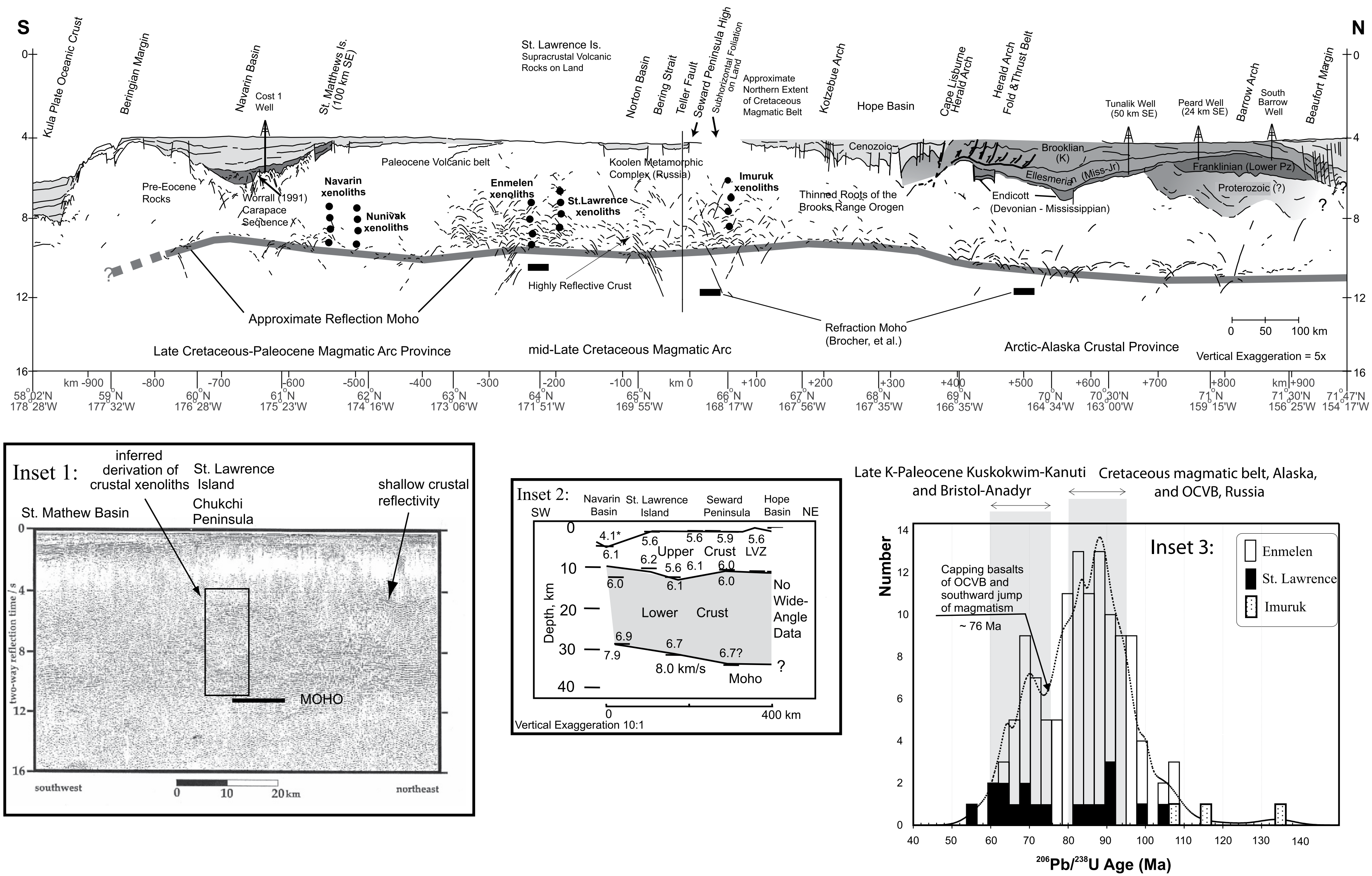


Figure 2. Line drawing and interpretation of reflectors in a deep crustal seismic profile (location shown in Fig. 1) with the projected location and range of depths of the xenoliths studied by Miller et al. (2002) and Akinin et al. (in press), modified from Klemperer et al. (2002). Inset 1 illustrates the nature of lower crustal reflectivity observed along the profile from Bering Strait to St. Matthew Basin. Inset 2 shows results of refraction studies and crustal velocity model from Miller et al. (2002). Inset 3 is a comparison of all U-Pb ages on zircons from xenoliths (histogram) compared to age range of the two major supracrustal plutonic and volcanic belts that cross the Bering Shelf from Alaska to Russia (see Figure 1 for location of the magmatic belts). Modified from Akinin et al. (in press).

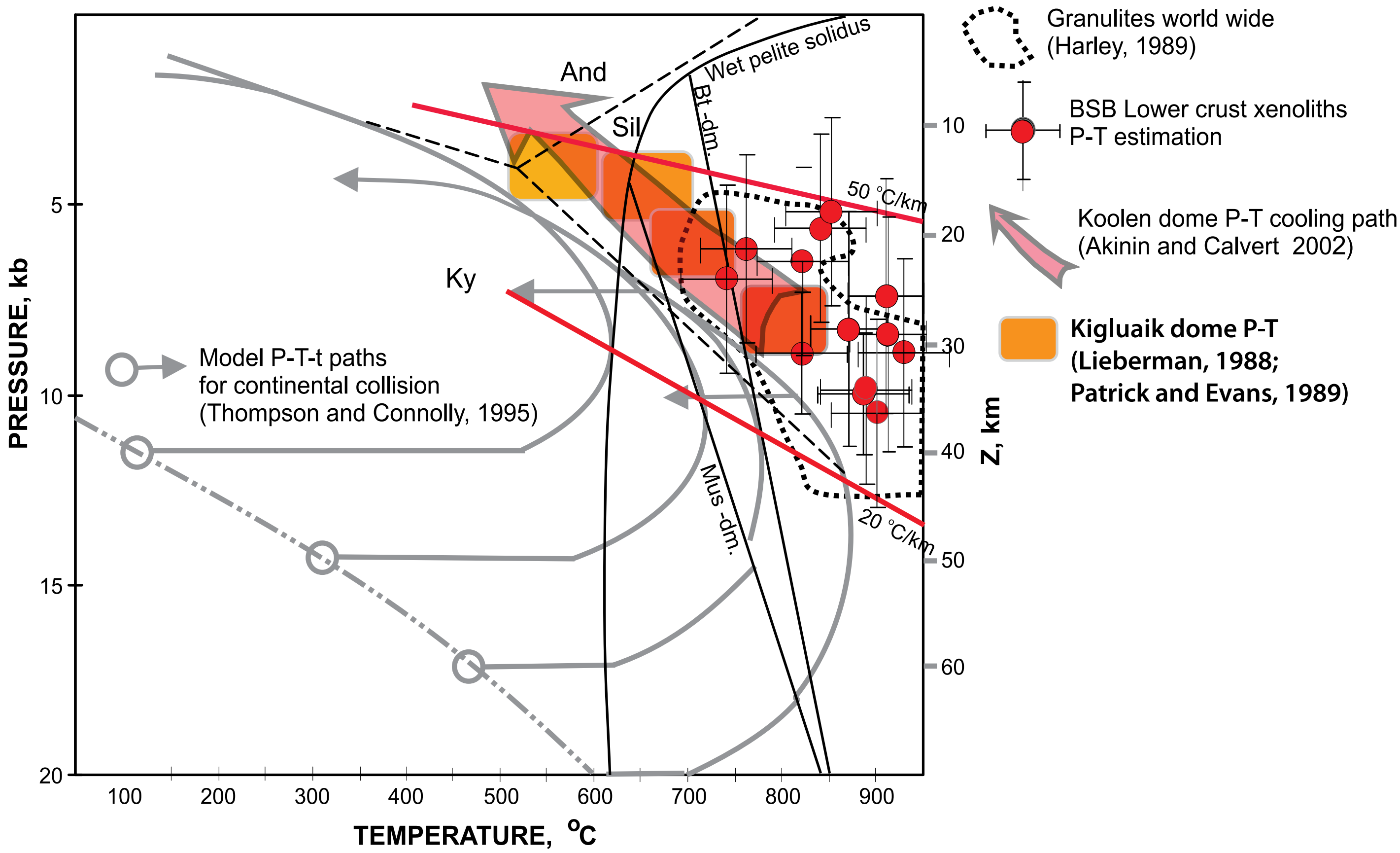


Figure 3. Pressure-temperature estimates compiled for plagioclase-bearing crustal xenoliths of Bering Strait region (red dots with black error bars) and their comparison with P-T paths of rocks in two of the better-studied gneiss domes. Kigluaik dome P-T path shown as a series of red to orange boxes based on the work of Lieberman (1988) and Patrick and Evans (1989). Pressure-temperature paths modeled for continental collision (grey lines and arrows) from Thompson and Connoly (1995) show that T conditions during collision are not sufficient to explain T's recorded in metamorphic rocks from gneiss domes and in the lower to middle crustal xenoliths (grey dash-dot line are initial P-T conditions after thrust burial). Mus-dm and Bio-dm are muscovite and biotite dry melting curves. Simplified from Akinin et al. (in press).

sional provinces around the world (e.g., Klemperer et al., 1986; Klemperer, 1987; Klemperer and Hobbs, 1991; Holbrook et al., 1991; Costa and Rey, 1995). More provocatively, the U-Pb isotopic data on zircons from crustal xenoliths (Fig. 2, inset 3) provide evidence for the extreme degree to which continental crust is modified or reconstituted from the bottom up during magmatism in an extensional tectonic setting. None of the zircons from the xenoliths contain any inherited older age components, which might be expected given that this region is inferred to have been underlain by Precambrian continental crust. In contrast, the high grade rocks of the gneiss domes do preserve their earlier (protolith) histories as evidenced by their U-Pb zircon ages (Amato and Miller, 2004). A cartoon summary of the relationships leading to the wholesale reconstitution of the crust during extension and magmatism beneath the Bering Shelf, based on all studies to date (Akinin et al., in press) is depicted in Figure 4.1.

INSIGHT INTO CORDILLERAN CORE COMPLEXES

The diapiric gneiss dome concept, applied to the Bering Strait gneiss domes (Amato et al., 1994; Calvert et al., 1999; Amato and Miller, 2004) has now been widely applied to many of the Cordilleran extensional metamorphic core complexes (e.g., papers *in* Whitney et al., 2004a). The high temperatures and rapid uplift recorded by metamorphic rocks in the Bering Strait gneiss domes (Fig. 2) and the intimate relationship of magmatism, metamorphism, partial melting, and crustal flow in these domes is most similar to relations documented in the southern Canadian and Washington core complexes such as the Shuswap and Okanogan metamorphic culminations (Table 1). The Ruby Mountains metamorphic core complex, Nevada, which lies in the Basin and Range proper, is the next most similar to these complexes in that it experienced upper amphibolite facies metamorphism (sillimanite is pervasive) and was intruded by a variety of magmatic rocks during its Tertiary extensional

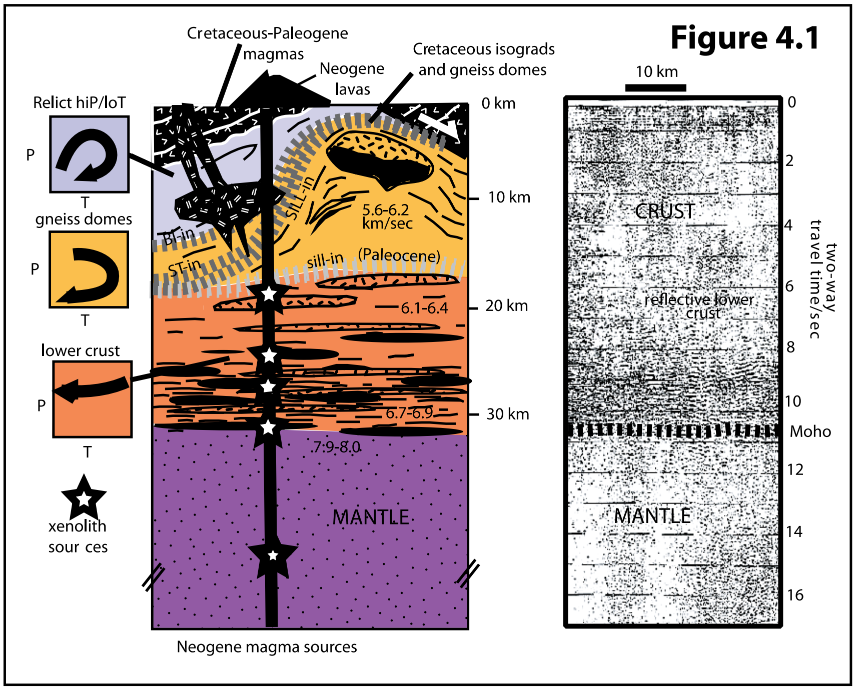
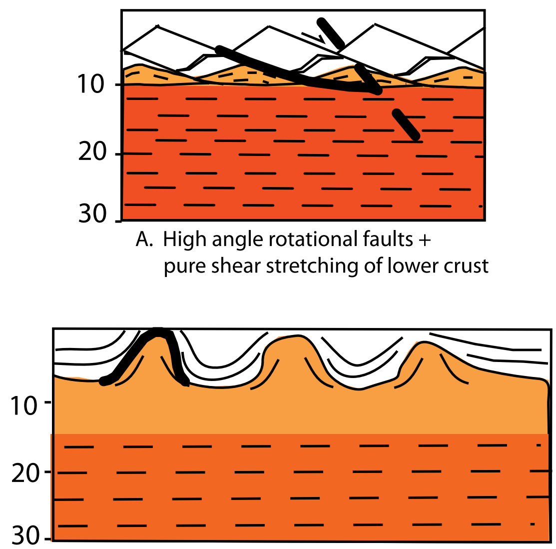
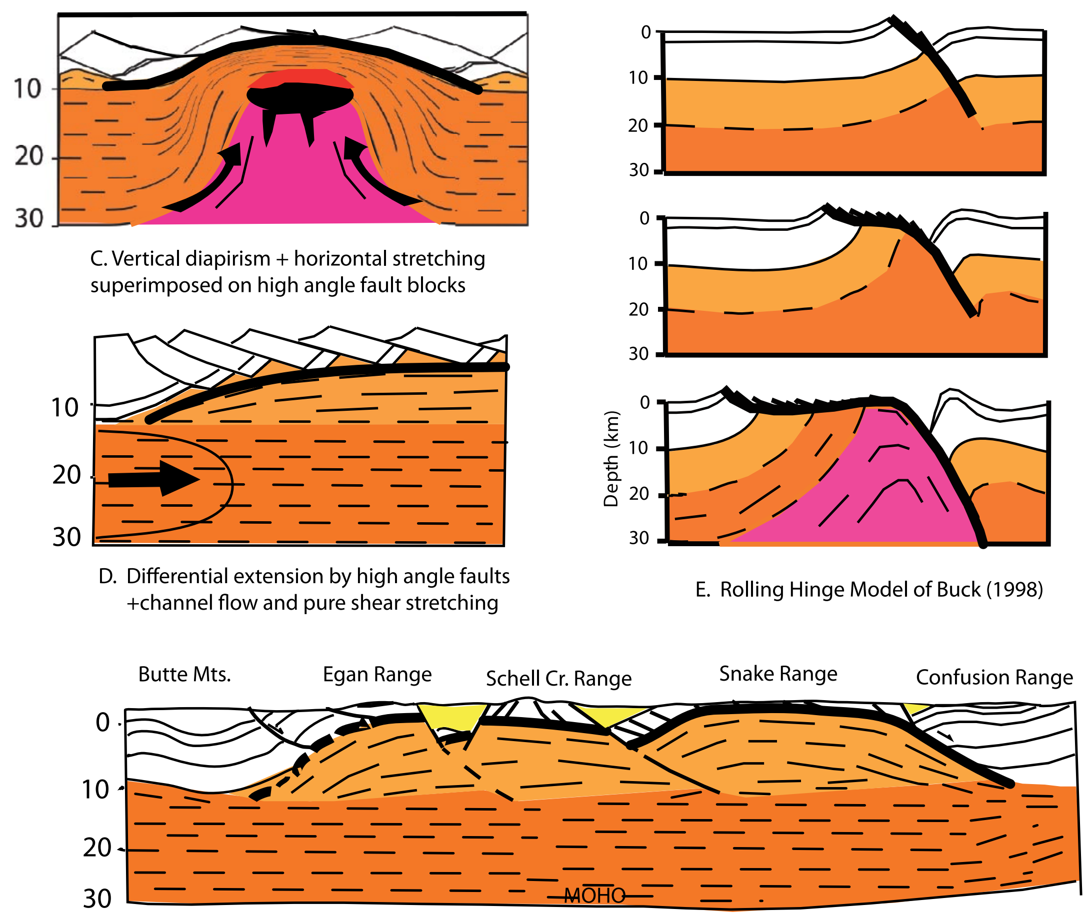


Figure 4.2



A. High angle rotational faults + pure shear stretching of lower crust

B. Density-driven diapirism + lower crustal flow with no net extension



C. Vertical diapirism + horizontal stretching superimposed on high angle fault blocks

D. Differential extension by high angle faults +channel flow and pure shear stretching

E. Rolling Hinge Model of Buck (1998)

F. Actualistic cross-section across east-central Nevada and Snake Range metamorphic core complex

Figure 4.1 (far left). Schematic cross-section summarizing and interpreting data discussed here in the context of the history of extended continental crust beneath the Bering Shelf region. Portion of seismic reflection profile is originally from Klemperer et al. (2002), modified by Akinin et al. (in press).

Figure 4.2 (left and lower left). The various processes within extending continental crust that might lead to the formation of metamorphic core complexes and detachment faults. In all examples, white represents the brittle crust and darker shades of orange represent successively younger fabric/flow of crustal rocks. Heavy black lines represent surfaces that could be termed detachment faults. **A.** Single generation high-angle rotational faults (by their very nature) cannot expose very deep parts of the flowing lower crust. **B.** Density-driven vertical diapirism of partially molten rocks and/or magmatic intrusions are capable of bringing deeper rocks to the surface but explain neither pervasive sub-horizontal fabrics in extended continental crust nor gently-dipping detachment faults. **C.** Combined magmatism, vertical diapirism, and channel flow of the deeper crust with high-magnitude stretching of continental crust (Kigluaik Mountains gneiss dome, Seward Peninsula, Alaska, after Amato et al., 2002). **D.** Differential supracrustal extension compensated by lateral flow of deeper crust from less extended to more extended regions (simplified from Surpless et al. 2001, Sierra Nevada-Basin and Range transition with younger faults removed). **E.** Rolling-hinge model for detachment faults modified from Buck (1998) (his Figure 7 using a fault angle of 60° and effective flexural rigidity of 0.5 km), with successive horizontal offsets of 15, 30 and 60 km. To the two-km-depth horizon of Buck (1998) we added 10, 20 and 30 km depth horizons to emphasize how much material must move into the region of the cross section with greater and greater extension. Orange, red, and magenta highlight rocks that end up at the surface after beginning their exhumation history at 10, 20 and 30 km depth, respectively. **F.** Actualistic cross-section of the entire crust across east-central Nevada and the northern Snake Range metamorphic core complex, emphasizing the minimum (10-15 km) component of differential vertical uplift across the region and the fact that extreme crustal stretching was compensated by lateral flow of the deeper crust into the more highly extended region, modified from Gans and Miller (1983).

history (Table 1). Metamorphic and geochronologic studies have shown that the rapid vertical rise of deeper crustal rocks is a hallmark of these complexes, both in the Bering Strait and in the northern Cordillera examples listed above (Table 1). Based on these P-T-t considerations, it is reasonable to conclude that a component of vertical rise or diapirism was involved in genesis of the complexes (e.g., Whitney et al, 2004b), driven by mantle-derived heating of the crust (Bering Strait) and/or by large percentages of extant partial melt in the crust (e.g., Whitney et al., 2004a, Kruckenberg et al., in press).

However, not all metamorphic core complexes in the Basin and Range experienced temperatures as high as those characterizing the more end-member "gneiss dome-like" core complexes. Table 1 lists the northern Basin and Range metamorphic complexes in terms of the maximum metamorphic grade experienced during extension and whether or not magmatism was associated with their genesis (at present levels of exposure). Metamorphic grade and the presence or absence of abundant syn-extensional intrusive rocks are key factors in explaining the differences between the more gneiss dome-like and the rest of these complexes (Table 1). In particular, the Snake Range and the Funeral Mountains metamorphic complexes experienced only greenschist-facies metamorphism during their extensional exhumation and are not intruded by syn-extensional plutons at present levels of exposure (Table 1). Complexes in the southern Basin and Range are more difficult to characterize in terms of their metamorphic temperatures because lower plate rocks are Precambrian amphibolite facies rocks and maximum temperatures during their core complex-related uplift are not as clear.

TABLE 1. TEMPERATURES EXPERIENCED BY VARIOUS CORDILLERAN CORE COMPLEXES (GNEISS DOMES) DURING EXTENSION (LISTED APPROXIMATELY FROM HOT TO COLD)

Core Complex	Metamorphism	Partial Melting?	Syn-Extension Plutons?	Older metamorphism?
1. Kigluaik gneiss dome	amphibolite to granulite	Yes, pervasive	Yes, 105-90 Ma	J-K blueschist facies
2. Shuswap - Thor Odin	upper amphibolite facies	Yes, pervasive	Paleogene leucogranites	Late K-Paleocene-amph.
3. Okanogan Dome	upper amphibolite facies	Yes, pervasive	Yes, 54 Ma	Late K-Paleocene-amph.
4. Ruby Mountains	amphibolite facies, sillimanite pervasive	Yes	Yes, 35-27 Ma	Late Cretaceous-amph.
5. Albion-Raft-Grouse	amphibolite, local sillimanite	Cenozoic plutons remobilize Precambrian	Yes, 42-25 Ma; 30-24 Ma batholith	Late Cretaceous (?) amph.(?)
6. Northern Snake Range	greenschist	No	No	Late Cretaceous-amph.
7. Funeral Mountains	low greenschist facies	No	No	Late Cretaceous-amph.

References: 1. Kigluaik gneiss dome, Seward Peninsula, Alaska: Amato and Miller (2004, and references within), Amato etal. (1994); this paper. 2. Shuswap -Thor Odin migmatite domes, southern British Columbia, Canada: Fayon et al. (2004, and references within). 3. Okanogan migmatitic dome, Washington: Kruckenberg et al. (in press), Kruckenberg and Whitney (2007), Hansen and Goodge (1988). 4. Ruby Mountains metamorphic core complex, Nevada: Snoke et al. (1990), Howard (2003, and references within). 5. Albion-Raft River-Grouse Creek complex, Idaho-Utah: Compton et al. (1977); Todd (1980); Strickland et al. (2007). 6. Snake Range metamorphic core complex, east-central Nevada: Miller et al. (1983), Lee et al. (1987). 7. Funeral Mountains, Death Valley, California: Mattinson et al. (2007, and references within).

In addition to differences in the metamorphic temperatures and magmatic histories of the core complexes listed in Table 1, other factors may have operated to yield the range of observations and relations we see in Basin and Range core complexes (Fig. 4.2). At least some of the features that have been termed metamorphic core complexes are gently dipping, large-offset normal faults (± 10 km) that bound tilted footwall blocks. Upon restoration, these faults can be shown to have had initially steep dips (Fig. 4.2a). By their very nature, large-offset, high-angle normal faults that formed during one episode of slip cannot cut or extend to depths much greater than the seimogenic base of the crust or the ductile-brittle transition zone (Fig. 4.2a) and alone cannot account for the near adiabatic rise of higher pressure rocks into the shallow crust (e.g., Fayon et al., 2004). Normal faults with footwalls that have undergone significant flow at high temperatures or complexes that adiabatically exhume very deep rocks must represent different phenomena that include a ductile, diapiric component of rise of footwall rocks as has been suggested for the Bering Strait gneiss domes (Fig. 4.2b). However, vertical diapirism alone does not account for the formation of gently dipping detachment faults and the widespread subhorizontal fabrics of many extended regions, which require large-magnitude stretching of the crust as well (e.g., the Seward Peninsula and Kigluaik gneiss dome, Fig. 4.2c).

Good examples of large-offset faults with significant associated tilts (Fig. 4.2a) are the Gold Butte Block (Reiners et al., 2000), faults in the Wassuk Range (Surpless et al., 2002; Stockli et al., 2002), and the Deep Creek fault along the Nevada-Utah border (Rodgers, 1987), but these fault footwalls do not expose significant, syn-extensional, ductile fabrics as do the Albion-Raft River-Grouse Creek, Snake Range, and Funeral Mountains core complexes (Table 1). These later systems require either more than one fault (Fig. 4.2a) or a component of syn-extensional pure shear stretching of lower and upper plate rocks (e.g., Figs. 4.2c and 4.2d). Buck's (1988) "rolling hinge" model provides a mechanically and rheologically reasonable way to obtain the resulting observed geometries of these core complexes (Fig. 4.2e) but does not discuss what the attendant, resulting flow geometry might be in lower plate rocks, despite the model's prediction of large material movement into the plane of cross-section (Fig. 4.2e).

It is now accepted that crustal flow (channel flow) beneath parts of the Basin and Range compensated for differing degrees of upper crustal strain (Fig. 4.2d; e.g., Klemperer et al., 1986; Gans, 1987; Royden, 1996; McKenzie et al., 2000). This process has been more thoroughly documented by the studies in the Bering Strait region. Flow of the lower crust into regions of greater extension provides the best explanation for the vertical component of rise beneath more highly extended regions in the Basin and Range (Fig. 4.2f; Gans, 1987). This differential component of uplift can significantly modify the geometry of supracrustal, brittle-to-ductile fault systems (Figs. 4.2d, e, and f), a factor not often taken into consideration when analyzing fault geometries in the upper, brittle crust.

In summary, it appears likely that several processes may operate singly or together during extension of continental crust (as depicted in Figure 4.2) and, depending on the total amount of strain, temperatures, and composition/rheology of the crust, may occur to differing degrees, producing the rather wide range of phenomena termed "metamorphic core complexes" in the Cordillera and elsewhere. Studies in Alaska and across the Bering Shelf summarized here provide compelling evidence that metamorphism, melting, and crustal flow are driven and aided by the tranfer of heat into the crust by mantle-derived magmas, a key additional factor that is likely to be of fundamental importance to the origin of the Basin and Range. The long-lived history of broadly syn-extensional magmatism in the Basin and Range and evidence for very high heat flow in the province today suggests a lower crustal history for the province like that documented by xenoliths from the Bering Shelf – granulite facies metamorphism of the deep crust as predicted by Sandiford and Powell (1986) and wholescale flow contemporaneous with extension. With this perspective in mind, metamorphic core complexes do in fact provide us with a glimpse of these postulated, elevated temperatures and of the degree and extent of the mobility and reconstitution of the deep crust beneath the Basin and Range.

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