Origin and evolution of the lower crust in magmatic arcs and continental crust

Mark D. Behn, Esteban Gazel, Bradley R. Hacker, Olivier Jagoutz, Peter B. Kelemen, Donna Shillington

Taking a broad view of the research supported by grants from GeoPRISMS[1] and elsewhere, we've conducted several recent reviews (Gazel et al. 2015; Hacker et al. 2015; Jagoutz & Behn 2013; Jagoutz & Kelemen 2015; Kelemen & Behn 2015; Shillington et al. 2013). A summary of our results is as follows.

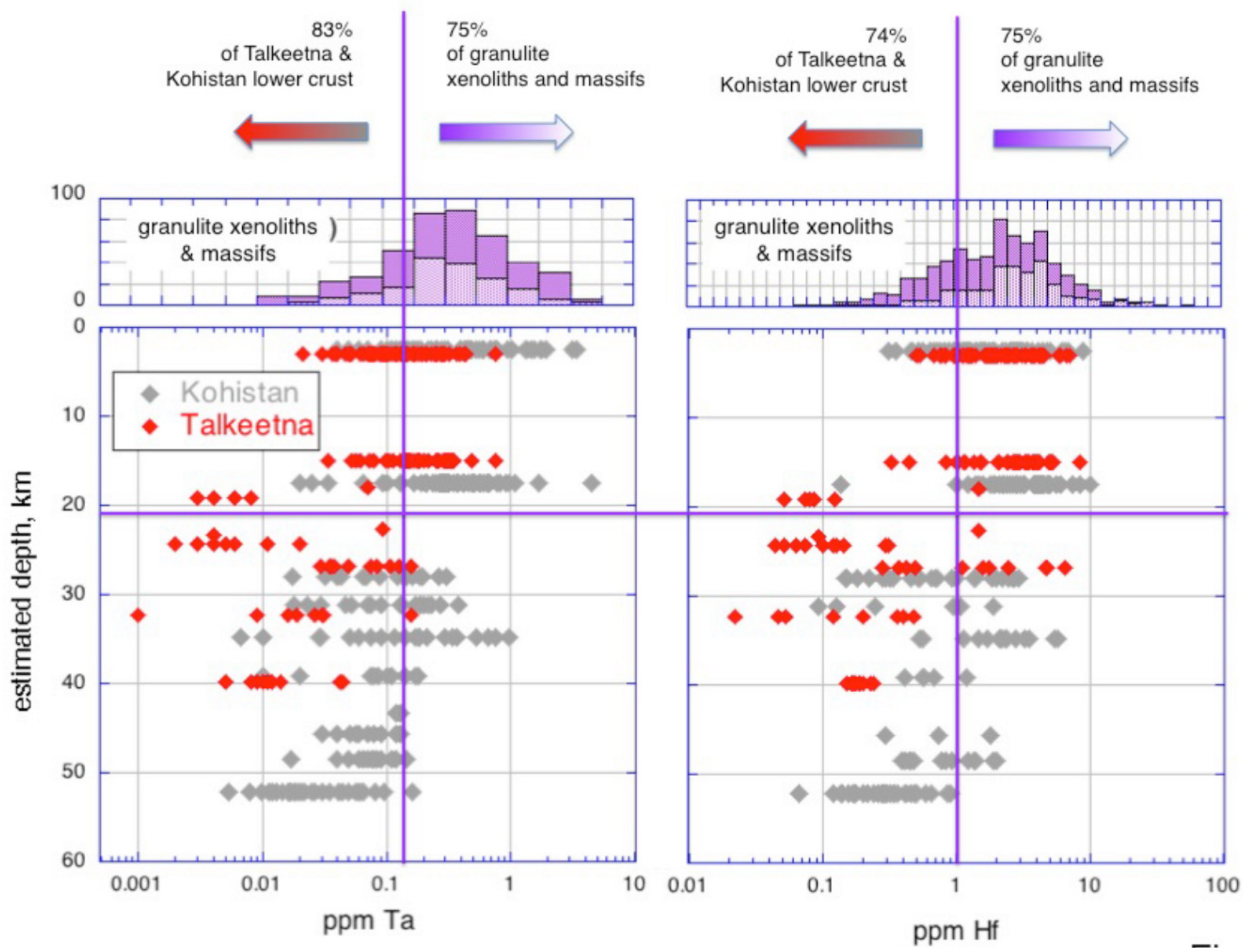
Thin oceanic crust is formed by decompression melting of the upper mantle at mid-ocean ridges, but the origin of the thick and buoyant continental crust is enigmatic. Juvenile continental crust may form from magmas erupted above intraoceanic subduction zones, where oceanic lithosphere subducts beneath other oceanic lithosphere. However, it is unclear why the subduction of dominantly basaltic oceanic crust forms andesitic continental crust. Gazel et al. (2015) use geochemical and geophysical data to reconstruct the evolution of the Central American land bridge, which formed above an intra-oceanic subduction system over the past 70 Myr. We find that the geochemical signature of erupted lavas evolved from basaltic to andesitic about 10 Myr ago—coincident with the onset of subduction of more oceanic crust that originally formed above the Galápagos mantle plume. We also find that seismic P-waves travel through the crust at velocities intermediate between those typically observed for oceanic and continental crust. We develop a continentality index to quantitatively correlate geochemical composition with the average P-wave velocity of arc crust globally. We conclude that although the formation and evolution of continents may involve many processes, melting enriched oceanic crust within a subduction zone—a process probably more common in the Archaean—can produce juvenile continental crust.

The composition of much of Earth's lower continental crust is enigmatic. Seismic wavespeeds require that 10–20% of the lower third is mafic, but the available heat-flow and wavespeed constraints can be satisfied if lower continental crust elsewhere contains 49 to 62 wt% SiO_2 (Hacker et al. 2015; also see Behn & Kelemen 2003). Thus, contrary to common belief, the lower crust in many regions could be relatively felsic, with SiO_2 contents similar to andesites and dacites. Most lower crust is less dense than the underlying mantle, but mafic lowermost crust could be unstable and likely delaminates beneath rifts and arcs as invoked by Jagoutz & Behn (2013). During sediment subduction, subduction erosion, arc subduction, and continent subduction, mafic rocks

[1]*NSF OCE-1144759: "Collaborative Research: Plutons as ingredients for continental crust: Pilot study of the difference between intermediate plutons and lavas in the intra-oceanic Aleutian arc", Kelemen, PI, Steve Goldstein, Sidney Hemming, M. Rioux(UCSB) co-PI's; NSF OCE-1358091/1356132, Marine Geology and Geophysics Program, "Advanced modeling for understanding fluid & magma migration in subduction zones", Cian Wilson, lead PI, P Kelemen, M Spiegelman & Peter van Keken (Univ. Michigan) co-PI's; NSF EAR-1457293: "Collaborative Research: Focused Study of Aleutian Plutons and their Host Rocks: Understanding the building blocks of continental crust",P. Kelemen lead PI,; NSF-EAR-0742451, "Collaborative Research: Element Recycling from UHP Metasediments: Evidence and Consequences" PB Kelemen and BR Hacker, PI's; NSF EAR-1219942, "What Determines Whether the Deep Continental Crust Flows [or not]?" BR Hacker & ARC Kylander-Clark; NSF #: EAR-1322032: A field study of the liquid line of descent of hydrous alkaline-rich magmas at elevated pressures (0.5-1.0 GPa); the Dariv alkaline intrusive complex, O. Jagoutz PI*

become eclogites and may continue to descend into the mantle, whereas more silica-rich rocks are transformed into felsic gneisses that are less dense than peridotite but more dense than continental upper crust. These more felsic rocks may rise buoyantly, undergo decompression melting and melt extraction, and be relaminated to the base of the crust. As a result of this refining and differentiation process, such relatively felsic rocks could form much of Earth's lower crust (Hacker et al. 2011, Kelemen & Behn 2015).

A long-standing theory for the genesis of continental crust is that it is formed in subduction zones. However, the observed seismic properties of lower crust and upper mantle in oceanic island arcs differ significantly from those in the continental crust . Accordingly, significant modifications of lower arc crust must occur, if continental crust is indeed formed from island arcs. Jagoutz & Behn (2013) investigated how the seismic characteristics of arc crust might be transformed into those of the continental crust by calculating the density and seismic structure of two exposed sections of island arc (Kohistan and Talkeetna). The Kohistan crustal section is negatively buoyant with respect to the underlying depleted upper mantle at depths exceeding 40 kilometres and is characterized by a steady increase in seismic velocity similar to that observed in active arcs. In contrast, the lower Talkeetna crust is density sorted, preserving only relicts (about ten to a hundred metres thick) of rock with density exceeding that of the underlying mantle. Specifically, the foundering of the lower



Talkeetna crust resulted in the replacement of dense mafic and ultramafic cumulates by residual upper mantle, producing a sharp seismic discontinuity at depths of around 38 to 42 km, characteristic of the continental Moho. Dynamic calculations indicate that foundering is an episodic process that occurs in most arcs with a periodicity of half a million to five million years. Because foundering will continue after arc magmatism ceases, this process ultimately results in formation of the continental Moho.

Jagoutz & Kelemen (2015) reviewed recent research on arc composition, focusing on the relatively complete arc crustal sections in the Jurassic Talkeetna arc (south central Alaska) and the Cretaceous Kohistan arc (northwest Pakistan), together with seismic data on the lower crust and uppermost mantle. Whereas primitive arc lavas are dominantly basaltic, the Kohistan crust is clearly andesitic and the Talkeetna crust could be andesitic. The andesitic compositions of the two arc sections are within the range of estimates for the major element composition of continental crust. Calculated seismic sections for Kohistan and Talkeetna provide a close match for the thicker parts of the active Izu arc, suggesting that it, too, could have an andesitic bulk composition. Because andesitic crust is buoyant with respect to the underlying mantle, much of this material represents a net addition to continental crust. Production of bulk crust from a parental melt in equilibrium with mantle olivine or pyroxene requires processing of igneous crust, probably via density instabilities. Delamination of dense cumulates from the base of arc crust, foundering into less dense, underlying mantle peridotite, is likely, as supported by geochemical evidence from Talkeetna and Kohistan. Relamination of buoyant, subducting material—during sediment subduction, subduction erosion, arc-arc collision, and continental collision—is also likely, as described more extensively by Behn et al. (2011) and Hacker et al. (2011, 2015).

Geochemical similarities between arc magmas and continental crust indicate that arc magmatic processes – and/or similar Archean processes – played a central role in generating continents. As noted above in the summary of Jagoutz & Behn (2013) an outstanding question is how arc crust formed from basaltic, mantle-derived magmas with 48 to 52 wt% SiO_2 is transformed to andesitic continental crust with more than 57 wt% SiO_2. One commonly invoked process removes dense, SiO_2-poor products of magmatic fractionation from the base of arc crust by "delamination", as in Jagoutz & Behn 2013. However, lower arc crust after delamination has significantly different trace element contents compared to estimates for the lower continental crust, and we present a simple, alternative explanation (Kelemen & Behn 2015).

In the alternative model of Kelemen & Behn (2015), buoyant magmatic rocks generated at arcs are first subducted, but upon heating these buoyant lithologies re-ascend through the mantle wedge or along a subduction channel, and are "relaminated" at the base of overlying crust. To test the relamination model, we review the average compositions of buoyant lavas and plutons for the Aleutians, Izu-Bonin-Marianas, Kohistan and Talkeetna arcs and show that they fall within the estimated range of lower continental crust compositions for major and trace elements. Relamination provides a more efficient process for generating the continental crust than does delamination and has important implications for the long-term evolution of heat producing elements in the Earth's crust.

Determining the bulk composition of island arc lower crust is essential for distinguishing between competingmodels for arc magmatism and assessing the stability of arc lower crust. Shillington et al. (2013) presented new constraints on the composition of high P-wave velocity (V_P = 7.3–7.6 km/s) lower crust of the Aleutian arc from best-fitting average lower crustal V_P/V_S ratio using sparse converted S-waves from an along-arc refraction profile. We find a low V_P/V_S of ~1.7–1.75. Using petrologic modeling, we show that no single composition is likely to explain the combination of high V_P and low V_P/V_S. Our preferred explanation is a combination of clinopyroxenite (~50–70%) and a-quartz bearing gabbros (~30–50%). This is consistent with Aleutian xenoliths and lower crustal rocks in obducted arcs, and implies that ~30–40% of the full Aleutian crust comprises ultramafic cumulates. These results also suggest that small amounts of quartz can exert a strong influence on V_P/V_S in arc crust.

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Different parental magmas for plutons versus lavas in the central Aleutian arc

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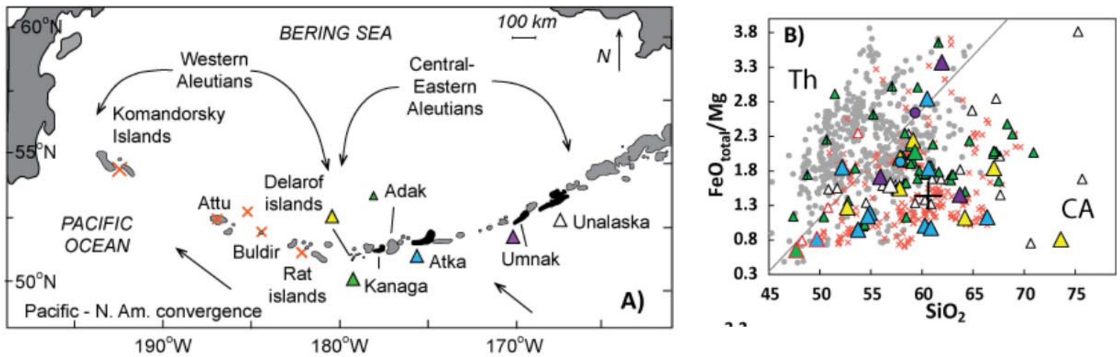
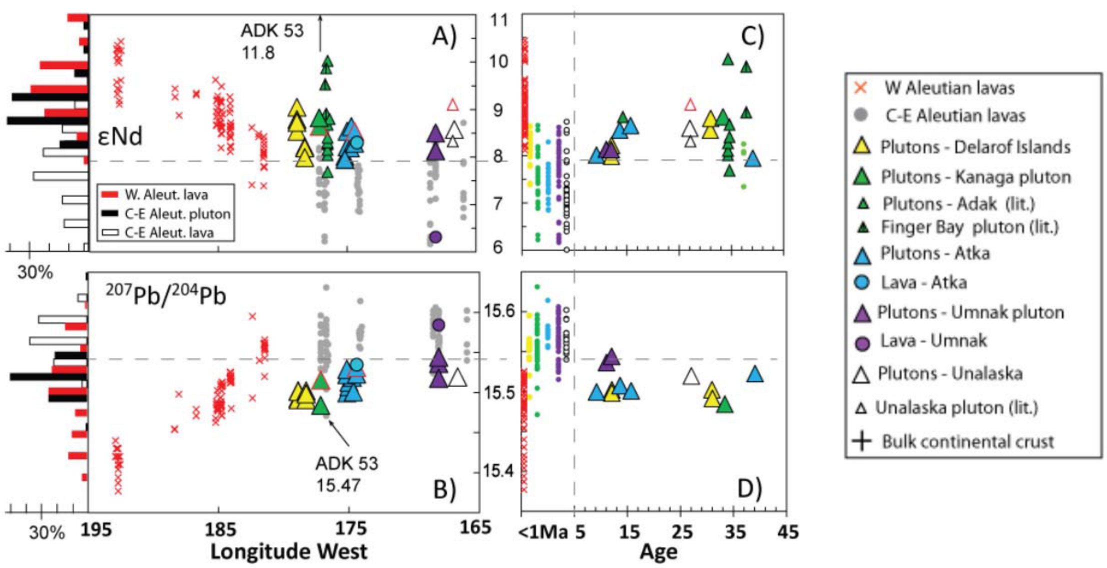
The oceanic, Aleutian magmatic arc has never been rifted, the crust is relatively thick compared with other Pacific arcs, the islands are relatively large, and thus the islands host extensive exposures of Eocene to Miocene plutons as well as Eocene to Holocene lavas. These large outcrops of plutonic rocks are unique among oceanic arcs worldwide, and offer an exceptional opportunity to study the mid-crust in such settings. Most geochemical work on the Aleutians has focused on Holocene lavas. With a pilot grant from NSF GeoPRISMS[1], we obtained samples of plutons from the Aleutians collected by the US Geological Survey from 1950 to 1980, and made modern trace element and isotope analyses of these samples. Prior to this, there were very few similar studies of Aleutian plutons. The results of our preliminary study are as follows.

Cenozoic plutons that comprise the middle crust of the central and eastern Aleutians have distinct isotopic and elemental compositions compared to Holocene tholeiitic lavas in the same region, including those from the same islands (Cai et al. 2013, 2014, 2015). Therefore the Holocene lavas are not representative of the net magmatic transfer from the mantle into the arc crust. Compared to the lavas, the Eocene to Miocene (9-39 Ma) intermediate to felsic plutonic rocks show higher SiO_2 at a given Mg/(Mg+Fe). In other words, the plutons are "calc-alkaline" whereas the lavas are dominantly tholeiitic. Crucially, the plutons also have higher εNd-εHf values and lower Pb and Sr isotope ratios than the lavas. In all of these ways, the plutonic rocks strongly resemble calc-alkaline, Holocene volcanics with "depleted" isotope ratios in the western Aleutians, whose composition has been attributed to significant contributions from partial melting of subducted basaltic oceanic crust. The new isotope data on the plutons data reflect temporal variation of central and eastern Aleutian magma source compositions, from predominantly calc-alkaline compositions with more "depleted" isotope ratios in the Paleogene, to tholeiitic compositions with more "enriched" isotopes more recently. Alternatively, the differences between central Aleutian plutonic and volcanic rocks may reflect different transport and emplacement processes for the magmas that form plutons versus lavas. Calc-alkaline parental magmas, with higher SiO_2 and high viscosity, are likely to form plutons after extensive mid-crustal degassing of initially high water contents. In any case, our isotope data have overarching importance because the plutonic rocks are chemically similar to bulk continental crust, whereas the central Aleutian lavas are not. Formation of similar plutonic rocks worldwide may play a key role in the genesis and evolution of continental crust.

During fieldwork in summer 2015, funded by a second GeoPRISMS grant[2], we will sample older volcanic rocks that are intruded by Paleogene plutons on Unalaska, Umnak and Atka Islands, ensuring that we have overlapping age coverage for volcanic and plutonic rocks in the central Aleutians. We can then test whether the isotopic and compositional differences between central Aleutian plutons and lavas reflect a temporal evolution in the arc, or the continuous presence of two distinct magma series throughout arc history.

We will also make detailed studies of some of the larger plutons in the Aleutians, including the Shaler pluton on Unalaska Island. There are fewer than five published analyses of the Shaler pluton, which is the largest exposed pluton in the arc. Prior to our pilot work there was only a single, imprecise, biotite $^{40}Ar/^{39}Ar$ age on the pluton from the Shaler.





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[1] *Research reported here was funded by NSF OCE-1144759: "Collaborative Research: Plutons as ingredients for continental crust: Pilot study of the difference between intermediate plutons and lavas in the intra-oceanic Aleutian arc", Peter Kelemen, PI, Steve Goldstein, Sidney Hemming, M. Rioux(UCSB) co-PI's, $150,000, 2011-2014.*

[2] *Ongoing field work in the is funded by NSF EAR-1457293: "Collaborative Research: Focused Study of Aleutian Plutons and their Host Rocks: Understanding the building blocks of continental crust",P. Kelemen lead PI, $200,000, 2015-17*

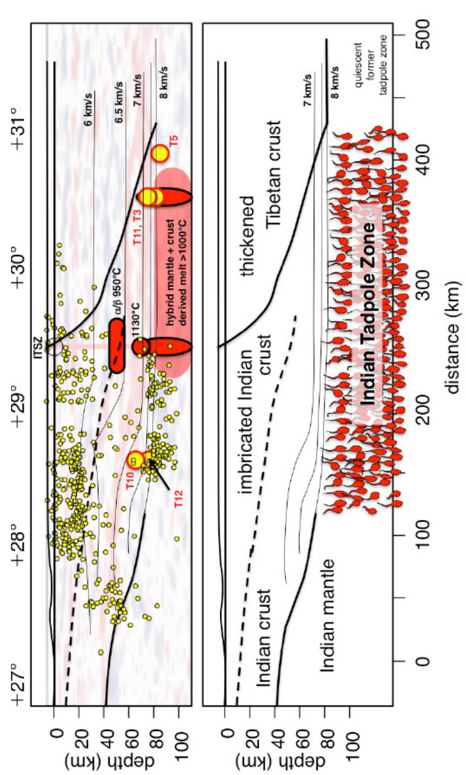
The Tadpole Zone: High temperatures and density filtering of Indian continental crust along the Moho beneath southern Tibet

Peter B. Kelemen, Bradley R. Hacker

Supported in part by past and present GeoPRISMS and related grants[1], we are preparing a paper outlining the following hypothesis.

Data indicate that the thick middle and lower continental crust of the central southern Lhasa block is hot and largely felsic. These data include: (1) the presence of 10–18 Ma volcanic rocks including primitive andesites and dacites formed by interaction between crustal melts and mantle peridotite, (2) thermobarometry on xenoliths in a 12.7 Ma dyke indicating temperatures greater than 1000˚C in the lowermost crust (2.6 GPa), (3) low seismic wavespeeds (VP < 7 km/s) characterize the upper 70 km of the crust, (4) an abrupt transition from low to high VP/VS ratios interpreted as the α/β quartz transition at 50 km depth and ~ 950˚C, and (5) high wavespeeds (VP > 7.5 km/s) between 70 and 85 km depth. Though these data indicate that the Moho has been at ~ 1000˚C or more since the Miocene, there are also (6) earthquakes at Moho depths in this region.

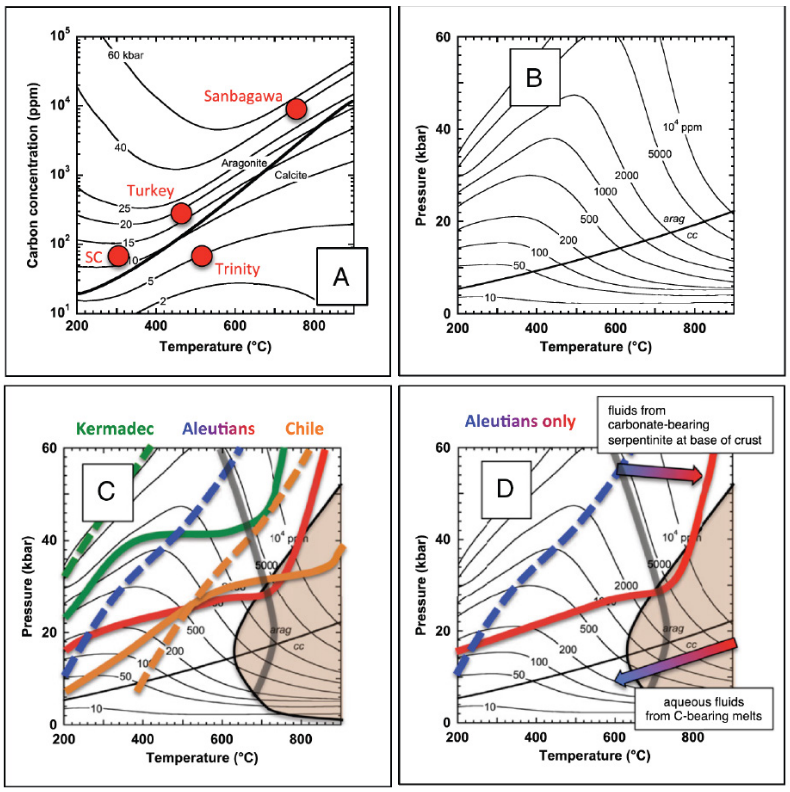
The well-defined Moho at ~ 80 km depth throughout this region may be due to the transition from garnet granulite to eclogite facies in the imbricated Indian crust subducting beneath Tibet. Along this horizon, as the Indian continental crust continues to be thrust northward beneath Tibet, mafic lithologies become dense eclogites that form diapirs sinking into the upper mantle, while buoyant, felsic lithologies remain in a steadily thickening crust. High temperatures close to the Moho arise from a combination of radioactive heating of thick, felsic crust and upward return flow of mantle material around descending eclogite diapirs. There is a belt of primitive, potassic magmas (Mg/(Mg+Fe) of 0.6 to 0.7) extending for ~ 1500 km, 0 to 100 km north of the Indus-Tsangpo Suture Zone, with an isotopic component derived from continental crust. These magmas probably formed via chemical interaction between mantle peridotite and partial melts of foundering eclogite. Earthquakes at Moho depth occur at high temperature, perhaps due to localized, non-Newtonian deformation coupled with thermal runaway in compositionally weak layers and/or the margins of diapirs.



[1]NSF OCE-1144759: "Collaborative Research: Plutons as ingredients for continental crust: Pilot study of the difference between intermediate plutons and lavas in the intra-oceanic Aleutian arc", Kelemen, PI, S Goldstein, S Hemming, M Rioux (UCSB) co-PI's; NSF OCE-1358091/1356132, Marine Geology and Geophysics Program, "Advanced modeling for understanding fluid & magma migration in subduction zones", C Wilson, lead PI, P Kelemen, M Spiegelman & P van Keken (U. Michigan) co-PI's; NSF EAR-1457293: "Collaborative Research: Focused Study of Aleutian Plutons and their Host Rocks: Understanding the building blocks of continental crust",P. Kelemen lead PI; NSF-EAR-0742451, "Collaborative Research: Element Recycling from UHP Metasediments: Evidence and Consequences" P Kelemen and B Hacker, PI's; NSF EAR-1219942, "What Determines Whether the Deep Continental Crust Flows [or not]?" B Hacker & ARC Kylander-Clark

Reevaluating carbon fluxes in subduction zones: What goes down, mostly comes up

Peter B. Kelemen, Craig E. Manning



We recently reviewed carbon fluxes in subduction zones (Kelemen & Manning 2015), supported in part by grants from GeoPRISMS and other sources . Carbon fluxes in subduction zones can be better constrained by including new estimates of carbon concentration in subducting mantle peridotites, consideration of carbonate solubility in aqueous fluid along subduction geotherms (Caciagli & Manning 2008; Dolejs & Manning 2010; Manning et al. 2013; Manning 2013), and diapirism of carbon-bearing metasediments (e.g., Kelemen et al. 2003; Behn et al. 2011).

Whereas previous studies concluded that about half the subducting carbon is returned to the convecting mantle, we find that relatively little carbon may be recycled. If so, input from subduction zones into the overlying plate is larger than output from arc volcanoes plus diffuse venting, and substantial quantities of carbon are stored in the mantle lithosphere and crust. Also, if the subduction zone carbon cycle is nearly closed on time scales of 5–10 Ma, then the carbon content of the mantle lithosphere + crust + ocean + atmosphere must be increasing. Such an increase is consistent with inferences from noble gas data. Carbon in diamonds, which may have been recycled into the convecting mantle, is a small fraction of the global carbon inventory.

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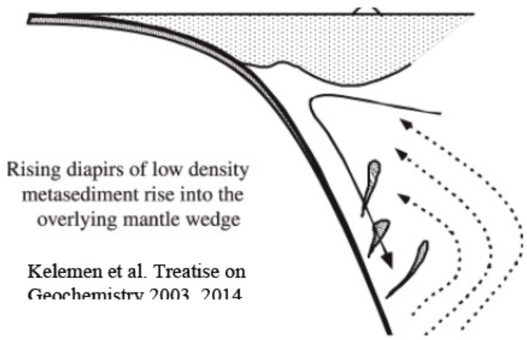

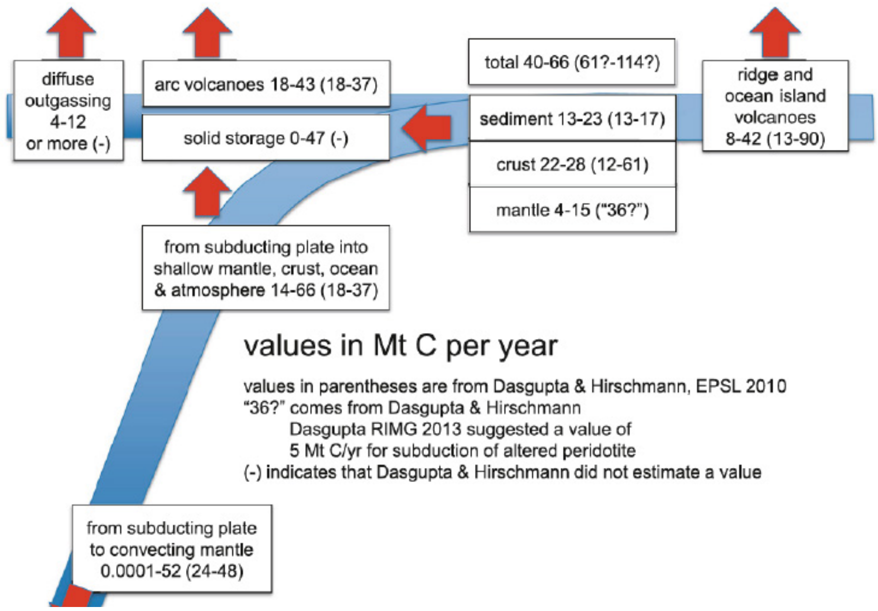

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