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Deploy the Amphibious Array to the Alaska-Aleutian Subduction System

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In 2009, NSF provided ARRA funds to build an amphibious geophysical facility onshore and offshore, providing support for MARGINS (GeoPRISMS) and EarthScope science objectives. The facility included onshore seismographs similar to USArray-Transportable Array seismographs, upgrades to PBO-GPS facilities, and a fleet of 60 ocean bottom seismometers (OBS's), twenty of which are specially designed for shallow water use. All data from these instruments are open and freely available as soon as they are recovered, so the facility forms an excellent backbone to a community-based initiative. The Amphibious Array facility is now being deployed off the Cascadia margin, and it future use is to be reviewed before completion of the 4-year deployment. The Amphibious Array should move to the Alaska-Aleutian subduction system upon completion of Cascadia work, to provide a critical base data stream for GeoPRISMS and EarthScope science.

For details see the 2009 Planning Workshop report, and for updates on current activities and status, see Cascadia Initiative links, all from *www.geoprisms.org/cascadia.html*.

Overview. Much of the Alaska-Aleutian subduction system straddles the coastline. Critical targets for GeoPRISMS include the thrust zone, the sub-arc mantle wedge, volcanic arc and backarc, and the incoming plate seaward of the trench. Any successful science program addressing these targets will include sampling of the seismic wavefield both to characterize sources (earthquakes, tremor, etc.) and to image the Earth's interior. Combined onshore-offshore imaging will be necessary to (for example} sample seismicity and tremor at the downdip end of the megathrust, to sample deep roots of volcanoes in the Aleutians, and to systematically image the subducting plate from seaward of the trench to its deepest extent. These seismic observations will then provide basic constraints for a host of related geologic, tectonic, geochemical, and geodynamic studies. In Alaska (and nearly all subduction zones) such seismology requires both offshore and onshore array deployments, precisely the kind of deployment that the Amphibious Array is designed to achieve. In fact, with the its fleet of shallow-water-capable OBS systems, the Amphibious Array may be the only tool capable of conducting the kinds of seismic experiments needed to make GeoPRISMS in Alaska a success.

Megathrust. Many of the largest recorded earthquakes on the planet have taken place in the Alaska-Aleutian system, including the great 1964 Mw 9.3 earthquake. These earthquakes pose a major seismic and tsunami hazard. Relatively little direct seismic monitoring of megathrust seismicity has taken place in the last couple decades, and almost no OBS recording since early forays around 1980. Nevertheless, earthquakes are abundant, constituting 80% of U.S. seismicity, and direct onshore and offshore recording will be critical to address GeoPRISMS objectives. In the 2006-9 MOOS broadband experiment in Kenai Peninsula (Abers/Christensen), we recorded a locatable thrust zone earthquake every 10 minutes within a 200x300 km array.

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Similar or higher seismicity rates were recorded during two 3-day active-source short-period deployments off the Alaska Peninsula in July 2011 (Shillington/Nedimovic/Webb). Nonvolcanic tremor has been well-recorded just downdip of Anchorage and more recently, near several volcano seismic stations in the Peninsula and Aleutians (Brown et al., Fall AGU 2010). Because much of the seismogenic zone is offshore, a shallow-water-capable OBS facility is essential to effectively capturing earthquakes. Unlike the Cascadia region, the Alaskan-Aleutian megathrust provides the opportunity to monitor small earthquakes and tremor along a thurst zone with highly variable coupling characteristics as determined by geodesy, ranging from stable sliding to locked.

Volcanic arc, magmas and volatiles. The transport of volatiles to depths in subducting slabs, the melting and flow in mantle wedges and the delivery of that melt to arc volcanoes all leave potential imprints in seismic images. Much of this plumbing remains poorly constrained, and a major motivator of MARGINS and GeoPRISMS has been resolving pathways, rates, and physical process of magma and volatile transport. The Aleutian Arc was chosen as a primary site in part because the arc has a long but fairly stable post-Eocene history while plate inputs (obliquity, convergence rate, sediment supply) vary in systematic ways along the arc, so models of the plumbing can be tested in fairly constrained ways. One of the main tools for evaluating structure at these scales has been deployment of fairly dense seismic arrays, such as has been done in MARGINS Focus Sites (Marianas, Central America) and a few other subduction zones around the planet. To do any kind of imaging deployment in the Aleutians will require both seismometers on the islands and extensive OBS arrays in the forearc, arc and back-arc. Even simple observations, such as constraining Wadati-Benioff Zone geometry, will require amphibious seismic arrays. Such deployments typically take 1-2 years, to record sufficient data, and given the typical station spacing in imaging arrays (10-50 km), a substantial investment in OBS deployments over the life of GeoPRISMS will be needed to achieve objectives.

Deployment Strategies. As with Cascadia, we envision a community process whereby a sequence of OBS (and on-shore) deployments are planned over the ~5 year duration of data collection in Alaska. Much will be learned from Cascadia that will inform any planning, but several issues seem obvious. One is that the 3000 km long Aleutian arc is large compared to the size of the available array, and focus corridors will be needed. Also, unlike Cascadia, seismicity is abundant and experiments can be designed to more directly target local earthquakes (and tremor-related phenomena). Finally, the oceanic nature of the (robust) Aleutian arc dictates OBS deployments to image magmatic systems, tightly linked to shore-based arrays, combining relatively low-noise land sites on islands and peninsulas to areally extensive offshore stations. The open-access data agreement for the Amphibious Array ensures maximal and rapid use of these observations.

In summary, a well-coordinated deployment of the Amphibious Array including onshore seismic and geodetic stations will be crucial to the success of Alaska/Aleutians as a Primary Site. At the same time, this setting offers phenomenal potential for scientific return from the array facility.

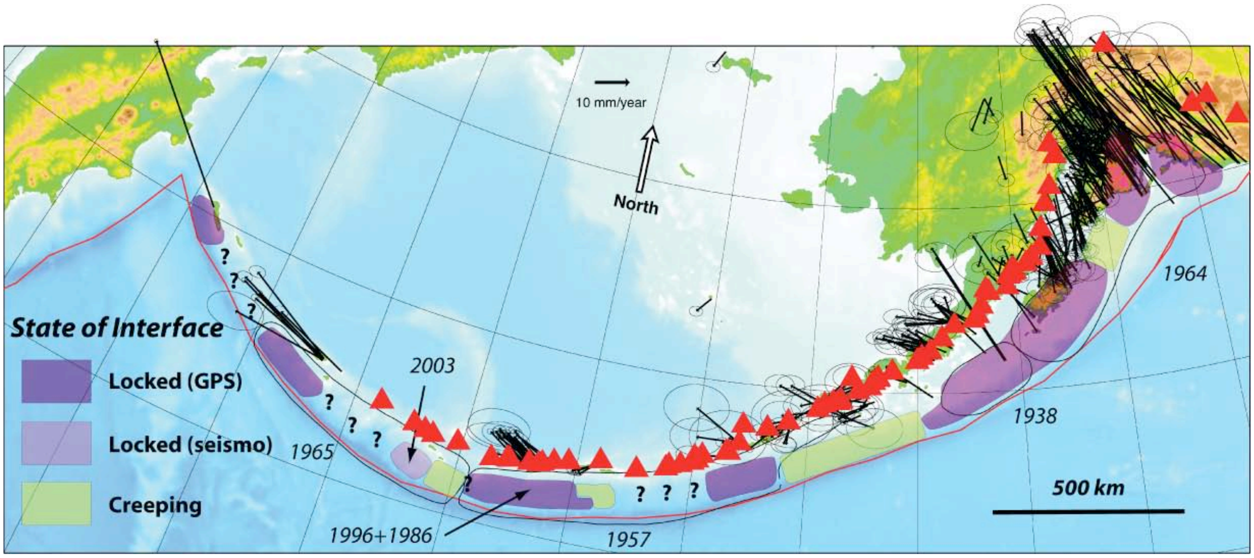

Figure 1. Alaska, volcanoes (triangles), and great earthquake rupture zones showing estimated geodetic locking and GPS-derived velocities relative to North America (after Freymueller et al., 2008, AGU Monogr. 179, p. 1-42).

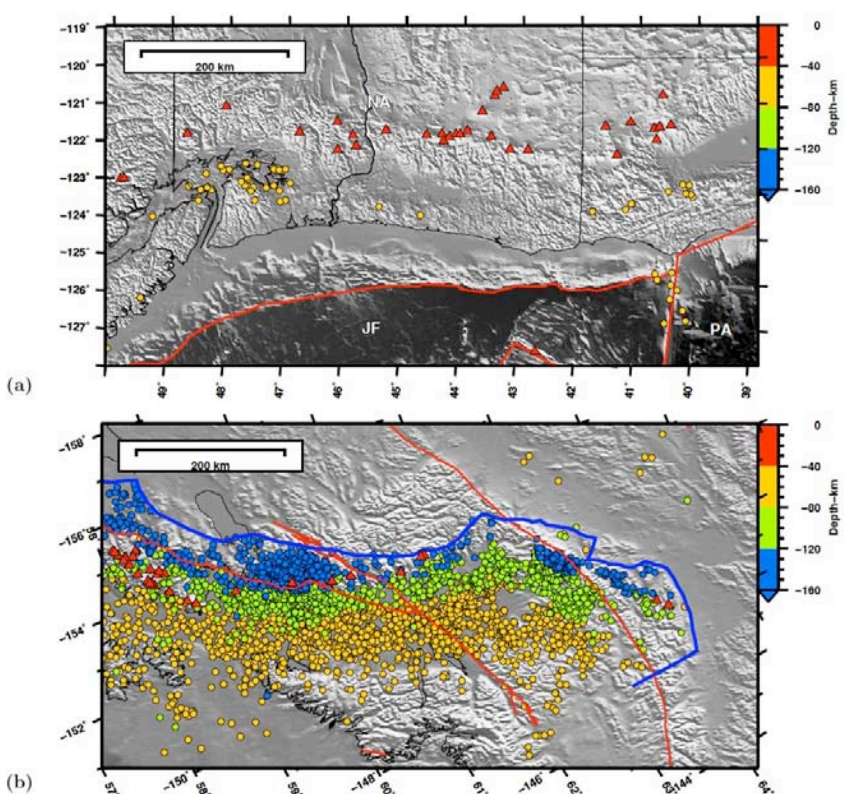

Figure 2. Scaled comparison between the Cascadia subduction zone and the eastern segment of the Alaska-Aleutian system. Seismicity, circles, show earthquakes with depth > 40 km, M > 3, 1900-2010. Red triangles denote active volcanoes.

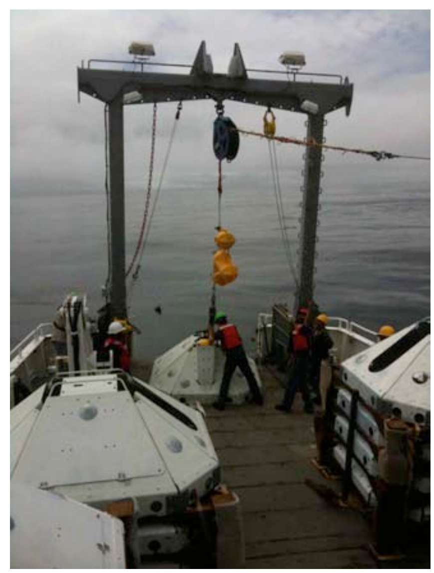

Figure 3. New trawl-resistant OBS's being deployed off Cascadia. From July, 2011 cruise report (Tolstoy, Trehu). http://pages.uoregon.edu/drt/CIET/doku.php

Collection of Potential Fields Data to Constrain Spatial Patterns of Deformation in South-Central, Alaska

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Potential fields data, especially gravity and magnetics, can be used to examine a number of important tectonic processes in the Cook Inlet and Prince William Sound regions of Alaska. Over the past 3 years we have conducted gravity campaigns in the Kenai Peninsula, Anchorage and Mat-Su Valley regions, collecting over 1000 new gravity data points (Figure 1). Our 2009 and 2010 campaigns focused on the Border Ranges fault system, while the emphasis in summer 2011 was on the Castle Mountain fault (CMF). These data are greatly enhancing our understanding of structural controls on the earthquake rupture along the plate interface and subduction processes, the relation of deformation to upper plate geology and structure, and the relation of lower crust/upper mantle serpentinite bodies to fluid migration.

Seismicity within middle Cook Inlet lies within a -75 mGal Bouguer anomaly low and magnetic high that may be related to serpentinized lower crust and upper mantle (Saltus et al., 2001; Haeussler and Saltus, 2001) (see Figure 2). Our 2.5-D modeling of newly acquired and existing gravity data indicates this serpentizined zone narrows to the northeast and ends near the projected subducted southwestern edge of the Yakutat microplate. This is in accord with the model of Haeussler and Saltus (2011) that suggests the subducting Yakutat microplate is less fluid rich than typical oceanic crust and that any fluid flow above the slab is channeled toward the southwest. Haeussler and Saltus (2011) further propose that the presence of fluids within the lower crust and upper mantle in this region has led to the rapid subsidence within upper Cook Inlet basin.

East of the Border Ranges fault (BRF) we observe a Bouguer anomaly high (> -50 mGal) throughout most of the eastern Kenai Peninsula, but a low (< -70 mGal) on the eastern side of the BRF east of Anchorage (Figure 2). We believe this change in gravity reflects the subduction of the less dense Yakutat microplate north of Turnagain Arm.

In the Prince William Sound region shallow (< 15 km) seismicity occurs at the edges of mafic and ultramafic bodies that are delineated at depth by aeromagnetic highs (Doser et al., 2008). The edges of the strongly coupled Prince William Sound asperity correlate well with the edge of the -20 mGal Bouguer anomaly associated with the shallowly dipping Yakutat microplate and Pacific plate beneath the region.

Our recent gravity survey along the CMF (completed mid-August 2011) was motivated by the observation that existing gravity data suggest that most recent seismicity along the fault occurs in regions where the Bouguer anomaly > -70 mGal. In contrast, paleoseismologic studies (e.g. Haeussler et al., 2002) show Holocene slip rates along the fault are higher in regions where the Bouguer anomaly < -100 mGal. Considering that the timing of M>7 events along the CMF appear to be similar to events along the plate interface (Haeussler et al., 2002) we hope the recent gravity data will help us resolve possible structural relationships between the CMF and the plate interface.

It is obvious that potential field data can greatly enhance our understanding of structural controls on the earthquake rupture and subduction processes. Unfortunately, gravity and magnetic data are sparse in many regions of south-central Alaska, and existing data were often collected several decades ago with lower resolution instrumentation and less precisely determined station locations. We propose to collect new gravity and magnetic data in tandem with other planned geophysical and geological studies of this region. This would include collection of marine data in conjunction with any new refraction/reflection surveys in Prince William Sound or Cook Inlet or the deployment of OBS for passive seismic studies. Collection of land data in regions accessible by 4-wheeler, snow machine, boat, float plane or helicopter during deployment of seismograph stations or other geological/geophysical studies would also be advantageous. Critical regions where we lack detailed coverage include much of offshore/onshore Prince William Sound, the southern Kenai Peninsula, the entire Susitna Basin, and the western shore of Cook Inlet

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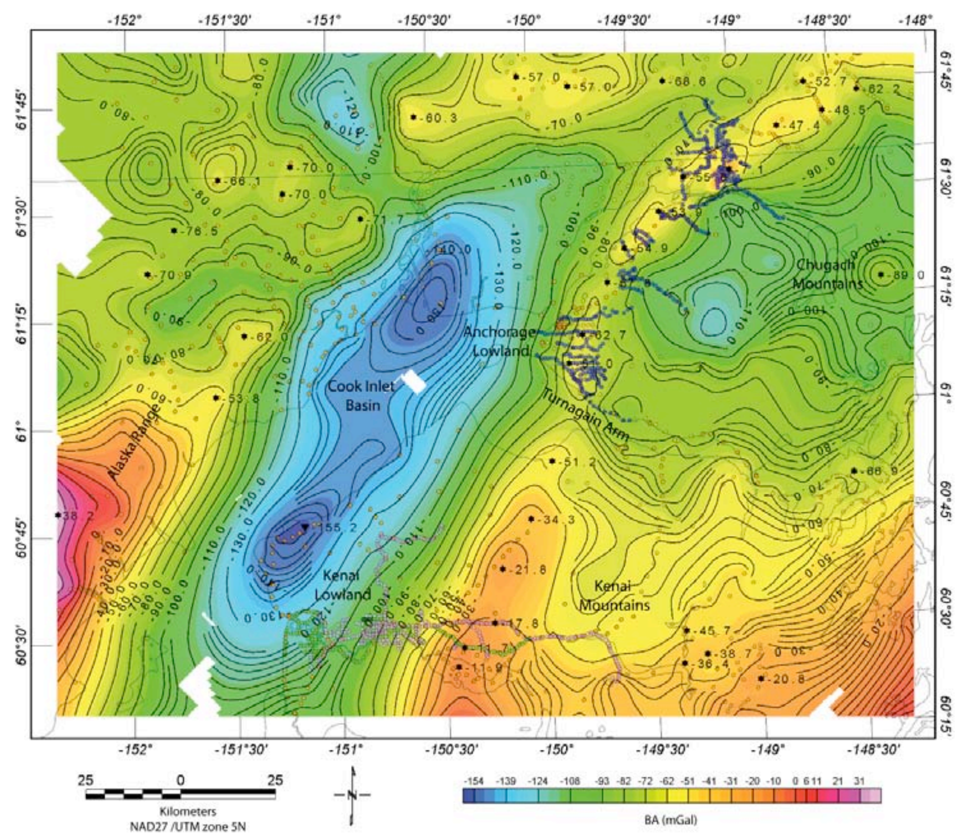

Figure 1 – Simple Bouguer anomaly map (with reducing density of 2670 kg/m^3). Gravity points were compiled from pre-1996 existing data, 2009 (pink and green points) and 2010 (blue points). A survey completed in mid-August 2011 collected ~400 new gravity readings in a region from 61.4 to 61.75°N and 148.7 to 150°W.

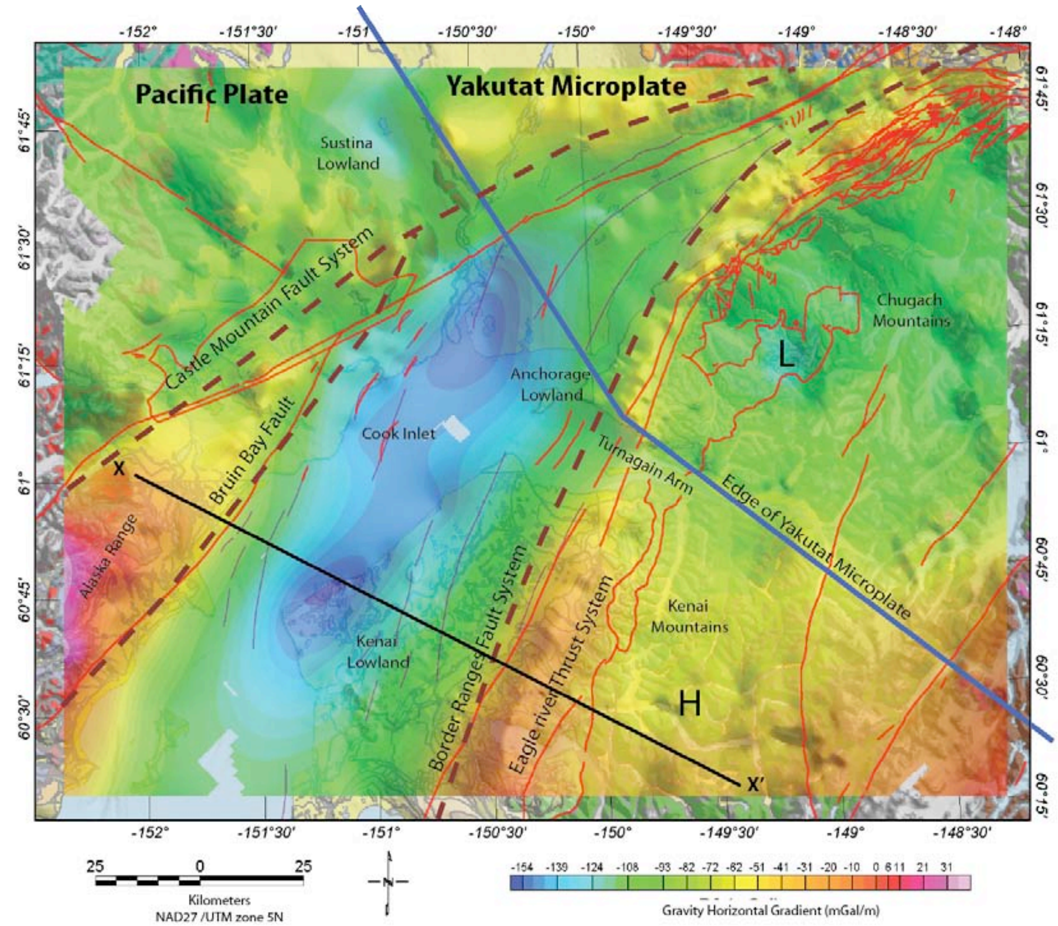

Figure 2. Horizontal gravity gradient compared to subducted edge of the Yakutat microplate (bold blue line, modified from Eberhart-Phillips et al., 2006). Gravity anomaly high (H) and low (L) east of the BRFS appear to be separated by the edge of Yakutat microplate

THE CASE FOR CONSIDERING THE ENTIRE ALEUTIAN SYSTEM

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Sites: Commander Islands, Kamchatka Pass, Kamchatka Cape

Themes: #5: Subduction initiation and evolution; Also: Generation of magma, earthquakes and tsunamis in relation to subduction geometry and dynamics; Accretion; Subduction-subduction collision

Discovery Corridor: Aleutian-Kamchatka collision zone

The Draft Implementation Plan for GeoPRISMs' Subduction Cycle and Deformation program observes that one of the scientific attractions of the Aleutian subduction zone, in addition to intense seismic, deformational, and volcanic activity, is the along-strike systematic variation of

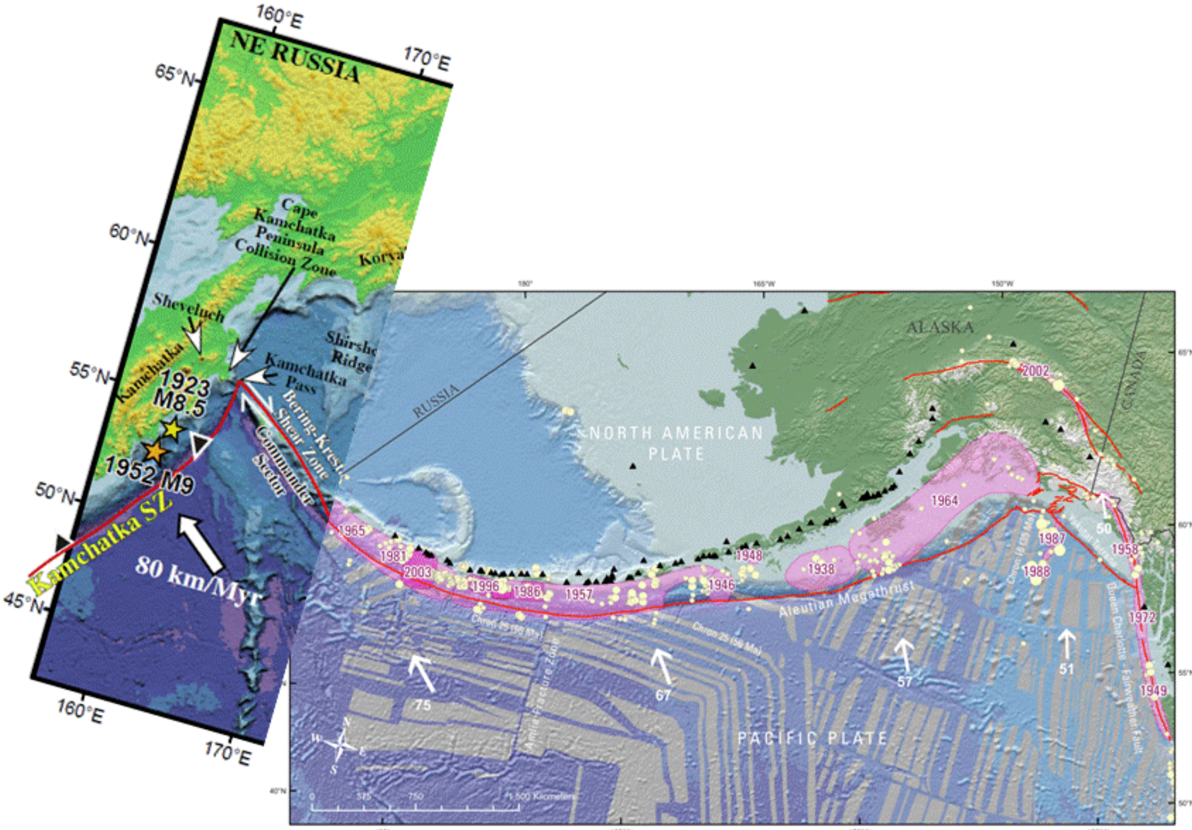

Figure 1: The American portion of the Aleutian subduction zone (from GeoPRISMS Draft Implementation Plan: 2. Subduction Cycles and Deformation) with the Russian portion superimposed (after Scholl, 2007). The latter segment includes the final transition from a convergent to predominately strike-slip plate boundary, and the collision of the Aleutian volcanic arc, here coupled to the Pacific plate, with the Kamchatka Peninsula.

parameters of subduction. These parameters include the angle between convergence and the plate boundary, transfer of arc coupling from one plate to the other, width of the arc-trench gap, the composition and thickness of the overriding plate, and the amount of sediment load in the trench.

The consequences of these characteristics for intensity and frequency of large earthquakes, the likelihood of great tsunamis, and the composition and flux of magma can thus be evaluated. These variations do not, however, stop at the international border of the United States with the Russian Federation. The subduction zone continues through the Commander Islands to its orthogonal collision with the Kamchatka subduction zone. There, the consequences of collision appear to include accretion of Aleutian arc material as capes, prodigious volcanism, and back-arc rifting of the Kamchatka Peninsula.

There are two issues pertaining to the Russian portion of the Aleutians, the Commander Sector, that are especially relevant to answering outstanding problems posed in the Draft Implementation Plan. One is the relationship of subduction structure to the composition of magmas being generated. The plan suggests that unusual composition of magmas in the west arise because of oblique convergence (and perhaps also an exposed, torn slab edge). An evaluation of this hypothesis should include the Commander Islands, as well as submarine Piip volcano and other submarine activity that may yet be discovered.

A second problem, one that represents Theme 5 of SCD, is the initiation of subduction. If the arc massif is forming in the dominantly convergent portion of the arc and then being torn and rafted by the Pacific plate towards Kamchatka, then the earliest record of Aleutian subduction lies in the Commander Islands and perhaps the Kamchatka Cape. It would seem difficult to develop a comprehensive view of the evolution of this subduction zone without including these features in the research.

From a hazard assessment, monitoring, and risk mitigation perspective, there is much to be gained by considering the entire system through bilateral collaboration, and much to be lost by not doing so. This is important for the relatively small but valued communities of the northern Pacific and for the much broader Pacific basin subject to Aleutian-launched tsunamis as well. One goal of bilateral collaboration should be the real-time exchange of seismic and deformation data, thereby improving early detection and characterization of hazard events.

The Russian Academy of Sciences, NSF, and USGS have a two-decade long history of highly productive collaborations in the Kamchatka region, encompassing both basic science and hazard monitoring. There also exists a wealth of information from the Soviet era, when Kamchatka was viewed as a natural laboratory for the study of volcanoes and earthquakes.

Without exception, tasks proposed in the Draft Implementation plan for Alaska should be extended to the entire Aleutian system: A) Data synthesis; B) Mapping, paleoseismology, seafloor sampling; C) Geochemistry and geochronology; D) Geophysical studies; E) Geodetic field campaigns; and F) Geodynamic modeling. In some cases, for example tephra and tsunami geochronology, such work is more advanced in the Russian portion of the system than the American. It would also be beneficial to target the Aleutian-Kamchatka collision zone as a Discovery Corridor, where ongoing accretion, deformation, and eruption are dramatically displayed.

Some territorial and political sensitivities in relations between our two countries remain, particularly in the area of ship-based observations. But if we work together and acquire the endorsement of our respective leaders at a sufficiently high level (this has already occurred in the area of disaster response and a dialog is beginning for geological hazards), there is reason to believe that the result can be a collaborative bilateral effort to understand the entire Aleutian system and the hazards associated with it. This will be an important contribution to subduction science and ultimately to the resilience of northern Pacific communities.

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The influence of the Yakutat microplate on the Alaska subduction zone

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The Gulf of Alaska margin is notable for the transition from ‘normal’ Pacific plate subduction along the Aleutian Trench to flat-slab subduction and oblique collision of the Yakutat terrane, an oceanic plateau. Crustal thickness of the Yakutat microplate ranges from ~15 km thick where it subducts beneath Prince William Sound to ~35 km thick where the collision is causing the uplift of the St. Elias Mountains. The 1964 Mw 9.2 Prince William Sound earthquake initiated on the Yakutat-southern Alaska plate boundary before jumping to the adjacent Aleutian megathrust and past earthquakes may have simultaneously ruptured the Aleutian megathrust and the Yakutat subduction interface between Prince William Sound and Icy Bay (Figure 1) [e.g., *Shennan et al.*, 2009]. Convergence between the Yakutat microplate and southern Alaska causes far-reaching impacts to both the subducting and overriding plates, and marks the end of the “simple” Aleutian subduction system. As the collision evolves with time, the Aleutian megathrust may extend to the east, initiating a new trench outboard of the Yakutat microplate.

The entire southern Alaska margin is made up of a set of blocks moving relative to North America. Immediately inboard of the Yakutat collision, the upper plate is rotating counterclockwise relative to North America [*Elliott*, 2011]. All of southern Alaska south of the Denali fault moves in a similar sense, although not as a single rigid block. GPS velocities from the Kenai Peninsula, Kodiak Island and Alaska Peninsula are consistent with lateral escape of a forearc block to the southwest at about 5 mm/yr. Combined with the evidence for a Bering plate farther to the west [*Cross and Freymueller,* 2008], these results mean that the overriding plate along the entire Aleutian megathrust is moving significantly relative to North America. In addition to the effects onshore, the Pacific plate in the Gulf of Alaska appears to be deforming in response to the Yakutat – southern Alaska collision. This deformation is highlighted by the formation of the Gulf of Alaska Shear Zone, a N-S oriented, mostly right-lateral zone of intraplate shear that extends over 200 km into the Pacific plate. Recorded seismicity at the shear zone began with a series of large M 7+ earthquakes that occurred from 1987-1992, and seismicity along the shear zone has continued to the present day. The Pacific plate may be reorganizing into blocks adjacent to and south of the Shear Zone, each moving and deforming independently, as evidenced by plate magnetic anomalies, seismic reflection data, and increased intraplate seismicity compared to the Pacific plate farther south.

The Alaska megathrust system incorporates both the Pacific and Yakutat plate interfaces with southern Alaska. The bathymetric expression of the Aleutian trench ends between Kayak Island and the Transition fault (Figure 1), which may be the northeastern extent of the Pacific-southern Alaska interface. However, the seismogenic subduction interface extends ~100 km to the east of this point. Offshore seismic data near Kayak Island as well as onshore geology show nearly vertical strata and steeply northwest dipping fault traces, defining a recently inactive fault zone. These observations indicate a possible evolution of faulting in the area that has resulted in the Yakutat-southern Alaska convergence primarily occurring at depth on the northeastern segment of the megathrust. This shallowly dipping (5 degree) subduction interface displays considerable variations in coupling, with the segments beneath the Bering Glacier, eastern Chugach Mountains, and northeastern Prince William Sound being nearly fully locked while central Prince William Sound and the Kayak Island area have between 40 -70% coupling. In addition, both the GPS results and geologic observations suggest that there is a fundamental change in behavior from slip on a single interface to distributed slip east of the Bering Glacier, but this change does not correlate to the change from Pacific to Yakutat basement. This abrupt shift in behavior may relate to differences in sediment input, erosion of the exhuming orogenic highland, variable thickness in the Yakutat microplate, or some combination of these factors, but this observation has important implications for how subduction systems operate at depth.

The recent results outlined above represent significant advances in our understanding of the Yakutat collision and the effects of the Yakutat microplate on the Alaska subduction system, but additional work is needed to resolve a number of remaining problems. Future efforts need to focus on improving the imaging of the subsurface Yakutat terrane within the 1964 earthquake rupture zone, particularly in the area where the western edge of the Yakutat terrane may link to the subducting Pacific plate. Within the apparently abrupt transition from collision-type distributed deformation to normal subduction, the locations of the active structures need to be more clearly delineated and their rates of motion more precisely determined. Throughout the region, the motions of the various segments of the upper plate should be better resolved. Another important question requiring further study is how surface geology and shallow structures correlate to deep structures.

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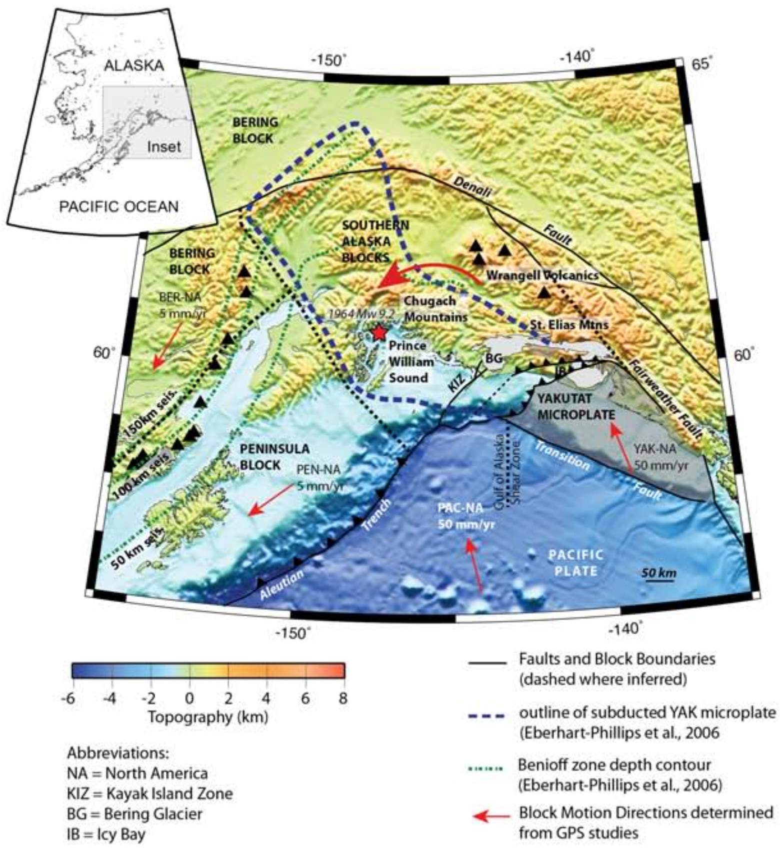

Figure 1. Tectonic Setting of the eastern Alaska subduction system. Modified from *Worthington et al.* [2010].

UNDERSTANDING ALASKA TSUNAMIS GENERATED BY SLOPE FAILURE

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Proposed sites - geoscientific transects across the margin at Unimak Pass and Chirikof/Trinity Islands
Theme – Can areas of potential large landslip failures that could source tsunamis be recognized?

Some investigators have argued that earthquakes may trigger catastrophic slope failures large enough to source transoceanic tsunamis but observations are insufficient to confirm this. Documenting mass movement coeval with an earthquake involves considerable marine surveying and coastal investigations. A noteworthy earthquake during which mass movement probably sourced a tsunami was the 1946 Unimak Alaska event (Fryer et al, 2004, Lopez and Okal, 2006). A 42m runup destroyed the Scotch Cap lighthouse and a coeval transoceanic tsunami inundated south Pacific islands and Antarctica. Lopez and Okal (2006) revised the earthquaie magnitude to possibly 8.6 which can explain the tsunami in the far field, but the huge runup at Scotch Cap seems to require an additional source such as an earthquake triggered slope failure (Fryer et al, 2004, Okal et al., 2003). Slope failure sources are limited to the upper slope by the time between shaking and inundation at Scotch Cap. Morphology at the constrained distance from Scotch Cap to the tsunami source contains upper slope failure features, but a slide volume estimated with modeling is insufficient to explain runup or a major transoceanic tsunami. Proposed alternatives are an unknown splay fault, or that a coeval slide and a tectonic shift of the seafloor occurred. A consensus explanation is still to be found. The compelling and broad scientific issue is recognizing environments in which a modest earthquake might trigger a slope failure large enough to produce local and perhaps transoceanic tsunamis. Slope failure features are common along convergent margins and particularly so where seafloor relief subducts. Deformation from subducting relief destabilizes the slope and by increasing slope steepness it enhances slope failure. Three extensive seamount chains and fracture zones subduct along the Alaska margin. This subducted seafloor relief destabilized the margin slope along sections that are oriented such that a transoceanic tsunami would be focused toward the US west coast.

Understanding the mechanics of the 1946 event requires further investigation to illustrate the character of past and the potential of future failure. Recent work indicates that the insights gained off Unimak Island can be applied to Alaska's other unstable slopes. The improved images from pre-stack-depth-migration revealed extensional deformation of the slope sediment apron presumably by increasing steepness. An upper layer of mobilized material and slide blocks were imaged. Rotational slumping of a coherent block 0.5km thick and over a ~20x22km area was imaged at the distance of the 1946 tsunami source in an area previously identified (Fryer et al, 2004). Vertical dislodgment of a large, coherent slump block would be much more efficient in generating a near –field tsunami than the displacement resulting from a fluidized debris flow as has been applied in previous tsunami modeling of the 1946 event. This adds a new dimension to investigation of the 1946 tsunami source and clarifies a direction for future work. Alaskan slope failure is similar to that of other margins where modern bathymetric mapping has shown much larger slumps. Large slumps and slope failure off Costa Rica occur where abundant seafloor relief subducts. Subducting ridges and seamounts are associated with a slump 55km long and 35km wide whose head wall is from 350m to 1000m high. The search for pre-historic tsunami deposits has not yet been conducted in the area nor has a rotational block model been analyzed. Even such large features are not obvious in conventional bathymetry. Similarly, multibeam bathymetric mapping in the Unimak area and in other unstable areas of the Alaska and Aleutian margins promises to result in discoveries of past slope failure. The Pamplona Zone/Middleton Island slope where the Yakutat Terrane subducts is an unstable area where large slide scars occur (fig. 1). Multiple seamounts subduct along the Fifty-eight degree fracture zone, the Kodiak-Bowie seamount chain, and the Patton-Murray-Aja fracture complex (Fig. 2). The latter was co-located with a rupture boundary during the 1938 and 1964 earthquakes, a segment of the margin where geodetic monitoring indicates current strong locking. Understanding dynamics where the Alaska convergent margin is unstable is important to anticipating potential tsunami hazards and facilitate tsunami warnings for the coasts of North America.

Basic to the organization of new work in areas of known unstable slopes is high resolution multibeam mapping (100% systematic coverage with ~10m resolution). The small areas surveyed with a 20 year old multibeam system indicates that with modern systems the mass wasting features of sub-km-scale can image significant failure features along the upper and middle slopes (Fig. 2). Mapping the Unimak and Chirikof/Trinity Islands areas can be accomplished in 2 to 3 weeks ship time. In the 1938 aftershock area, the reprocessing of existing USGS seismic data with modern depth migration seismic processing systems can improve resolution sufficient to image large slide deposits. In addition, there is a critical need for establishing a paleo-tsunami history for the Alaskan margin with conventional cores at sea and trenching in coastal areas on land such as has been demonstrated along the Cascadia subduction zone. Thus advances in understanding Alaska tsunami sources can be achieved with existing academic facilities and modeling can be greatly improved over past studies.

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Fryer, Gerard, Philip Watts, Lincoln Pratson; 2004, Source of the great tsunami of 1 April 1946' a landslide in the upper Aleutian forearc; Marine Geology, 203, 201-218.

Lopez, Alberto, and Okal, Emil, 2006; A seismological reassessment of the source of the 1946 Aleutian "tsunami" earthquake; Geophysical Jour.. International 165, 835-849-

Fig. 1 Slide scars on the continental slope where the Yakutat Terrane trailing flank subducts. Multibeam and conventional bathymetric images are combined. The vertical axis is ~ 200km

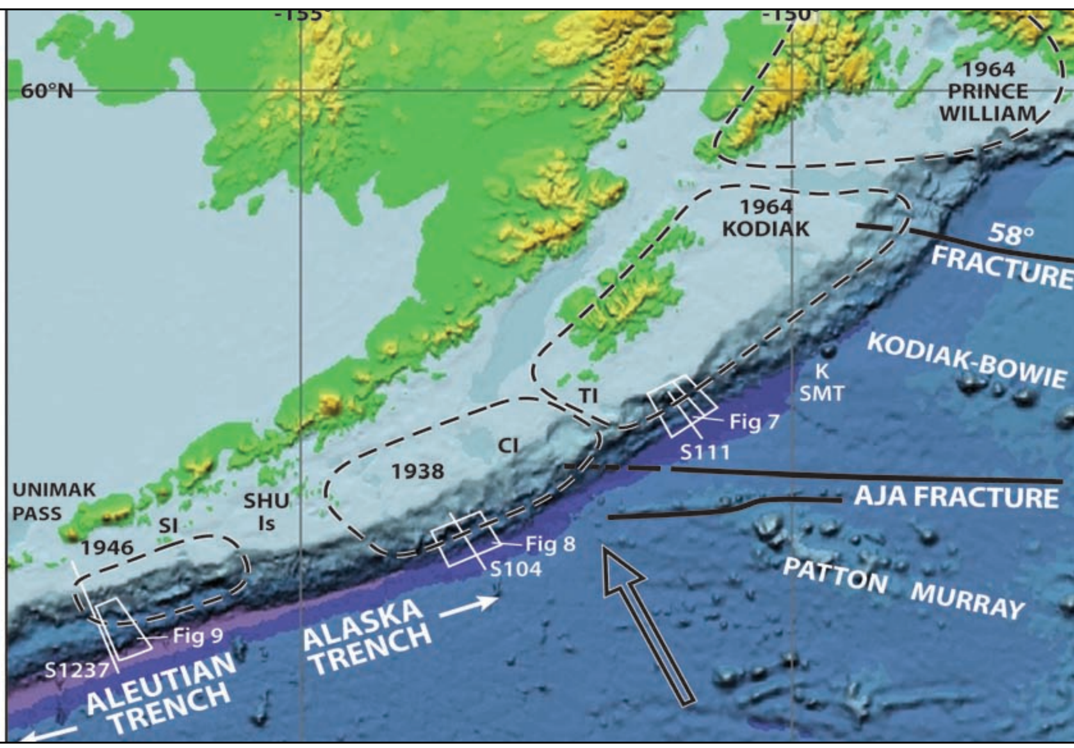

Fig. 2 Map from manuscript in review showing small areas of 16-yr.-old multibeam bathymetry (rectangles). Aftershock areas with dates, Lines with S-numbers are published seismic images. TI, Trinity I., CI, Chirikof I., Shu, Shumagin I., SI, Sanak I. K SMT, Kodiak Smt,

GeoPRISMS Data Portal

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1) Introduction

The GeoPRISMS Data Portal of the Marine Geoscience Data System is funded by NSF under the IEDA Facility cooperative agreement to provide data services to the GeoPRISMS community. For each GeoPRISMS primary site, the data portal has been 'seeded' with a range of existing high-priority terrestrial and marine data sets. For the Alaska primary site, this includes, for example, Ewing and Langseth multi-channel seismics cruises and links to USGS surveys along the Aleutian arc. The portal offers customised searches for GeoPRISMS-related data, and the GeoPRISMS bibliography database seamlessly links papers to the data sets and to funding awards.

GeoMapApp, Virtual Ocean and EarthObserver are map-based tools that provide rich data exploration, analysis and visualisation functionality (Figure 1).

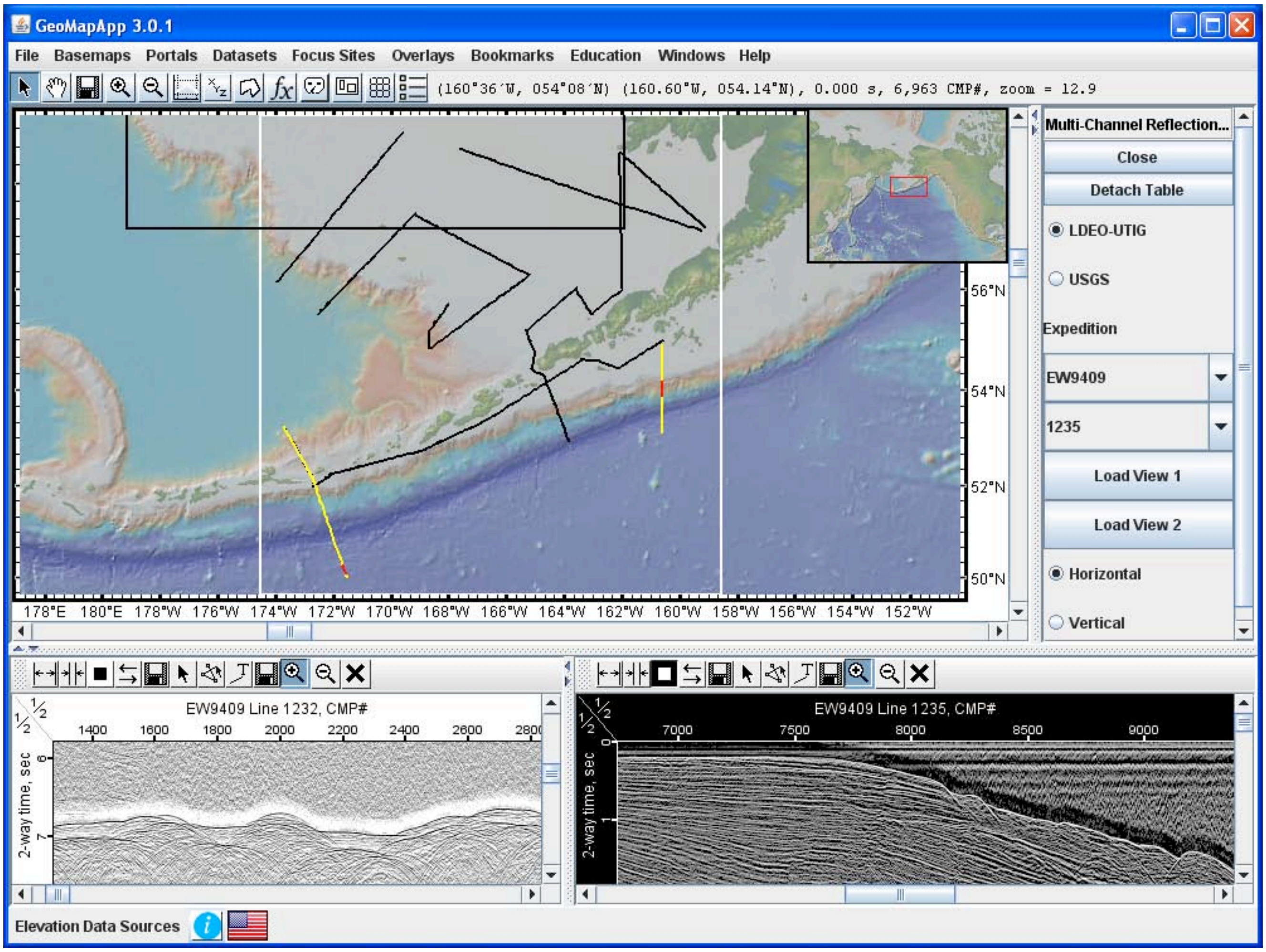


Figure 1: GeoMapApp screenshot showing Ewing EW9409 MCS lines 1232 (lower left) and 1235 (lower right, with inverse video turned on) across the Aleutian arc. The seismic lines are displayed on the map in yellow, with red portions representing the extent of the two profiles shown in the lower panes. A digitiser function allows horizons to be quickly delineated and saved to disk. The base map is the global multi-resolution topographic synthesis that offers ~60m horizontal resolution of Alaska's on-land elevations and 100m or better resolution in the oceans and on the shelves.

2) Services

- **Data Portal**
  The GeoPRISMS data portal, like the predecessor MARGINS portal, is fully integrated with the wider Lamont database system and offers a compilation of pre-existing data sets of interest to the community. Links are provided to Alaska-related projects such as BEAAR, KALMAR, MOOS, STEEP, TACT and EDGE, and a simple search function, described below, provides user access to the data. As funding for GeoPRISMS research projects gets underway, the portal will work with PIs, members of the community and the GeoPRISMS Office to ensure appropriate capture of marine and terrestrial field program information and derived data products.
  http://www.marine-geo.org/portals/geoprisms/

- **Search for Data**
  Data can be found (Figure 2) by searching on key words such as data or device type, name of field program or investigator, by geographic location, and even by award numbers. Filtered searches and auto-complete technology help speed users towards data.
  http://www.marine-geo.org/tools/new_search/index.php?initiative=GeoPRISMS

▸Data at Other Repositories

Click on title above to show/hide digital data sets

Data Set	Device Information	Repository	Event Information	Investigator	References
Seismic:Reflection:MCS	Array Seismic:MCS(LDEO,Ewing)	UTIG	Show/Hide	Diebold, J.	Shillington et al., 2004 Van Avendonk et al., 2004
Seismic:WideAngle	R/V Maurice Ewing Seismic:Seismometer(IRIS:PASSCAL)	IRIS	NotApplicable	Klemperer, S. Fliedner, M.	Fliedner and Klemperer, 2000 Fliedner and Klemperer, 1999 Van Avendonk et al., 2004

Figure 2: Example of data portal links to data for the EW9409 MCS cruise (PIs McGeary, Diebold, and Klemperer) to the Aleutian arc. Links at left take the user to MCS data files. Links at right display various publications associated with the data sets.

- **Data Visualisation and Exploration**
  The GeoMapApp and Virtual Ocean tools offer a rich variety of options for users to plot, analyse and visualise their data in a geographical setting (Figures 1 and 3). EarthObserver, a recently-released app for the iPad™, iPod Touch™ and iPhone™ offers instant access from mobile devices to a large range of built-in data sets.
  http://www.geomapapp.org/ , http://www.virtualocean.org/ , http://www.earth-observer.org/

- **Bibliography**
  The GeoPRISMS references database provides an integrated, searchable resource that links publications to data sets and funding awards. Currently comprising more than 175 papers of direct relevance for GeoPRISMS science, the database can be searched on author, title, journal, year, and primary site. All displayed results can also be exported in EndNote™ format. The bibliography page provides a simple tool to allow anyone to submit references for inclusion in the database.
  http://www.marine-geo.org/portals/geoprisms/references.php

- **Data Management Plan Tool**
  Since January 2011, all proposals submitted to NSF must be accompanied by a Data Management Plan. With NSF input we created a simple web page that allows PIs to fill in information boxes and generate a data management plan in PDF format to be attached to the proposal.
  http://www.iedadata.org/compliance/plan

- **Data Compliance Reporting Tool**
  Currently under development, this tool will help PIs demonstrate compliance with funding agency data policies by allowing PIs to inventory their data contributions, with links to award numbers.

3) Data Policy

Led by Susan Schwartz, the GeoPRISMS data policy was compiled by a sub-committee of the GeoPRISMS Steering and Oversight Committee, with input from NSF and the database group.
http://www.geoprisms.org/data-policy.html

4) Community Outreach and Accountability

A representative from the database group plans to attend a number of GeoPRISMS meetings to act as a liaison with the community, to increase awareness about the data portal services, and to solicit feedback and advise on products and resources. A report on database activities will appear in the GeoPRISMS twice-yearly newsletter, and, at each GeoPRISMS Steering and Oversight Committee meeting, a report will be given and data-related discussions held.

The GeoPRISMS data manager, Andrew Goodwillie, and the database team are keen to help the community with any questions related to data, analysis tools or the GeoPRISMS bibliography.

5) References

GeoPRISMS Data Portal Status Report, *GeoPRISMS Newsletter*, Spring 2011, vol 26, page 26.
http://www.geoprisms.org/images/stories/documents/newsletters/issue26.pdf

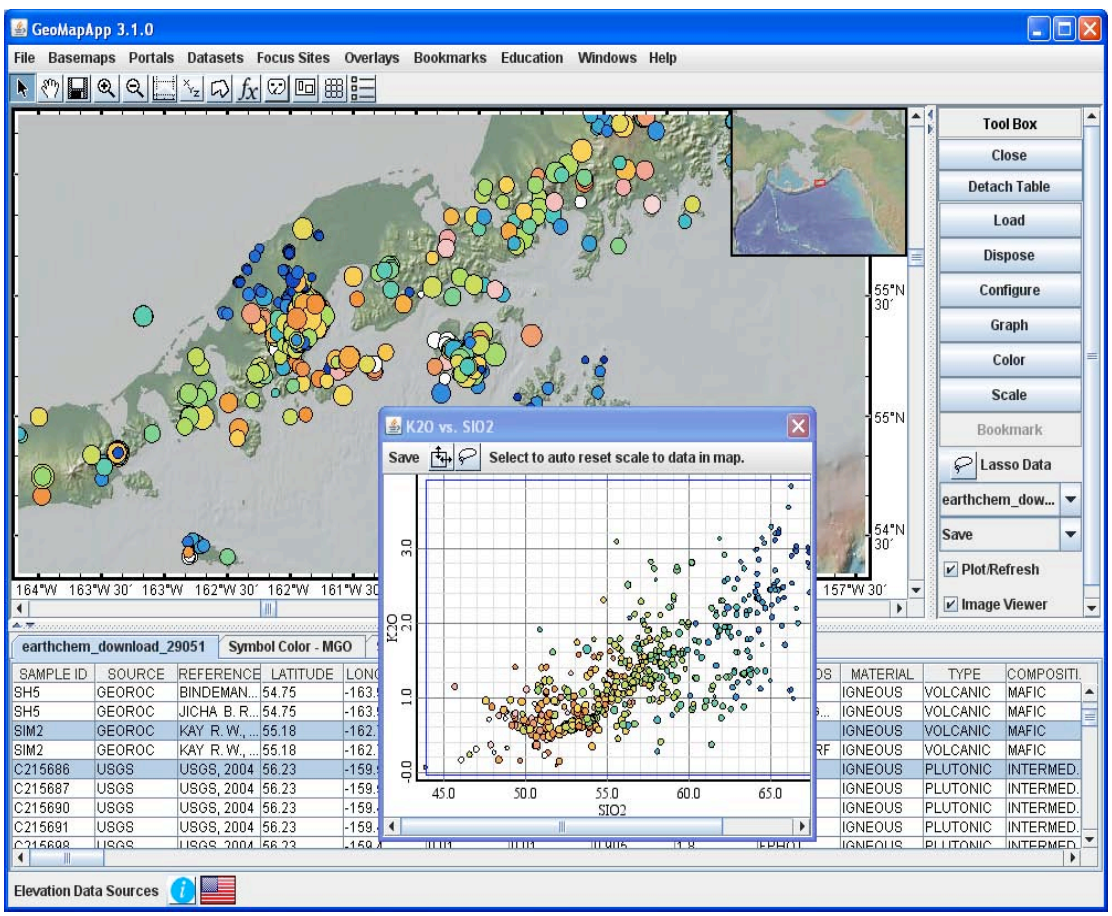


Figure 3: Geochemistry data from the EarthChem database is plotted for the Aleutian arc in GeoMapApp. Sample analyses are scaled w.r.t. Al_2O_3, coloured according to MgO content, and the inset shows K_2O graphed against SiO_2. Samples can be selected by either clicking the symbol on the map or the record row in the table. A lasso tool lets users grab data selections.

Discovery Corridors, Islands, and Megathrust Earthquake Ruptures
aka
The Megathrust Megaswath

Peter Haeussler (USGS, Anchorage), Sean Gulick (U. Texas Institute for Geophysics), Jeff Freymueller (U. Alaska Fairbanks/Geophysical Institute), Tom Parsons (USGS, Menlo Park), Donna Shillington (Lamont)

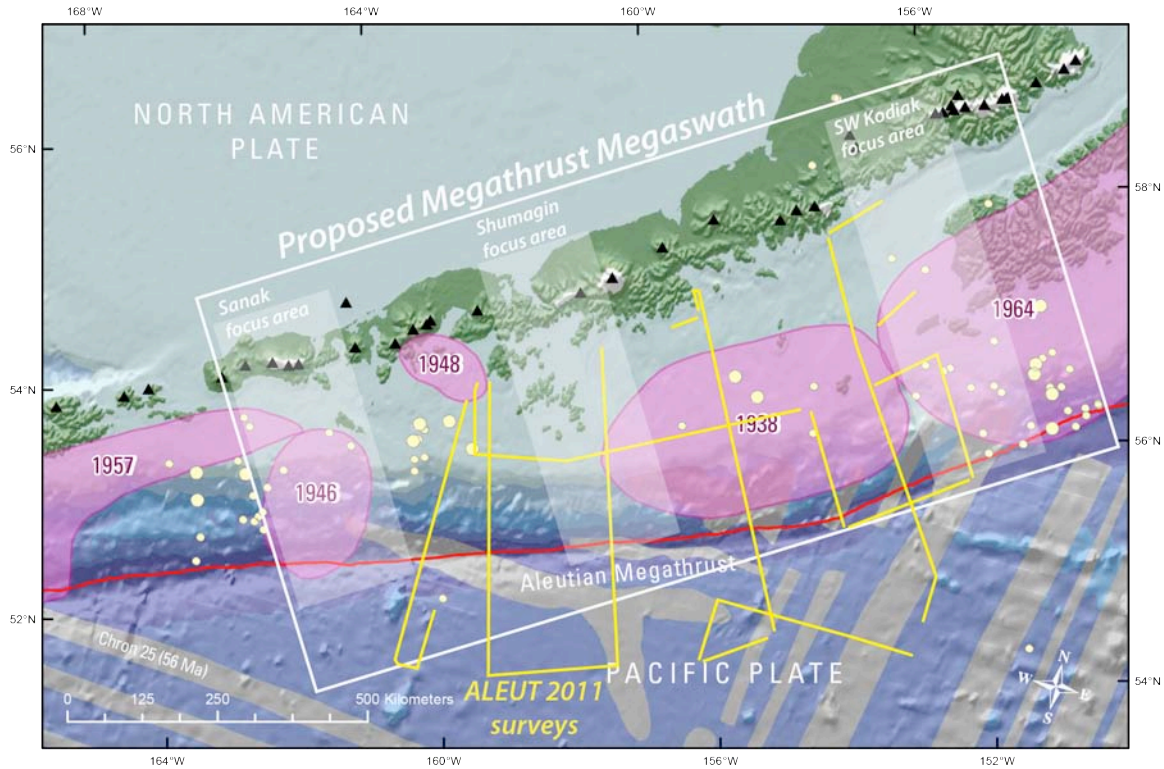
One of the most fundamental earthquake hazard questions associated with subduction zones, is, what controls the extent of megathrust earthquake ruptures? To address this question, we suggest that one of the Alaska GeoPRISMS 'discovery corridors' should not be as narrow as a corridor, but rather it should be a wide swath - or in this case - a 'megathrust megaswath'. Moreover, we need to examine a region with islands located between the arc and trench. Islands allow instrumentation of the modern subduction zone for geodesy and seismology. Islands allow for investigation of paleogeodesy, paleoseismology, and paleotsunamis. And islands allow inexpensive ground truth of what is observed on marine seismic reflection and refraction data: stratigraphy, structure, sedimentology, thermal history, exhumation, and erosion.

We suggest a megathrust megaswath between the southwestern end of the Kodiak Island group and Sanak Island. This region spans the 1964, 1938, 1948, and 1946 megathrust ruptures, the 'tail' of the 1957 rupture, the Shumagin seismic gap, and it likely includes much of a region that ruptured in 1788. It spans megathrust rupture areas in different parts of their cycles. Additional marine geophysical work is needed for understanding structural variations along the megathrust. One or a few traverses of the accretionary prism is not enough to evaluate variations in structural or subduction parameters. Also, this region is a depocenter for glacial and interglacial systems originating in Cook Inlet, as well as a transition in thickness of sediments being delivered to the Aleutian Trench along strike. Moreover, the Zodiak abyssal fan, the Patton-Murray sea mount chain, and the Aja fracture zone are entering the trench in this region, all of which may affect locking and rupture processes. Thus it is an area that would be a good case study for the interaction of surface processes and subduction dynamics.

Past, present, and planned research efforts make this an excellent region for study. Previous work by the USGS in the 1970s and 1980s provided important context and the STEEP and 2011 USGS Extended Continental Shelf data farther north provide information on the sediment inputs. The 2011 ALEUT project collected a backbone of state-of-the-art seismic reflection and refraction data within the "megaswath". The so-called 'Shumagin seismic gap' was identified in the early 1980s and geodetic work in the region has continued to the present day, including PBO continuous stations on some of the islands and on the Alaska Peninsula. Bedrock geology of the islands was mapped by the USGS in the 1970s and 1980s, and there are excellent exposures of rocks from Late Cretaceous through Pliocene time. Although prior paleoseismic and paleotsunami investigations in this region are lacking, there were USGS-led teams to three different outer islands the last two summers. The USGS Alaska earthquake hazards project is committed to future field efforts in the broader region for the next decade.

We suggest subfocus areas southwest of the Kodiak Islands, the Shumagins area, one near Sanak Island, and one or more along-strike deep seismic lines to link these regimes together. Perhaps doubling the density of lines collected by the ALEUT project would yield sufficient resolution. The Sanak area would involve new data collection efforts. This approach would leverage the ongoing work, and allow GeoPRISMS to expand on legacy data collection efforts. By broadening a discovery corridor to a megathrust megaswath, models for barriers to rupture can be tested.

Lastly, rupture barriers imply a characteristic large earthquake distribution rather than a Gutenberg-Richter power-law distribution. However, the recent M=9.0 Tohoku earthquake in Japan ruptured through inferred rupture barriers, and caused some rethinking about the magnitude distribution in the Japan Trench, and subduction zones in general. The magnitude-frequency distribution is crucial to earthquake and tsunami hazard assessment because the rate of moderate to large events can vary dramatically, as can the maximum magnitude. This question is fundamental in seismology, but unfortunately, modern catalog data have not provided a resolution to the issue. When studied comprehensively, the Alaskan subduction megaswath and its many islands has the potential to reveal its hidden paleoearthquake and tsunami history. In combination with structural observations, repeated and cross-referenceable earthquake and tsunami signatures promise an unparalleled opportunity to apply constraints on the regional extent of past and future large ruptures, and thus their tsunami and earthquake magnitude distribution.



Map showing the location of the proposed 'megathrust megaswath'. Seismic reflection profiles collectud during the summer of 2011 for the ALEUT project are shown in yellow. Red line shows the toe of the Aleutian megathrust. Black triangles are volcanoes with Holocene activity. Pink blobs show areas of megathrust earthquake rupture, with year listed inside. Yellow dots are M5+ earthquakes. Grey bars on Pacific Plate show marine magnetic anomalies.

Glacial-Marine Sedimentation: an important dimension of the Alaska/Aleutian Margin

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Proposed themes addressed: interconnections between surface processes, subduction zone dynamics, and margin evolution

a) Overview

The GeoPRISMS Draft Implementation Plan (DIP) highlights diverse impacts of sediments on the Alaska/Aleutian Margin, as well as on the more general theme of long-term margin evolution and material transfer. *Surprisingly, the source of sediment is hardly mentioned and yet it is severely understudied; it merits considerable more attention.* Statements regarding sediments include 1) "Sediment influx appears to influence megathrust slip behavior. The largest megathrust events are associated primarily with the sediment rich eastern-half of the subduction zone, where Neogene glacial erosion led to an elevated flux of sediment to forearc basins and the trench." 2) "The age of the subducting oceanic lithosphere changes little along the arc, but... sediment flux to the trench… change systematically along the arc." 3) "recycling of sediment/continental materials occurs in the eastern part of the arc [close to the sediment sources, where sediments fill the trench], but not in the west." 4) "explicit inclusion of sediment transport and deposition along subducting margins will increase our understanding of… geologic hazards such as landslides and tectonic or climate-driven shoreline change." Moreover, in the discussion of w*hat controls the segmentation of a subduction zone*, the DIP mentions that the eastern sector of the "Alaskan-Aleutian trench… receives a large sediment supply that is probably sourced mostly from the glaciated Gulf of Alaska; this flux likely has varied as glacial coverage has evolved in the Neogene. Increased sediment supply from the glaciated northern end of the subduction zone may contribute to the along trench variability in seismogenesis, although long-distance axial transport needs to be quantified…Segmentation may be controlled by …in roughness of the plate interface, which is influenced by,,, sediment thickness beneath and seaward of the trench wedge; and uneven distribution of sediment composition… Fully characterizing the composition of the incoming plate sediments could significantly improve understanding of the role of sediments in controlling seismogenic segmentation."

In view of the importance of sediments on the Alaska/Aleutian Margin, a substantial gap in GeoPRISMS Implementation Plan is the lack of focus on studies that illuminate the diverse sources of sediments, the underlying processes, and their variation in time and space. Glaciers are obvious sources, which are sensitive to climate, but we understand all too little how glaciological processes and the rates at which they operate control the production of sediment, its volume and character, and its transport to proximal and distal portions of the margin. Such studies are also critical for guiding and assessing numerical models of the influence of climate on the internal dynamics of actively deforming collisional margins, especially as Alaska has "experienced profound changes with the onset of Neogene glaciation". Ample motivation also exists for studying glacial-marine sedimentation in its own right, as outlined below.

b) Glacial-Marine Sedimentation

Glacial-marine sedimentation responds to and provides sedimentary archives for a diversity of important processes associated with continental-margin dynamics. Glaciers are extremely effective in eroding mountains, transferring much ice and sediment to the sea, and aiding continued uplift. In areas with high coastal mountains, the ice commonly extends to sea level as tidewater glaciers (e.g.: southern Alaska;

Patagonia; south island New Zealand; Antarctic Peninsula). Today, in these settings, the glacial sediments are typically released into a fjord (Fig. 1) with nearly complete entrapment of erosion products, forming a well-preserved sedimentary record of uplift, ice build-up, associated climatic variations, erosion, and transfer events. Through much of the Quaternary, however, ice cover was much more extensive and the sediments were shed off the continent, constructing exceptionally wide continental shelves off the southern coast of Alaska and other glaciated margins. Our understanding of the linkages between glaciers, glacial and periglacial processes, and tidewater sedimentation is, however, very sparse.

c) Tectonics, Subduction and Uplift

Spectacular coastal mountain ranges, including the St. Elias Mountains, can form where continental terranes coupled to oceanic crust converge with continental plates. Based on much work in this area, Berger et al. (2008) hypothesize that "alpine glaciation in late Cenozoic time modified denudation and deformation within numerous mountain belts worldwide. This is consistent with climate as the driver of observed changes in exhumation rates, sedimentation rates and relief within many orogenic systems over the past few million years. Where present, glaciation may thus have a significant role in the internal processes of mountain building, empirically supporting the paradigm that orogenic architecture, kinematics and evolution may be heavily influenced by external climatic processes." This influence remains poorly understood, however.

d) Glacial Erosion

Glacial erosion is receiving much attention due to the high erosion rates documented for many active glaciers (e.g., Hallet et al., 1996; Delmas et al., 2009), and its role in curtailing the height of mountain ranges, the "glacier buzzsaw" (see Fig. 2; Egholm et al., 2009). Because many active orogens were extensively glaciated during the Plio-Pleistocene and now contain only small alpine glaciers, studies of the coupling between glacial erosion and tectonic processes are largely based on geomorphic studies of formerly glaciated landscapes, and on models (Tomkin and Roe, 2007). With rare exceptions (e.g., Enkelmann et al., 2009), little is known about erosion rates in extensively ice-covered active orogens.

e) Tidewater Glacial-Marine Sedimentation

Sedimentation proximal to the calving ice front impacts glacial advance and retreat, and the distal sedimentation records their history. Many tidewater glaciers advance slowly into deep water over a period of centuries with little sensitivity to climate variability, by keeping before them a moraine shoal that drastically reduces ice loss by calving (Meier and Post, 1987). This shoal, which can buttress not only a tidewater glacier but the massive ice sheet behind it, is slowly moved forward by erosion on the glacier side and deposition on the far side. The sediment accumulation on the seabed, which decreases with distance from the ice front (Syvitski, 1989; Cowan and Powell, 1991; Domack and Ishman, 1993; Jaeger and Nittrouer, 1999), and the detailed sedimentary signatures record the rich histories of the climate, ice masses and the supply and release of sediment. More detailed studies of glacier-sediment systems that extend well beyond the water line are needed to improve the interpretation of this record.

f) Sea-Level Rise

Glacial retreat around the world has been used as dramatic and visible evidence of climate change, and has considerable practical importance because it directly contributes to global sea-level rise, which is one of the largest potential threats of future climate change. However, the controls on the fluctuations of some of the most important outlet glaciers are only partly related to climate variability (Fig. 1), and these non-climatic controls remain poorly understood. On a global scale, the complex behavior of outlet glaciers and rapid ice-marginal changes are prime factors limiting confidence in predictions of impending sea-level rise. So, along glaciated continental margins, the record of recent history and the prediction of future events (e.g., next century) have great scientific, environmental and human value.

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Fig. 1 – One example of a tidewater glacier from a coastal mountain source is Columbia Glacier, a massive (1000 km^2; 60 km long) calving glacier in south-central Alaska that flows into Prince William Sound. During the 1980s, it began a rapid retreat controlled largely by factors affecting ice loss at its marine terminus (modified from Pfeffer et al., 2007).

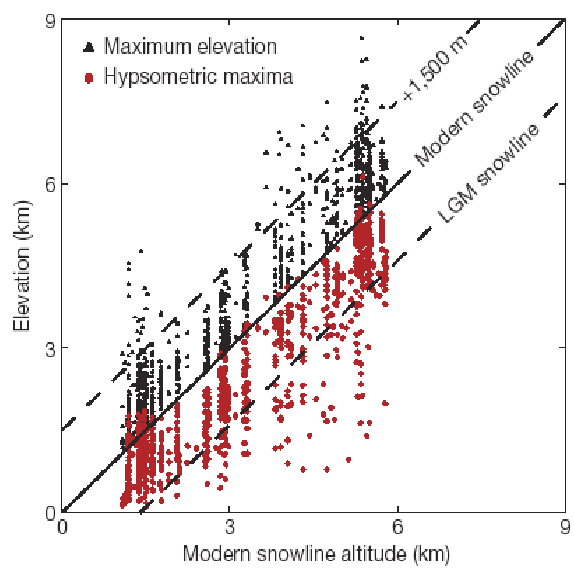

Fig. 2 – A global compilation of maximum elevations (peaks) and hypsometric maxima elevations. They correlate well with local snowline altitudes despite large spatial variation in factors that are generally recognized to control rates of uplift and erosion, including rock type, amounts of precipitation, and rates of exhumation/uplift. Hence mountain-range height seems directly influenced by glaciations through an efficient denudation mechanism known as the glacial buzzsaw (from Egholm et al., 2009).

Seismic structure of the Aleutian island arc near Adak: Finally, a Subduction Factory that actually makes continental crust?

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An important goal of the GeoPRISMS program will be to answer the following question: "What are the geochemical products of subduction zones, from mantle geochemical reservoirs to the architecture of arc lithosphere, and how do these influence the formation of new continental crust?" This question is driven in large part by the long-standing "andesite paradox" – that is, the discrepancy between the bulk composition of continental crust (~andesite) and that of island arcs studied to date (~basalt). Recent studies in the Izu-Bonin-Marianas arc have only deepened the mystery: despite the presence of thin mid-crustal layers that might be relatively silicic ("boninite"), the seismic velocities of the island arc crust are significantly higher than that of continental crust and indicate a bulk composition that is essentially basaltic. This raises important questions: Have island arcs ever been a significant contributor to continental growth? If so, does this imply that island arc compositions in Earth's past were different than today? Are there any modern island arcs that produce crust that looks "geophysically" like continental crust?

The best place in the world to address this question is the central Aleutians near Adak. Lavas and (especially) plutons near Adak are more similar to the composition of continental crust than are magmatic rocks from any other oceanic arc (Fig. 1). This is true of both major and trace elements. The compositional contrast between lavas, which tend to be more basaltic, and plutons, which tend to be intermediate to felsic, raises fundamental questions about the composition of primary magma(s) in the arc and the fractionation processes that take place within the crust.

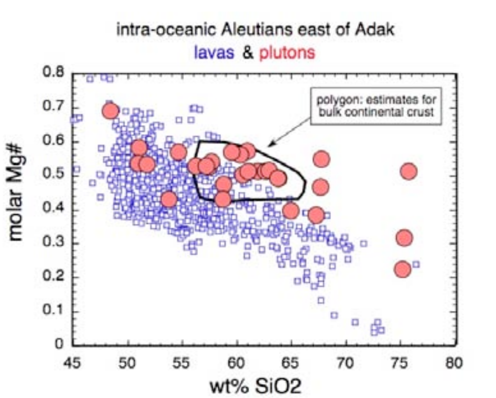

Fig. 1. Compiled geochemical data for the intra-oceanic Aleutian arc east of Adak Island. The major-element chemistry of Aleutian plutonic rocks is similar to bulk continental crust.

Lavas erupted from the Aleutian arc show a fundamental, first-order along-arc change in major-element composition on a regional scale, from dominantly tholeiitic east of Adak to dominantly enriched, calc-alkaline west of Adak. Presumably, this contrast indicates that fundamentally different magmatic processes occur in the eastern and western Aleutians. Two hypotheses that can explain this contrast are: 1) the composition of the primary magma might vary along the arc, from basaltic to (high-Mg) andesitic, perhaps due to changes in mantle wedge processes, sediment flux, or slab melting as subduction becomes oblique; and 2) primary arc magmas might be relatively invariant (basaltic) along the arc, but fractionation processes might vary, following a tholeiitic trend east of Adak but a calc-alkaline trend to the west

These hypotheses predict substantially different seismic structures along the arc. Fractionation processes may present a variety of crustal structures, summarized in Fig. 2, depending on at what depth both fractionation and magmatic focusing occurs. This figure depicts basaltic-composition magmas crossing the Moho. Along-arc changes in primary-magma bulk composition would be expressed in these cartoons as a bulk shift to higher silica. A successful test of these two hypotheses thus requires well-resolved images of internal crustal structure and well-constrained estimates of bulk composition. It also requires that the fundamental assumption of such a test be true, namely that crustal structure reflects a simple time integration of quasi steady-state arc crustal construction processes. On this last requirement, the Aleutians also excels as a primary site for such a study. Unlike the now well-studied arcs of the western Pacific, the Aleutians has not had a long history of arc rifting, and it is not actively rifting now. The time-integrated crustal products of arc magmatism are intact. In addition, the oceanic lithosphere upon which the arc was built is quite simple – it has not, for example, been affected by LIP magmatism. This simplicity, including the lack of active back-arc basin processes, will be crucial for identifying the potential effects of a third process that could alter the bulk composition of the crust, lower-crustal delamination. We would argue that it is only within a very simple arc setting, lacking complex mantle-wedge dynamics, and through a program where ancillary geodetic and passive seismic programs are likely to occur, that this substantial "X factor" can be assessed.

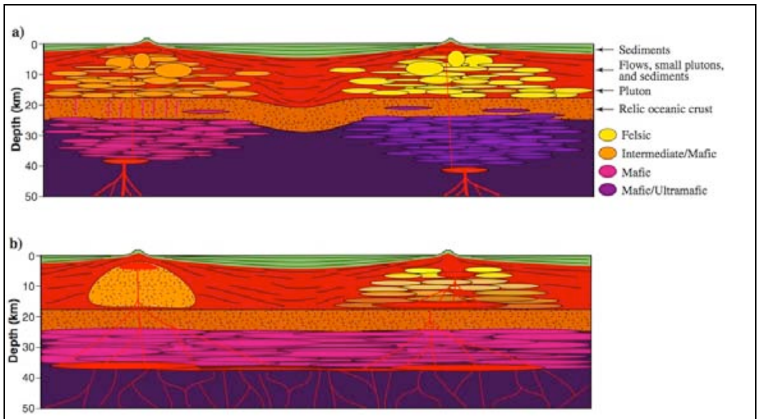

Fig. 1. Cartoon showing possible structures beneath Aleutian volcanic centers. Top: magma flux into the arc may be focused beneath volcanic centers. Bottom: magma flux may be uniform, with focusing occurring in the crust. Intracrustal fractionation affects the distribution of felsic vs. mafic rocks in both scenarios.

A crustal-scale seismic survey of the Aleutian arc near and west of Adak (Fig. 3) will test several critical hypotheses regarding the role of island arcs in forming continental crust: (1) Island arc magmatic processes can (and thus may have in the past) produce crust that resembles continental crust chemically and geophysically. (2) Bulk crustal composition changes along the arc and correlates with lava chemistry, subduction velocity and/or subducted sediment flux; and (3) Magma flux in the Aleutians changes in concert with bulk crustal composition. Total magma flux can be estimated by determining crustal thickness; major-element crustal composition can be estimated from crustal P- and S-velocities. In concert with studies of the ages and geochemistry of Aleutian lavas and plutonic rocks likely to occur through GeoPRISMS, such a study has the potential to finally put to rest the "andesite paradox."

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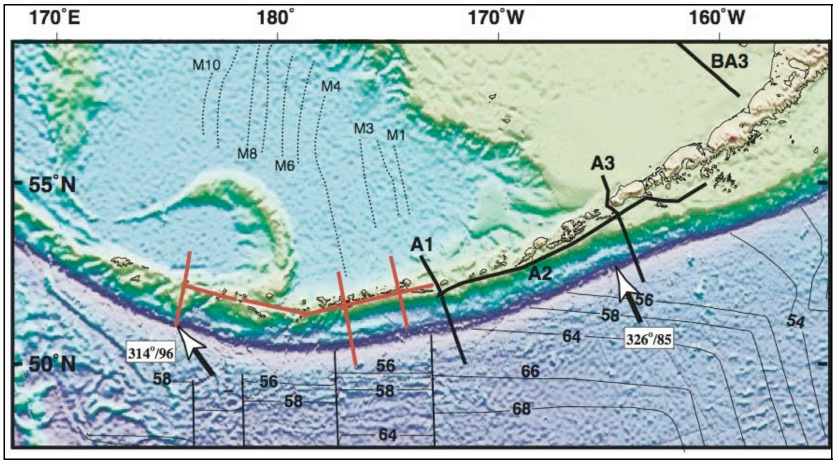

Fig. 3*:* Notional seismic survey across the central/western Aleutians. Red lines show a possible layout of deep-crustal seismic surveys; bold lines A1, A2, A3, BA3 are seismic lines of the 1994 Aleutian seismic experiment. Ligh lines on the Pacific plate are lithospheric isochrons in m.y., and dashed lines in the Bering Sea are Cretaceous magnetic lineations of the relict Kula plate. Large arrows indicate Pacific plate vectors, labeled with azimuths and speeds in km/my.

3D Numerical Modeling of the Alaska and Central America Subduction Zones: Implications for Plate-Mantle Decoupling

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Theme 2: Understanding Mantle Wedge Dynamics.
GeoPRISMS Primary Site: Alaska Subduction Zone.
MARGINS Primary Site: Central America Subduction Zone.

Plate-Mantle Decoupling in Subduction Zones. Away from subduction zones, the surface motion of oceanic plates is well correlated with mantle flow direction, as inferred from seismic anisotropy (*Conrad et al.*, 2007). However, this correlation breaks down in subduction zones where shear wave splitting studies suggest the mantle flow direction, both in the mantle wedge and beneath the slab, is spatially variable and commonly non-parallel to plate motions (*Long and Silver*, 2008). This implies local decoupling of the lithosphere from the mantle, yet the magnitude of this decoupling is poorly constrained.

Regional 3D Modeling Examples. Regional 3D numerical models, constrained by subduction zone geometry and observations of seismic anisotropy, can be used to further explore this decoupling of mantle flow from surface plate motion, in terms of both direction and magnitude (Figure 1). A set of 3D

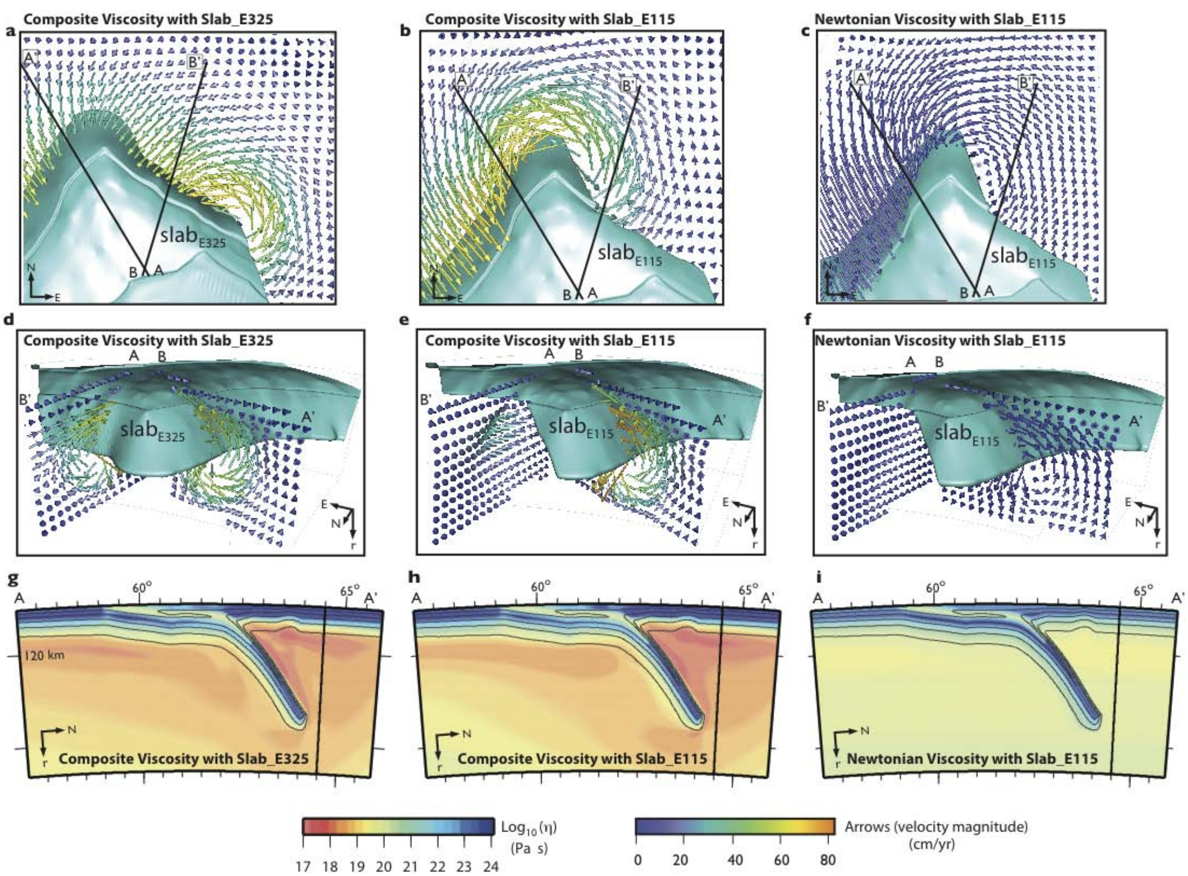

Figure 1: Map view (a-c) and cross sections (d-f) from three models of the Alaska subduction zone that vary the slab shape and the rheology (*Jadamec and Billen*, In Review). The slab is colored by viscosity and mantle velocity vectors are colored by velocity magnitude. Upper plate not shown. Cross section AA' of viscosity (g-i) for the three models. In models using a composite viscosity, a low viscosity region ($< 10^{18}$ Pa s) emerges in the mantle surrounding the slab and allows for rapid mantle velocities (> 80 cm/yr) within 500 km of the slab (*Jadamec and Billen*, 2010).

regional numerical models of the eastern Alaska subduction-transform plate boundary system showed that, in models using the composite viscosity, a laterally variable mantle viscosity emerges surrounding the slab as a consequence of the lateral variations in the mantle flow field and strain-rate (*Jadamec and Billen*, 2010) and (*Jadamec and Billen*, In Review) (Figures 1 and 2). In this region of low viscosity, mantle velocity magnitudes can be up to 80 cm/yr. The same models that produce the rapid mantle flow, predict surface plate motions of less than 10 cm/yr, comparable to observed plate motions, and predict toroidal mantle flow around the slab edge consistent with observations from seismic anisotropy (*Jadamec and Billen*, 2010) (Figure 2). These results show a power law rheology, i.e., one that includes the effects of the dislocation creep deformation mechanism, can explain both observations of seismic anisotropy and decoupling of mantle flow from surface motion. This suggests that partial decoupling of the surface plate motion from the underlying mantle flow field, in terms of both direction and magnitude, may be common in subduction zones. We expect that short slabs are more likely to induce localized rapid flow in the mantle at subduction zones, as these slabs are not supported by the higher viscosity lower mantle and therefore are more free to move in response to the local forces. We will further test this hypothesis with 3D geodynamic models of the Costa Rica-Nicaragua subduction zone (Jadamec NSF-EAR Postdoc Fellowship), a region where previous geochemical studies (*Hoernle et al.*, 2008) and observations of seismic anisotropy (*Abt et al.*, 2010) have predicted rapid trench parallel mantle flow in the mantle wedge.

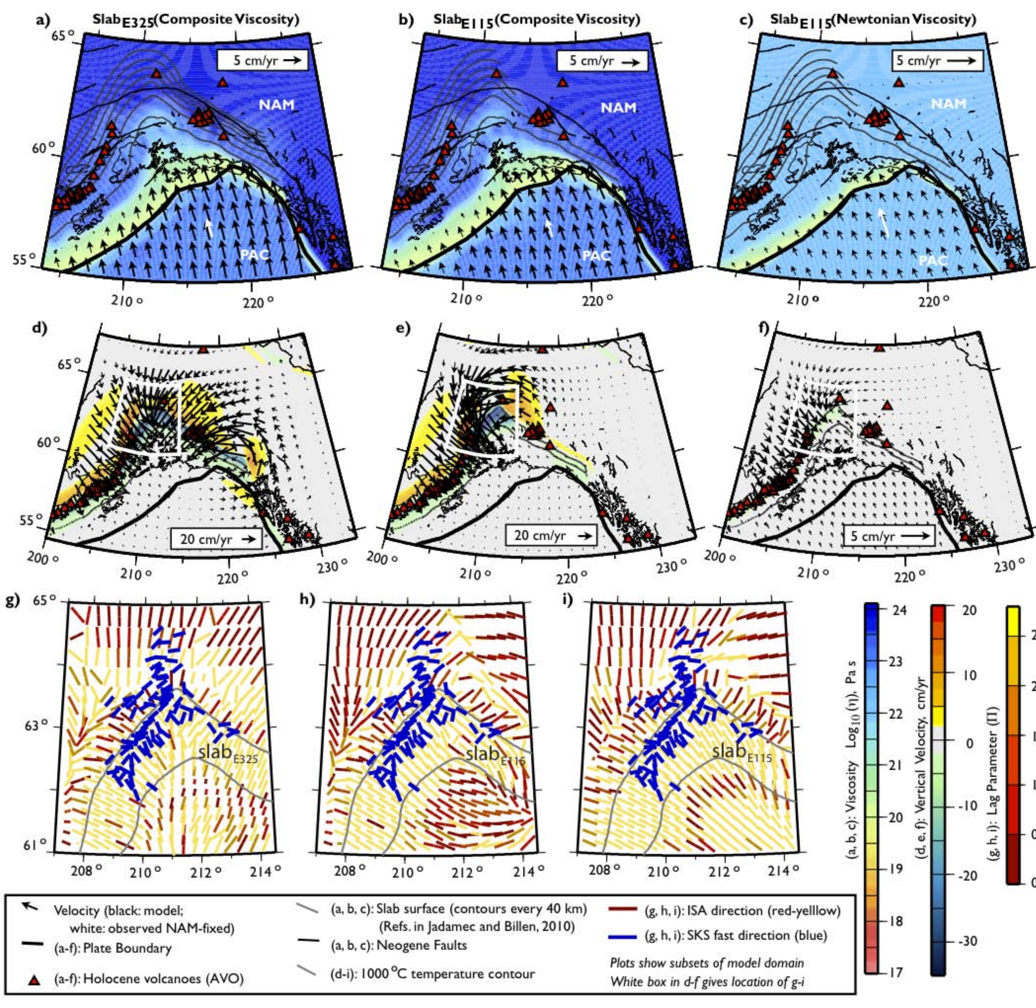

Figure 2: Model predicted surface velocity (a-c) and velocity at 100 km depth (d-f) for three models in Figure 1 (Modified from *Jadamec and Billen* (2010)). Model predicted infinite strain axis (ISA) orientation (g-i) for region outlined by white box in (d-f) (Modified from *Jadamec and Billen* (2010)). Observed SKS fast directions projected at 100 km depth from *Christensen and Abers* (2010). Plate boundary from *Bird* (2003). Faults from *Plafker et al.* (1994).

3D Modeling For Thematic Studies and Local Tectonic Questions. A value of using regional 3D models to investigate a thematic question, such as what is driving mantle wedge dynamics, is that local geologic and geophysical observations can be used to independently constrain model input and output. In addition, these models can provide insights to tectonic questions particular to the region being studied. For the Alaska tectonic boundary, we have shown here 3D geodynamic models that include both an overriding plate and slab, and where the negative buoyancy of the slab drives the flow, result in rapid mantle flow and significant local plate-mantle decoupling in models using a non-linear rheology. The prediction of rapid mantle wedge velocities (*Jadamec and Billen*, 2010) will be tested in the central America subduction zone, in particular the role of rheology, water and melt will be investigated. Thus, comparison of results from regional models of a MARGINS and GeoPRISMS primary site can provide insights to the nature of flow in the mantle wedge.

In the 3D models of Alaska, the fit between the anisotropy and the ISA directions suggests a two-tiered slab beneath south central Alaska with a deeper slab edge at approximately 212° longitude and a shorter edge farther east (*Jadamec and Billen*, 2010). The numerical models show that the relative depth of the slab tip and base of the overriding lithosphere influences whether there will be flow induced in the mantle (*Jadamec and Billen*, In Review). The models showed that a two-tiered slab shape, with the slab beneath the Wrangell volcanics only extending to 115 km, induces toroidal and poloidal flow around the Aleutian slab edge located west of the Wrangell volcanics, matching observations of seismic anisotropy, but that the eastern part of the slab was too short to induce toroidal or poloidal flow east of the Wrangell volcanics. However, anisotropy data were lacking east of the Wrangell volcanics to test whether toroidal or poloidal flow should be induced there. Additional seismic anisotropy observations that could be collected from the EarthScope and GeoPRISMS initiatives in Alaska can better constrain the slab geometry east of the Wrangell volcanics.

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The Timing of Aleutian Arc Inception and Nascent Magmatic Evolution: Current Status and Future Prospects

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The Alaska/Aleutian subduction zone was chosen as the highest priority Primary site for Subduction Cycles and Deformation (SCD) research because it is the most seismically and volcanically active region in North America and opportunities for new discoveries abound. Moreover, several unique characteristics of the Aleutian Arc prompt the testing of fundamental hypotheses. For example, the origin of large, systematic variations in fault-slip behavior and magma composition can be investigated along-strike, and the lack of back-arc extension and longitudinal intra-arc rifting that produces remnant arcs means that the entire record of arc growth via magmatic additions is mostly preserved. The latter makes it possible to tightly link the composition and volume of plutonic, extrusive, and metamorphic rocks to seismic measurements of crustal structure (Holbrook et al., 1999; Shillington et al., 2004) and time scales of crustal growth (Kay and Kay, 1985; Jicha et al., 2006).

Among the key questions to be addressed through SCD research are: *What are the physical and chemical conditions that control the development of subduction zones, including subduction initiation and the evolution of mature arc systems?* and, *What are the geochemical products of subduction zones and how do these influence the formation of new continental crust?* Perhaps the best-studied oceanic case—the Izu Bonin-Marianas (IBM) system—reveals not only the timing (Ishizuka et al., 2011), but also the subsequent compositional evolution of magmatism (Reagan et al., 2008, 2010) associated with subduction initiation. These and other studies of the IBM system provide a model and hypotheses against which data from the Aleutian Arc can be compared. However, our understanding of how subduction initiated along the Aleutian Arc and how the initiation process influenced the course of mantle wedge evolution, magma generation, crust formation, and seismicity remains clouded, due in large part to the scarcity of data that bear on the ages and compositions of the earliest arc rocks.

Several advances of the past decade, including new geochronologic results, novel tectonic models, and forthcoming results from international expeditions to the adjacent fossil subduction zones of the Bowers and Shirshov Ridges (Fig. 1; Portnyagin et al., 2011; Kawabata et al., in press) make now the appropriate time to begin to answer the question: ***How did subduction initiate beneath the Aleutian arc, and how did this influence the evolution of its magmagenetic systems and seismogenic zones?*** First, recent $^{40}Ar/^{39}Ar$ dating and paleomagnetic studies have revealed that: between 81 and 47 Ma the Emperor seamount chain reflects southward motion of the Hawaiian mantle plume, the Hawaii-Emperor bend formed at 47 Ma, after which the Hawaiian seamounts reflect northwestward motion of the Pacific plate over a relatively fixed mantle plume (Fig. 1; Sharp and Clague, 2006; Tarduno, 2007). These findings do not exclude a change in plate motion associated with the bend itself, but are consistent with a several million year period between about 50 and 45 Ma for any change in plate motion to have occurred (Norton, 1995; Tarduno, 2007; Sharp and Clague, 2006). Second, $^{40}Ar/^{39}Ar$ and U-Pb dating of basaltic lava flows and underlying gabbro in

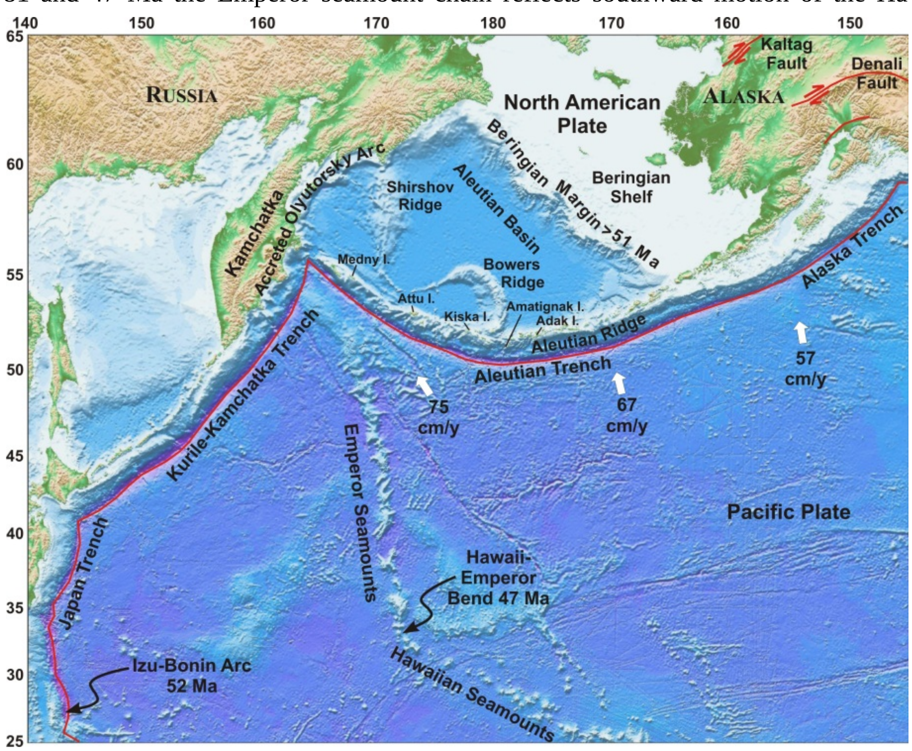

Figure 1. Physiographic and tectonic map of the Aleutian Arc relative to other major features of the north Pacific.

the IBM forearc indicate that the initiation of subduction in the western Pacific took place at 51-52 Ma (Ishizuka et al., 2011), about 4 myr before the Hawaii-Emperor bend formed (Fig. 1). Third, the inception and evolution of the Aleutian Arc may be understood in the framework of new tectonic models, including one that combines elements of subduction zone "obstruction" along the Olyutorsky (accreted) margin along the Kamchatka Peninsula, and continental margin "extrusion" of crustal blocks westward out of Alaska along major strike slip faults (Scholl, 2007; Fig. 1). Obtaining new geochronologic and geochemical information is crucial to linking the initiation of the Aleutian Arc temporally and dynamically to these discoveries and to testing current tectonic models.

Geochronologic data that constrain the inception and earliest evolution of the Aleutian Arc are few in number and several decades old. Only 32 $^{40}Ar/^{39}Ar$ ages have been obtained in the last decade from Aleutian rocks that are Miocene or older. The oldest reliably-dated rocks currently known to have formed in the Aleutian Arc are an andesitic lava dredged from 3000 m depth in Murray Canyon (Jicha et al., 2006) and a primitive basaltic lava that crops out on Medny Island in the Komandorsky Islands, both of which are 46 Ma (Layer et al., 2007; Minyuk and Stone, 2009; Figs. 1 & 2). The only U-Pb data in the Aleutian Arc is the ~30 Ma age of apatite in diorite on Umnak Island (McLean and Hein, 1984; Fig. 2).

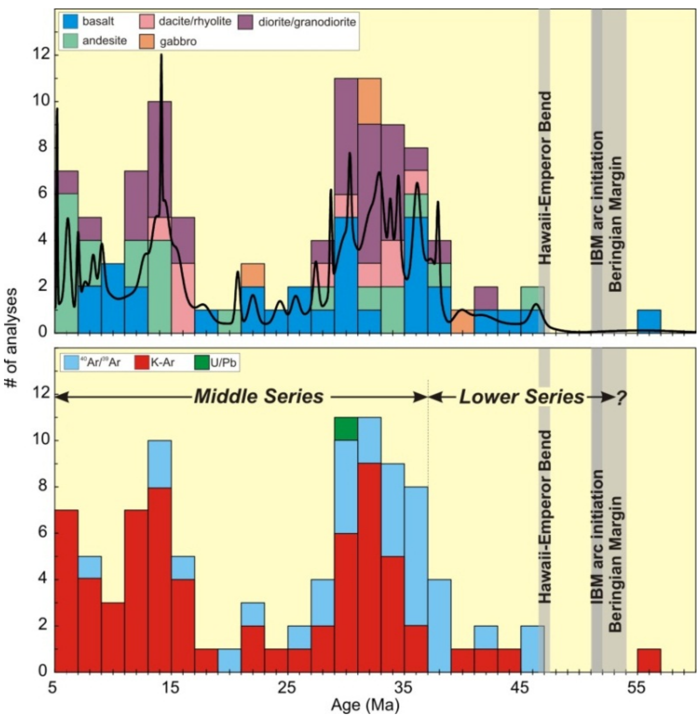

Figure 2. Histograms of published geochronologic data >5 Ma for Aleutian Arc west of 164° W. Each 2 Ma increment is subdivided by rock type (top) and method (bottom). Ages of Hawaii-Emperor Bend (47 Ma), IBM arc initiation (51-52 Ma), and Beringian margin magmatism (51-54 Ma) from Tarduno (2007), Ishizuka et al. (2011), and Davis et al. (1989), respectively. Solid black line is a probability density function that weights each age determination according to its uncertainty. Data sources available from authors.

The timing of Aleutian Arc inception and subsequent compositional evolution through the initial stages of arc growth are poorly known. Early estimates of Aleutian Arc inception varied from 70 to 40 Ma (Grow and Atwater, 1970; Cooper et al., 1976; Marlow et al., 1973), but were based on little or no geochronologic data. K-Ar, $^{40}Ar/^{39}Ar$ ages and one U-Pb age from subaerially exposed granodiorites and calc-alkaline arc lavas dredged from the Beringian margin (Davis et al., 1989; Fig. 1) range from 51-54 Ma. However, the relationship between Beringian arc magmatism and the Aleutian Arc remains unclear. $^{40}Ar/^{39}Ar$ ages of ~46 Ma from andesite in Murray Canyon (Jicha et al., 2006) and a basalt from Medny Island (Layer et al., 2007) provide a cursory minimum age for the initiation of subduction beneath the Aleutian Ridge. These ages closely match the oldest K-Ar dated lava reported by Tsvetkov (1991) from the Komandorsky Islands farther to the west. The tectonic model of Scholl (2007) proposes that initiation of the Aleutian Arc produced these middle Eocene magmatic rocks earlier than 46 Ma, but not before ~50 Ma. Because the start-up phase of arc growth is a voluminous outpouring across a broad front, it can be surmised that middle Eocene basement rock recovered from the crest of the Aleutian Ridge is not going to be significantly younger than the massif deeply buried beneath the ridge's forearc slopes, or the missing seaward sector of the arc massif removed by subduction erosion and transcurrent faulting (Scholl, 2007).

Determining precisely how and when the Aleutian Arc began to form is one of the key pieces of the plate tectonic puzzle of the Bering Sea–Alaska–North Pacific region. The acquisition of a modest number of $^{40}Ar/^{39}Ar$ and U-Pb zircon ages from previously mapped subaerial and submarine plutonic and volcanic rocks – coupled with new trace element and Sr-Nd-Pb isotope data – could rapidly revolutionize our understanding of nascent Aleutian Arc processes and link them to other circum-Pacific phenomena. We draw attention to several islands in Figure 3 that are prime targets because they: (1) are situated in the forearc or extend significantly south of the modern volcanic axis, (2) have been partially mapped, and (3) have published geochronologic data indicating Eocene-Oligocene magmatism. Results from this type of study could fuel a more comprehensive effort by a wider group of GeoPRISMS investigators in the near future to understand Aleutian Arc initiation by delineating specific places along the forearc that hold the greatest potential for exploration using submersible ROVs, dredging, and geophysics.

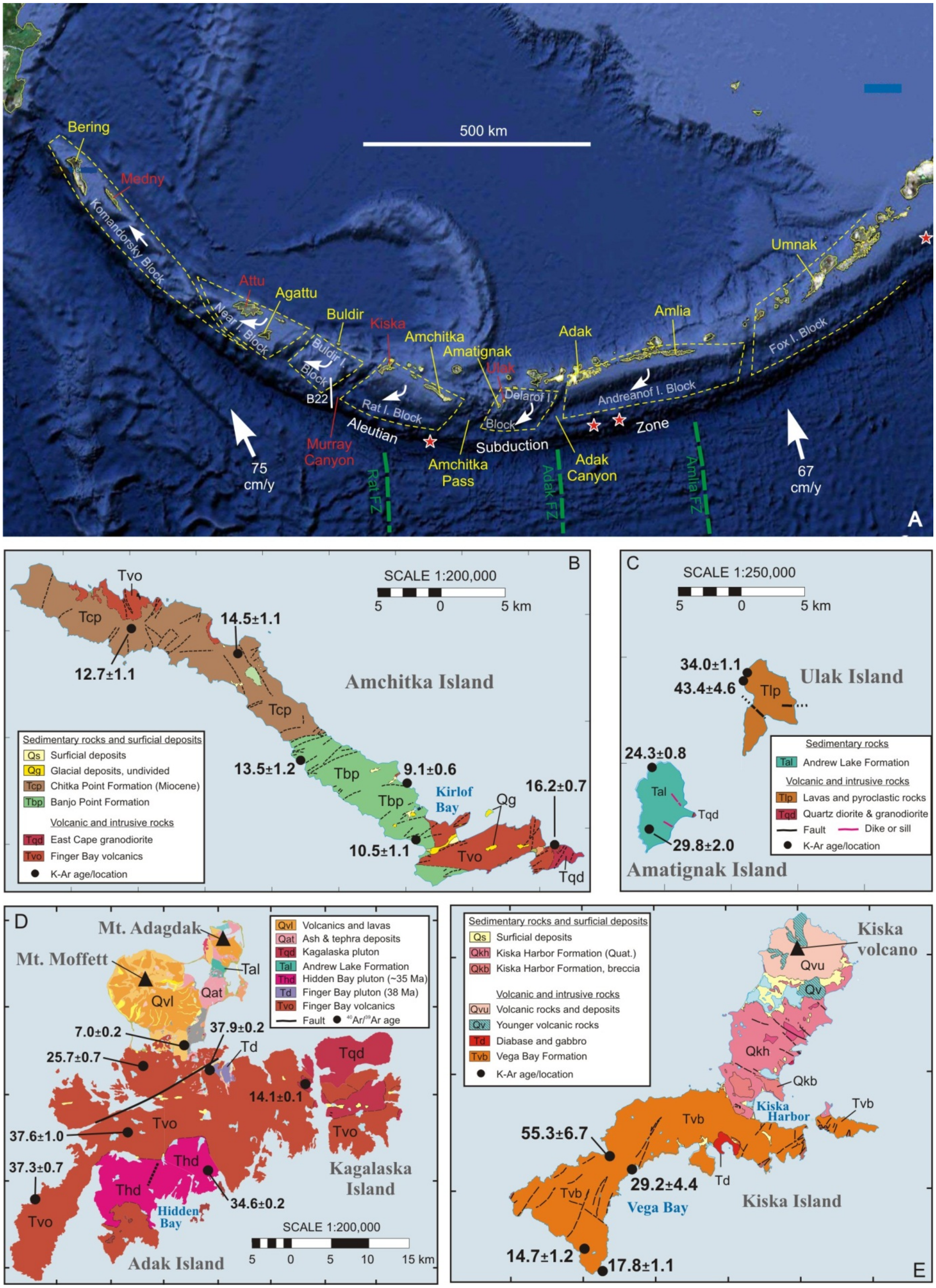

Figure 3. **A**) Google Earth map of the Aleutian Arc. Islands and dredge locations which contain lavas >40 Ma in red font. Dashed yellow lines outline clockwise-rotating crustal blocks. From west to east, the red stars correspond to the following great earthquakes of the last 65 years: 1. 1965 Mw=8.7 Rat Island; 2. 1957 Mw 8.7 Andreanof Islands; 1986 Mw 8.0 Andreanof; 1946 Mw 8.6 Unimak island. Geologic maps of: **B**) Amchitka, **C**) Amatignak and Ulak, **D**) Adak, and **E**) Kiska Islands, modified from Wilson et al. (2006). Sample locations for published K-Ar ages are shown as black dots.

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White Paper for Alaska Primary Site Planning Workshop

Impact of the Lithological Input into the Alaska/Aleutian Subduction Zone on Hydrology and Physical State of the Subducting Zone

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This white paper addresses some aspects of three of the key GeoPRISM SCD questions:

"How do volatile release and transfer affect the rheology and dynamics of the plate interface, from the incoming plate and trench through to the arc and backarc?"

" How are volatiles, fluids, and melts stored, transferred, and released through the subduction system?"

"What are the geochemical products of subduction zones and how do these influence the formation of new continental crust?"

It also addresses the 3rd SCD process-based theme on "Fore-arc to Back-arc Volatile Fluxes.

The lithological input into subduction zones (SZs) is an essential parameter that effects both the physical properties of the subducting slab and the volatiles budget of the system. The input of hydrous phases and thermal state constrain the dehydration reactions (e.g. Moore and Saffer 2001) and subsequent metamorphic reactions (e.g. Peacock 1990; Hyndman and Wang).

The Alaska SZ is unique in its incoming lithology, diatoms comprise a significant portion of the incoming sediments. Diatoms contain ~10 wt% structural water. Unlike clay minerals with 2 well defined types of water, one that dehydrates at <110 °C and the other at >350 °C, and mostly at 400-500 °C, diatoms have 5 types of water that are released step-wise (with minor overlapping) between 25 > 300 °C; the dehydration approximate temperatures were determined (Knauth and Epstein, 1982), hence, the release of water from diatoms has a distinct pattern: some of it overlaps with that of the 1st type of water in clays, and some precedes the 2nd type in clays, hence, should influence the hydrology and volatile cycling at this SZ. The transport and release of H_2O through the megathrust zone is a key question and the diatom input has an important impact on it.

Furthermore, the dehydration of diatoms and the high silica concentrations in pore waters in diatom-rich sediments, should effect clay dehydration and transformation reactions, they may be delayed to occur at higher temperatures than in the absence of diatoms. This topic is not well explored as yet, and should be addressed both experimentally and by modeling.

Diatoms, if at high concentration, also strongly effect the physical properties of sediments, in particular, the permeability and the porosity reductions with burial depth. Diatmaceous sediments even at shallow burial depths have high porosities but unusually low permeabilities controlled by the ultramorphology of diatoms, by the interlocking of the diatom frustules; this has been documented in such sediments, for example in the Monterey Formation, CA (Isaacs, 1981; Issacs et al., 1981). Diatom-rich sediments also do not follow the classic marine sediments porosity-depth reduction profiles (Hamilton, 1976), instead, the porosity reduction is a step function that is controlled by the transformation of opal-A opal-CT (e.g. Isaacs et al. 1981). The high dissolve silica in the pore water during the diagenesis to opal-CT may also impact the sediment strength by early cementation (e.g. Kastner, 1981).

All the above are strongly influenced by the thermal structure of the region, as yet only sparsely characterized.

The segmentation of this SZ, is most likely at least partially controlled by the differences in sediment type and thickness along-strike, (the eastern half of the megathrust is more sediment-rich and is associated with the largest megathrust evens), and the sediment composition in turn is influenced by the diatom content that varies along-strike. It influences both the amount of H_2O in the system at various temperatures and the Si concentration at the depth of magma generation, hence the composition and therefore viscosity of the magma. This may contribute to the along-strike variation in the composition of the volcanic rocks composition .

(The Bering Sea sediments were well characterized during DSDP Leg 19, Hein et al., 1978, and IODP Expedition 323).

For all the above, the incoming sediments must be fully characterized along-strike at representative sites that reflect the main variations in sedimentology-lithology (both composition and thickness) and thermal regimes. Also, new data on the pressure and temperature of clay dehydration and transformation reactions in diatom-rich, high Si and high volatile environments, must be determined, both experimentally and via modeling; also, the seismological consequences of the volatile cycling in diatom-rich sediments will need be considered.

(This white paper complements the White Papers by Spinelli and Harris and by Hallet Nittrouer.).

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Proposed studies of plutons in the oceanic Aleutian arc: Building blocks for continental crust via arc magmatism

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Mike Perfit, Matt Rioux, Dave Scholl, Brad Singer, Tracy Vallier and Gene Yogodzinski

The Aleutian arc is unique among active intra-oceanic arcs in its widespread exposure of Paleogene and Neogene, mid-crustal plutonic rocks, as well as the lavas and sediments that these plutons intruded. In most arcs, plutons are inferred to be abundant, but are hidden beneath a veneer of lava and volcanoclastic debris. Aleutian plutonic rocks are predominantly felsic – quartz diorites and granodiorites – whereas Aleutian lavas are mostly mafic basalts (Kelemen et al. AGU Monograph 2003a). Aleutian relationships mirror global differences between arc plutons and lavas (Kelemen et al. Treatise on Geochem 2003b). Although there is plenty of variability, erupted arc lavas worldwide are dominantly basaltic. In contrast, in ancient, intra-oceanic arc crustal sections, plutonic rocks with 0.5 < Mg# < 0.7 have an average of 55 wt% SiO2 and felsic plutonic rocks comprise more than half of the outcrop area (e.g., Talkeetna-Alaska Peninsula, Rioux et al. GSAB 2007, Tectonics 2010; Kohistan, Jagoutz et al. CMP 2009, 2010).

Felsic plutonic rocks formed in arcs are buoyant with respect to mantle peridotite over the entire range of relevant pressures and temperatures. They tend to remain at the Earth’s surface, to form the fundamental building blocks of continental crust (CC). In the Aleutians, most felsic plutonic rocks have compositions that overlap estimates for the bulk composition of CC (Figure 1), *unlike* felsic arc plutonic rocks from Talkeetna, Kohistan, and Tanzawa that are depleted in light rare earth elements (LREE) and large ion lithophile elements (LILE) compared to CC. Understanding the genesis of Aleutian felsic plutonic rocks is a key to understanding continental genesis and evolution via arc magmatism, which is a central science goal for the MARGINS and GeoPRISMS Initiatives.

Aleutian plutonic rock compositions are significantly different from spatially associated lavas (Figure 2). This is fundamentally important because most studies of geochemical cycling in subduction systems assume that primitive basaltic lavas are representative of the compositional flux through the arc Moho, and/or the bulk composition of arc crust. These assumptions are rarely tested. The trace element data in Figure 4 suggest – *but do not prove!* – that many Aleutian plutonic rocks are derived from parental magmas that are geochemically distinct from typical basaltic lavas in the arc, perhaps because relatively hydrous magmas degas and stall in the mid-crust. If so, basaltic lavas might not be representative of arc bulk composition, or of net magmatic flux through the Moho into arcs. Alternatively, perhaps the plutonic rocks formed from similar parental magmas but via different chemical differentiation paths (e.g., Kay et al. CMP 1983). Or, they could contain “cumulate” accessory minerals, such as monazite, allanite or apatite, that are rich in incompatible trace elements. In any case, because the plutonic rocks are more similar to CC than the spatially associated volcanic rocks, it is important to make a systematic comparison of the composition of coeval Aleutian plutonic and volcanic rocks.

Continental crust has been generated via geochemical processes similar to arc magmatism, perhaps followed by later reworking of arc crust. However, arc lavas worldwide are dominantly “mafic”, or basaltic, while continental crust is “felsic”, with an andesitic or dacitic bulk composition. A variety of processes have been proposed to produce felsic crust from a mafic protolith, including (1) formation of a felsic mid-crust via magmatic differentiation of basalt, followed by (1a) “delamination” of dense, mafic or ultramafic lower crust, or (1b) subduction and then “relamination” of buoyant, felsic mid-crustal rocks during subduction erosion and arc-arc collisions. Alternatively, (2) mid-crustal plutons, or entire arc sections, may be derived from mantle-derived andesitic magmas, rather than from basaltic magmas.

Notably, recent seismic data on the Izu-Bonin-Mariana (IBM) arc, together with reconstructed arc seismic sections for the Jurassic Talkeetna arc and the Jurassic-Cretaceous Kohistan arc, all suggest that these intra-oceanic arcs have a relatively felsic bulk composition, at least above the seismic Moho (Behn & Kelemen JGR 2006; Jagoutz & Schmidt, submitted; Jagoutz & Kelemen in prep.). Perhaps (as in hypothesis 1), all three arcs underwent substantial modification by delamination. And, perhaps mafic to ultramafic cumulates are still present below the Moho (Aleutians: Fliedner & Klemperer JGR 1999; IBM: Tatsumi et al. JGR 2008). Alternatively, (as in 2) voluminous, early arc magmatism may have included a large proportion of primitive andesite. Seismic velocities for Aleutian lower crust appear to be higher than for IBM (compare Shillington et al. G-cubed 2004, Kodaira et al. JGR 2007), but interpretation of the Aleutian data is complicated by the unusual nature of the two arc crossings, and the oblique fore-arc to arc geometry of the single strike line. In any case, our focus here is on the plutonic middle crust.

Systematic study of coeval felsic and mafic rocks in the oceanic Aleutian arc will provide essential information needed to unravel these different hypotheses. For example, hypothesis (1) predicts that there is no systematic difference in radiogenic isotope ratios between felsic plutons and coeval mafic lavas, since both are derived from the same mantle source. Alternatively, systematic isotopic differences between felsic plutons and mafic lavas would support hypothesis (2). This is crucial, since (2) suggests that primitive basalts are not representative of the net magmatic flux through the Moho to form arc crust.

Furthermore, understanding the genesis of felsic plutons spatially associated with mafic lavas can provide fundamental insight into the processes of arc magmatism, regardless of whether felsic plutons are differentiated from typical arc basalts or not. Perhaps there has been a geochemical evolution in Aleutian magmatism, and the compositional distinction between plutons and lavas arises from the age difference between dominantly Miocene plutons, and the mainly Holocene lavas analyzed to date. On the other hand, perhaps plutons and *coeval* lavas are compositionally distinct. In this case, maybe high temperature, low-H_2O mafic melts with low viscosity erupt readily, whereas lower temperature, higher-H_2O felsic magmas undergo degassing in the mid-crust, and become too viscous to ascend further (Kay et al. CMP 1983; Kelemen et al. AGU Monograph 2003, Treatise on Geochem 2003). To understand general features of arc magmatism, it is essential to evaluate quantify any systematic sampling bias that could arise from such physical processes. For example, studies of H_2O in melt inclusions in erupted phenocrysts might not yield an unbiased estimate of H_2O contents in Aleutian primary magmas.

Current understanding of these topics is seriously limited by the paucity of data. Other than USGS U/Pb data for 4 samples, there are no Pb or Hf isotope ratios or ICP-MS trace element analyses for any Aleutian plutons. There are 11 Sr isotope ratios and 2 Nd isotope ratios for Aleutian plutons east of Adak (Perfit et al. CMP 1980; McCulloch & Perfit EPSL 1981). Published K/Ar ages from the 50's and 60's have proven to be unreliable in some cases, and a poor guide to the igneous crystallization age in others, while paleontological age constraints are approximate.

We propose an extensive study of Paleogene and Neogene plutonic rocks and coeval volcanic rocks, together with volcanoclastic rocks in the Aleutians. We need to compare samples from the same island that have similar ages, so an important secondary outcome of our study will be extensive data on the geochemical evolution of the arc over time. Volcanic and plutonic samples will undergo zircon and $^{40}Ar/^{39}Ar$ geochronology, XRF and ICP-MS geochemistry, and radiogenic isotope analyses, and we will undertake geochemical and detrital zircon studies on volcanoclastic rocks.

The groundwork for our proposed study was laid primarily by the US Geological Survey (USGS Bulletin 1028: Byers et al. 1959; Coats 1956a, 1956b, 1956c, 1961; Drewes et al. 1961; Fraser & Snyder 1959; Hein et al. 1984; Morgensen et al. 1985; Powers et al. 1960) evaluating the geology and mineral resources of the Aleutians. More detailed studies of the most accessible plutons, near commercial and military airports on Unalaska, Adak, Amchitka and Attu Islands, followed in the 70's and 80's, undertaken mainly by the Cornell group (Citron PhD 1980; S. Kay and R. Kay CMP & Geol 1985a,b; S. Kay et al. JGR 1982, CMP 1983, GSA SP 1990, GSA DNAG 1994; Perfit et al. CMP 1980; Yogodzinski et al. JGR 1993). These studies added trace element concentrations determined via Instrumental Neutron Activation Analysis (INAA), and some Sr and Nd isotope data for samples from Adak.

Preliminary work can be done on existing samples from [a] more detailed studies (Captains Bay pluton, Unalaska Island; Hidden Bay and Finger Bay plutons, Adak I.; Kagalaska pluton, Kalalaska I.), [b] reconnaissance mapping (large plutons other than Captains Bay on Unalaska I., southern parts of Atka I., Umnak I., Amchitka I., Attu I., Amlia I., Komandorksy Is.), and [c] dredging and submersible studies south of Adak and Kiska I. These will provide ages – including detrital zircons in volcanoclastic rocks – to extend $^{40}Ar/^{39}Ar$ work, and geochemical data for initial constraints on the extent of isotopic variability within and between plutonic and volcanic suites.

Following these initial studies, we propose to conduct field work on several islands containing a variety of plutons of varying ages, together with their older volcanic host rocks and younger, overlying volcanics. Because Adak is relatively well-studied, the best targets seem to be the southern part of Atka, where excellent reconnaissance mapping suggests great potential, and the relatively accessible plutonic rocks on Unalaska and Umnak. Away from Unalaska, outcrops are mainly on sea cliffs along the shore (e.g., Figure 3). Depending on the level of funding, this field work can be conducted via Zodiak, or – preferably – with helicopter support from a research vessel such as the Maritime Maid (http://www.maritimehelicopters.com/).

To expand our spatial and temporal coverage, we will propose separate dredging and/or submersible studies of steep topography in the fore-arc. (The oldest known sample from the Aleutian arc is a plutonic rock from Murray Canyon, south of Kiska I). And, we will seek continuing collaborations with Russian colleagues to continue studies of Paleocene to Eocene volcaniclastic arc rocks (Aleutian? pre-Aleutian?) in the Komandorsky Islands, with the understanding that we would be happy to assist in sample analyses.

Our study will provide crucial information on mid-crustal rock compositions, together with the extent of fracturing and metamorphism, which can be used to interpret existing and proposed, new seismic data on the Aleutian arc. Similarly, petrological studies will provide constraints on the nature of deeper plutonic rocks in the middle and lower crust, that can be compared to inferences from seismic investigations to refine our understanding of arc lower crust, and the genesis and evolution of continental crust via arc magmatism.

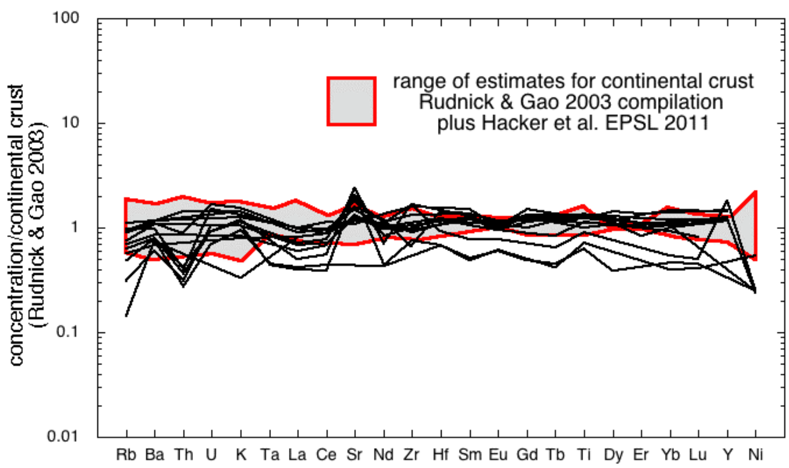
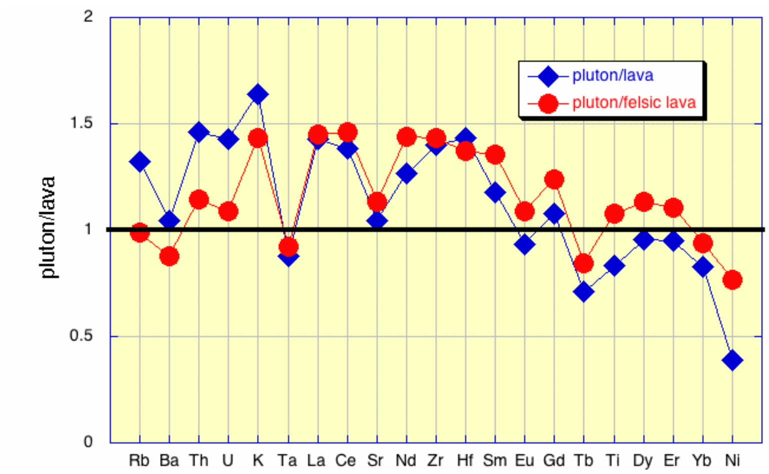


Figure 1: All Aleutian plutons with major elements similar to continental crust that have INAA trace element data, normalized to continental crustal estimate of Rudnick & Gao Treatise on Geochem 2003.

Figure 2: Average Aleutian felsic plutons as in Fig. 1, compared to average lavas (Kelemen et al. AGU Monograph 2003; Singer et al. JGR 2006), and average felsic lavas (56 < wt% SiO_2 < 65, 0.4 < Mg# < 0.6).



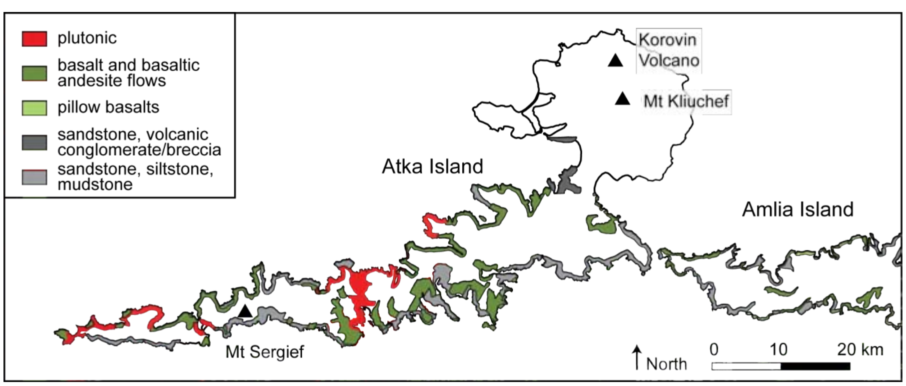


Figure 3: Geologic map of Atka Island, with its sister island Amlia extending to the east, redrawn from Hein et al. (USGS Bull 1609, 1984). Myers et al. (CMP 2002) published a detailed map of the volcanic northern peninsula.

Variations in Seismicity Along the Central Aleutian Arc: An Opportune Site for GeoPRISMs Research

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Introduction

Despite the abundant seismic activity along the Alaska-Aleutian subduction system as a whole, several sections of the megathrust have not produced large-magnitude seismic events in recorded history, and display different seismic behavior. The Shumagin "gap" is perhaps the most-often cited of these anomalous segments. The Amlia region further west, near Seguam and east of Atka and Amlia islands, is also an apparent or possible seismic "gap", with lower levels of background seismicity (Fig. 1) and only limited rupture during past great earthquakes (e.g. House and Jacob, 1983). This region also has documented distinct geochemical variations along-strike that are spatially correlated to the observed structural and seismogenic variation.

This white paper advocates for tightly-coupled studies of seismicity, deformation, subduction zone structure (slab, arc, fore-arc, mantle wedge), and geochemistry of the arc within the Amlia-Andreanof region. Detailed studies here have the potential to aid in distinguishing between proposed down-dip limits on the seismogenic zone (e.g. the Moho vs. a temperature limit), will characterize the physical and seismic properties of a megathrust boundary that has produced multiple large earthquakes in recorded history, and determine how these properties transition into a seismically quiescent segment, both in terms of background seismicity from 1960-present and great earthquakes.

Tectonics and seismicity of the central Aleutian margin

The Rat and Andreanof Islands regions, including the Amlia sector, form part of the intra-oceanic Aleutian arc within the transition from nearly orthogonal plate convergence to convergence with a significant arc-parallel component. Fore-arc and summit basins preserve a history of oblique plate convergence and deformation. The 1957 (Mw 8.6), 1965 (Mw 8.7), 1986 (Mw 7.9) and 1996 (Mw 7.9) earthquakes nucleated within the central Aleutian arc and ruptured much of the plate boundary (Tarr et al., 2010). However, an abrupt change in seismicity occurs near 173°W, correlating with the intersection of the Amlia Fracture Zone (AFZ) with the oceanic trench. Rupture during the 1986 earthquake did not continue east of this boundary, and although the 1957 earthquake ruptured across this segment, a lack of aftershocks in the zone immediately east of the AFZ (Boyd et al., 1995; Okal, *personal communication*, 2009) suggest that the rupture may have jumped the segment with little strain release. GPS data and modeling suggest that a section of the megathrust may be freely slipping in this area (Cross and Freymueller, 2007), possibly similar to the Shumagin region ~900 km to the northeast (Fournier and Freymueller, 2007). Variability in recorded seismicity and cumulative moment release from 1960-present along-strike in this region is pronounced (Fig. 1), suggesting a possible discontinuity in the properties of and/or coupling at the plate interface.

Multi-channel seismic reflection data from USGS studies (1980 and 1981) crossed the trench and fore-arc, and an Ewing cruise in 1994 crossed the central Aleutian trench, fore-arc, and volcanic arc. These reflection data, combined with satellite gravity and magnetic data, indicate a distinct and systematic difference in slab, mantle wedge, and upper-plate structure/properties between the segments of the margin that display varying seismogenic behavior. Slab dip is shallow beneath the Andreanof Islands west of the AFZ (Ryan and Scholl, 1989), and steepens abruptly east of the fracture zone (Holbrook et al., 1994). Deformation within forearc sediments transitions from compressional in the western segment to extensional on the eastern side, and the spacing between adjacent volcanoes is disrupted as is the trench-volcano distance at the AFZ (e.g. Nye et al., 2010). To the west of this transition, the mantle wedge produces a higher-amplitude magnetic anomaly than east of the AFZ (Blakely et al., 2008). The subdued magnetic anomaly could indicate a lack of serpentinite, or alternately, higher temperature (above 580°C) in the mantle wedge east of the AFZ. Geochemical data from the volcanic arc support and reflect the systematic variation in structure observed in geophysical data (e.g., Singer et al., 1996; 2007; Jicha et al., 2004). Seguam volcano, above the seismically anomalous segment east of the AFZ, indicates an order of magnitude higher degree of partial melting than nearby volcanoes (Jicha et al., 2004). The arc west of the AFZ typically has small-volume, crystal-rich calcalkaline magmas which are andesite to dacite in whole-rock composition with dacite to rhyolite groundmass glass. In contrast, the segment east of the AFZ contains volcanoes which are larger, basaltic andesite to andesite, tholeiitic, with dramatically lower crystal contents and more mafic groundmass glass (Nye et al., 2010).

The correlation between the abrupt change in the number of earthquakes with the distinct transition in geochemistry and slab, upper-plate, and mantle wedge structure suggests that the thermal structure of the upper mantle, melt generation, and melt pathways change across this transition as the slab decouples from the upper plate east of the AFZ.

Summary

Studies integrating the structure and thermal/geochemical/rheological properties of the central Aleutians/Amlia region with amphibious studies of local seismicity and plate coupling will provide critical insight into the governing factors on the ‘size, location and frequency of great subduction zone earthquakes, and the relationship to the spatial variation of slip behavior observed along subduction faults’ (Science Plan objective 4.1). Results from the Amlia region will be most valuable when compared to and integrated with results from previous (Nedimovic et al., 2003) and current (Nedimovic et al., 2011; Shillington et al., 2011) studies of changes in seismogenesis at the plate interface, e.g., at Cascadia and in the Shumagins, respectively. Detailed studies in locations with different parameters (oceanic vs. continental margins, direction and speed of convergence, age of the plate, etc.) will aid in the discrimination of globally vs. locally important controls on seismogenesis. Additionally, the detailed nature of the spatial correlation of the distinct geochemical variation along-strike to observed structural and seismogenic variations (Nye et al., 2010) is an intriguing research target. The variability is proposed to reflect varying stress state and migration pathways for melts, affecting the transfer and release of these fluids within the subduction system and the ultimate geochemical products of the system (Science Plan objectives 4.4,4.5).

We suggest that further research in the central Aleutian arc, particularly spanning the Amlia Fracture Zone, may lead to significant advances in our understanding of subduction processes, seismogenesis, and arc construction.

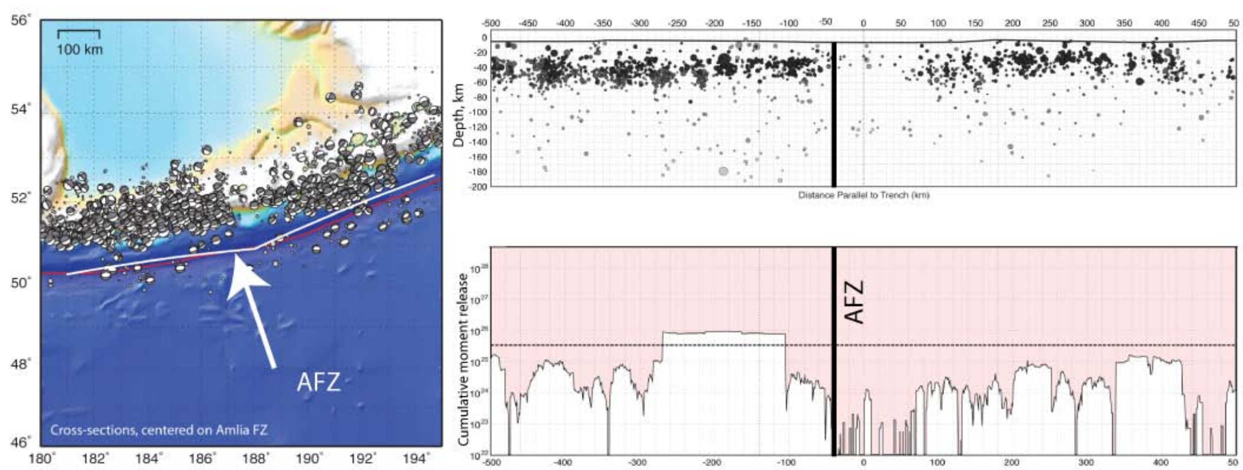

Figure 1: Gap in seismicity (1960-present) and cumulative moment release east of the Amlia Fracture Zone (images courtesy of G. Hayes, NEIC).

The Importance of the Land-Based Paleoseismic Record of Giant Subduction Earthquakes Under Southern Alaska as Possible Reference Markers in the Trench Turbidite Record West of Kodiak Island

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The source of much of the thick trench fill in the Alaska subduction zone west of Kodiak Island seems unlikely to be from the Alaska Peninsula and the Aleutian Islands owing to the limited sediment source areas. Westward migration of sediment derived from glaciated southern continental Alaska would seem the likely source, perhaps transported by turbidite flow triggered by earthquake strong ground motions. Gary Carver and George Plafker (2008) have documented paleoseismic evidence from five sites east of Kodiak for nine giant (M>8.8) megathrust earthquakes (in addition to the 1964 event) during the last 5600 years (Table from Carver and Plafker, 2008). Subject to testing of this hypothesis by sampling the turbidite record south of the source area, this chronology will likely serve as a reference set of dates that will, along with the Holocene tephra record of ten caldera-forming volcanic eruptions, help to date smaller turbidite flows sourced in the Alaska-Peninsula/Aleutian-Islands segment of this 3400 km-long subduction system.

Earthquake	Age Range (2 sigma Cal B P)	Median Age (yrs Cal B P)	Median Interval (years)
1964	-14	-14	
			(517)
EQ Kod 1	533-473	503	875
			(358)
EQ 1	913-808	861	
			618
EQ 2	1522-1324	1479	
			649
EQ 3	2374-2025	2128	
			574
EQ 4	2754-2650	2702	
			357
EQ 5	3134-2984	3059	
			333
EQ 6	3464-3320	3392	
			721
EQ 7	4255-3971	4113	
			366
EQ 8	4784-4199	4479	
			551
EQ 9	5277-4783	5030	

Mean median interval including EQ Kod 1 (11 events) = 504 years
Mean median interval excluding EQ Kod 1 (10 events) = 560 years
Mean median interval for Kodiak segment (5 events) = 437 years

Carver, Gary and Plafker, George (2008), Paleosesimicity and Neotectonics of the Aleutian Subduction Zone: An Overview, pp. 43-63, Geophysical Monograph 179, American Geophysical Union, Washington DC [ISBN 0065-84.48]

Off-trench Earthquakes in Alaska and Their Tectonic Significance

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Off-trench normal-faulting earthquakes were first described by William Stauder in 1968 as a consequence of bending deformation of oceanic lithosphere as it descends into trenches, using as the first examples the off-trench events in the Aleutians. In the 43+ years since that discovery, thousands of such earthquakes have been documented in the instrumental record worldwide and hundreds pre-1968 events have been relocated definitively to the outer-trench-slope/outer-rise region. These earthquakes are important for several reasons. First, for exceptional great events of this kind, they represent potential tsunami sources in the near and far fields, such as the M8.1 event 2009 in Tonga/Samoa and the 1933 Sanriku earthquake in Japan. Second, they reflect the potential for great and giant interplate thrust earthquakes because many occur following such megathrust events and some may represent long-live aftershocks of giant off-trench events in the past. Third, they represent at least temporary sources of seafloor roughness that can cause tectonic erosion of the base of subduction forearcs and thereby affect the structure of the megathrust boundary and long-term forearc kinematics. Fourth, their focal mechanisms reflect not only bending stresses referenced to the local orientation of the trench axis, but also a faulting anisotropy inherited from the plate history of seafloor spreading and regional stresses associated with subduction obliquity (Mortera-Gutiérrez et al., 2003). We focus on these aspects of off-trench events for the Alaska/Aleutian margin.

In Alaska, hundreds of off-trench earthquakes with reliable epicenters have occurred in the instrumental era. Most of these events have occurred west of the Shumagin Islands where the Pacific Plate is older, thicker, and presumably more resistant to flexure. Among these, there are less than a hundred earthquakes large enough to have published focal mechanisms. Most of these earthquakes have normal faulting mechanisms (See map figure) with some tendency in the eastern Aleutians to have nodal planes skewed toward the generally E-W orientations of magnetic anomalies and away from the local trench azimuths, indicating a strong mechanical influence of seafloor spreading fabric. This deviation from strict parallelism with trench azimuths is also consistent with the trends of fault scarps revealed by the USGS Gloria surveys (Masson, 1991; Mortera-Gutiérrez *et al.*, 2003). There are also some scattered strike-slip mechanisms, including the remarkable sequence of strike slip earthquakes in 1987 and 1988 and their aftershocks in the Gulf of Alaska. Remarkably, even in the western Aleutians where relative plate motions are largely trench parallel, most events are normal faulting, although nodal planes are skewed away from the trench axis by the regional shear couple. The largest off-trench earthquakes occurred in 1929 (Kanamori, 1972) and 1965, both with moment magnitudes of about 7.8. Noteworthy blooms of off-trench earthquakes occurred after the giant megathrust earthquakes of 1957 (Mw ~8.6; Johnson and Satake, 1993) and 1965 (Mw 8.7; Kanamori, 1977) along the sectors of greatest megathrust slip, presumably caused by a kinematic transfer by megathrust slip that increases flexural deformation in the Pacific Plate. How slow block rotations in the forearc affect the stress state of the off-trench Pacific Plate has not been established.

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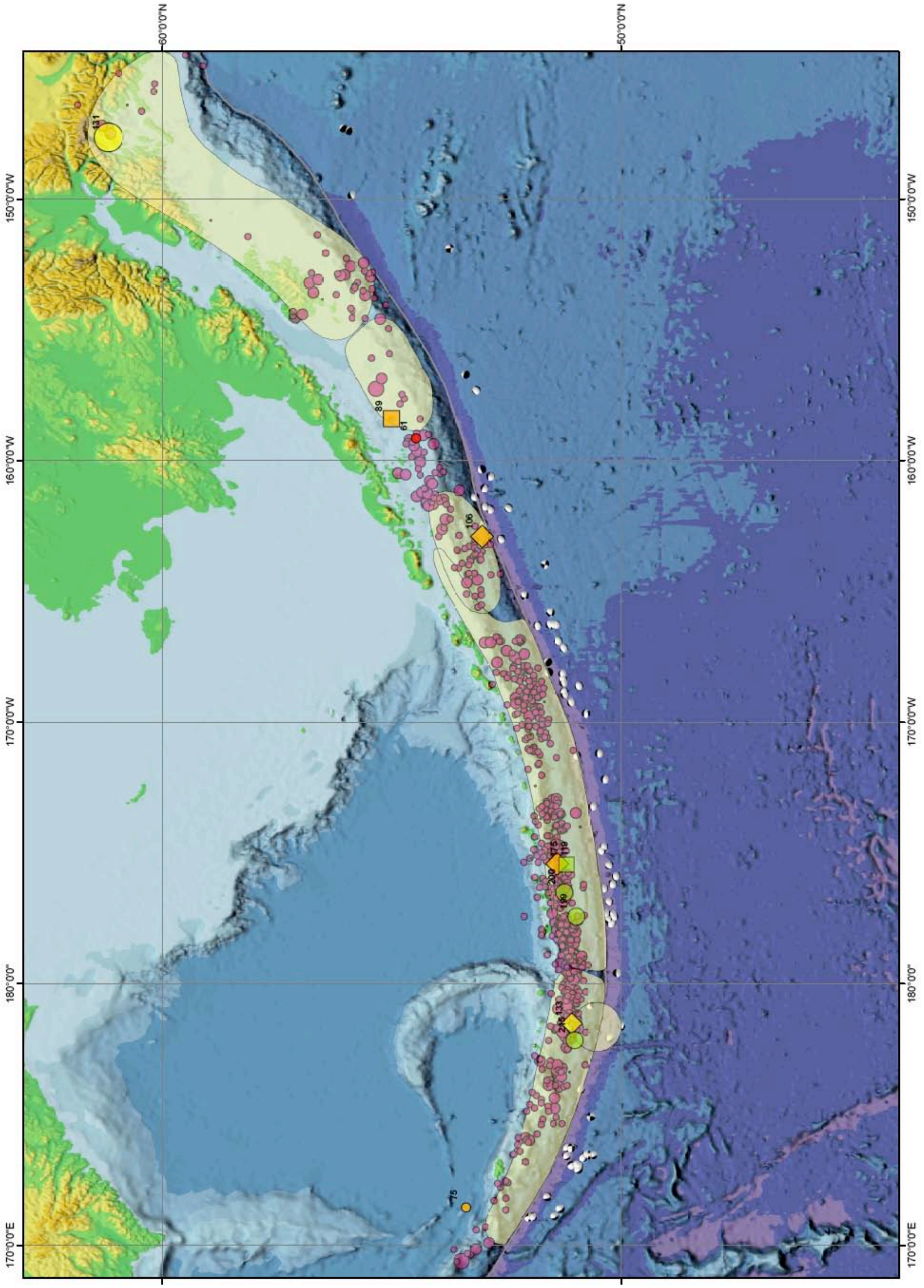

<u>Caption</u>: Focal mechanisms of off-trench earthquakes in Alaska (upper hemisphere) and epicenters of large megathrust boundary earthquakes (pink filled circles). The colored filled squares and circles represent notable large megathrust earthquakes and the light green filled "sausages" represent aftershock zones of great and giant megathrust earthquakes (USGS/NEIC). Note that most off-trench events occur west of 160°W longitude and hence off the Aleutian archipelago where the bending lithosphere is older. Most off-trench events show normal-faulting mechanisms and a small number of strike-slip and reverse-faulting mechanisms.

Coastal Paleoseismology and Paleotsunami Studies in the Eastern Aleutians: A Focus Region for the GeoPRISMS Subduction Cycles and Deformation Plan

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Key SCD Questions Addressed:
What governs the size, location and frequency of great subduction zone earthquakes and how is this related to the spatial and temporal variation of slip behaviors observed along subduction zones?
How does deformation across the subduction plate boundary evolve in space and time, through the seismic cycle and beyond?

Subduction zone paleoseismology, as recorded by land-level changes during earthquake cycles and the tsunamis accompanying great earthquakes, directly addresses the above questions because it is the only means to reconstruct the history of individual great earthquakes and accompanying crustal deformation over many earthquake cycles. Few subduction zones have historical records of great earthquakes and accompanying tsunamis that span more than an earthquake cycle. GPS instrumentation coupled with increasingly sophisticated modeling is identifying previously unresolved patterns of megathrust deformation. But because GPS measurements span only fractions of most cycles, many aspects of ongoing plate-deformation lack a unique interpretation (Wang, 2007). Coastal paleoseismology fills the gap between instrumental measurements and long-term geologic studies of plate subduction in the critically important time span of a century to several thousands (typically 3000-7000) of years. This is also the most important time span for assessing hazards from strong earthquake shaking and tsunamis.

It is difficult to understand what controls the lateral, updip, and downdip extent of individual subduction-zone ruptures, how ruptures vary from one earthquake cycle or supercycle to the next, and how rupture patterns change over many cycles, if a subduction zone's earthquake history—in this case at the Aleutian arc—is known only for the past century and a half. At the Shumagin gap, which part of the earthquake cycle are we in now? Did the 1788 earthquake and tsunami reported from a few Russian settlements rupture as large a region as depicted in Figure 1? Chirikof Island near the gap's eastern boundary is currently dropping at 10 mm/yr (Figs. 1 and 2).

To address research questions and assess hazards along southern Alaskan and the west continental U.S. coasts, in 2010 the U.S. Geological Survey began a reconnaissance investigation of the great earthquake and tsunami history of the eastern Aleutians between Sanak Island and Kodiak Island (Figs. 1, 2, and 3). Similar studies in the easternmost segments of the Aleutian-Alaska subduction zone, where the orthogonally subducting plate dips gently beneath a wide forearc, have revealed signs of as many as nine great earthquakes in the past 5000 years at tens of sites spanning 650 km of the subduction zone (Kodiak segment of Fig. 3; Carver and Plafker, 2009; Shennan et al., 2009). But west of central Kodiak Island (Fig. 1) investigation of the record of prehistoric earthquakes and tsunamis began only in the past year.

As in all paleoseismology studies, finding sedimentary archives of prehistoric earthquakes and tsunamis is severely limited by the rarity of productive sites. An additional difficulty in the Aleutians, which largely explains the lack of previous studies, is the cost and logistical problems of working at coastal sites with the greatest potential. Most Aleutian islands lie well arcward of modeled areas of regional forearc uplift during plate-boundary earthquakes. Even the islands closest to the trench—Chirikof, the outermost Shumagins, and the Sanaks—are no closer to the trench than southwest Kodiak Island, which was just arcward of the zone of coseismic uplift during the 1964 earthquake. Oblique subduction and steepening plate-boundary dips westward along the arc suggest that regional zones of coseismic uplift and subsidence are too narrow to intersect many island sites. Prospects for identifying and dating coseismic subsidence are better than for identifying uplift because (1) past zones of regional coseismic subsidence may encompass some southerly islands, (2) some of these islands have tidal marshes likely to preserve a record of sudden subsidence, and (3) new microfossil methods of reconstructing relative sea-level changes (precision $<\pm0.2$ m) allow previously undetectable changes to be measured (e.g., Shennan and Hamilton, 2006). A few weeks ago, cores with probable evidence for rapid relative sea-level changes were collected from Sitkinak Island (Fig. 3). Small lakes at elevations of 2-25 m are common on some islands (e.g., Sanak, Fig. 1) and a detailed relative sea-level history might be reconstructed if cores could be obtained from an elevational succession of lakes.

The best prospects for identifying signs of great earthquakes in the Aleutians lie with detailed mapping and dating (^{14}C, ^{137}Cs, ^{210}Pb, optical stimulated luminescence) of tsunami deposits. Imagery shows many islands have several or more inlets with 300-3000-m-wide beach ridge sequences and(or) adjacent 3-to-25-m-high lakes or sphagnum bogs. On Chirikof Island we are evaluating a sequence of sand beds in two freshwater peat bogs dating from the past 5000 years (Fig. 3) to distinguish among storm, eolian, and tsunami origins. Distinguishing large local tsunamis generated by volcano flank collapse or submarine landslides—such as the 1946 tsunami that obliterated buildings at Scotch Cap on Unimak Island—from tsunamis produced by regional seafloor displacement will depend on the characteristics, number, and location of sites that can be studied. Our recent fieldwork on Sitkinak Island suggests that we will be able to correlate deposits of 2-4 high tsunamis with times of sudden coastal subsidence or uplift identified through microfossil-based paleogeodesy studies in adjacent tidal marshes.

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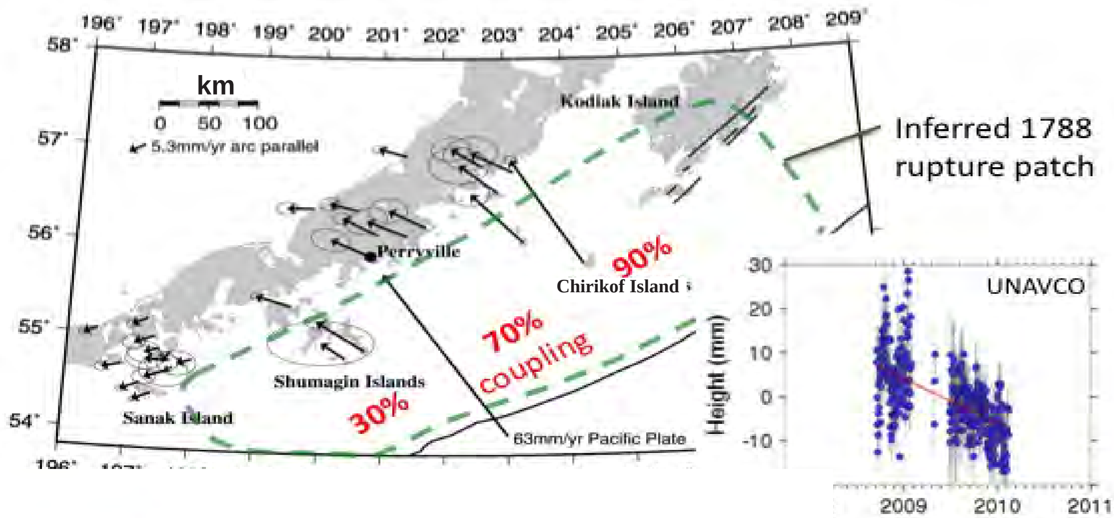

Figure 1. GPS velocities relative to the Pacific plate for sites in the eastern Aleutians (Fournier and Freymueller, 2007), UNAVCO vertical GPS velocities from Chirikof Island (inset) showing ~10 mm/yr subsidence of the island, and a posible rupture area for the great 1788 earthquake inferred from minimum tsunami heights recorded by Russian settlements. Chirikof Island lies above a highly coupled section of the megathrust.

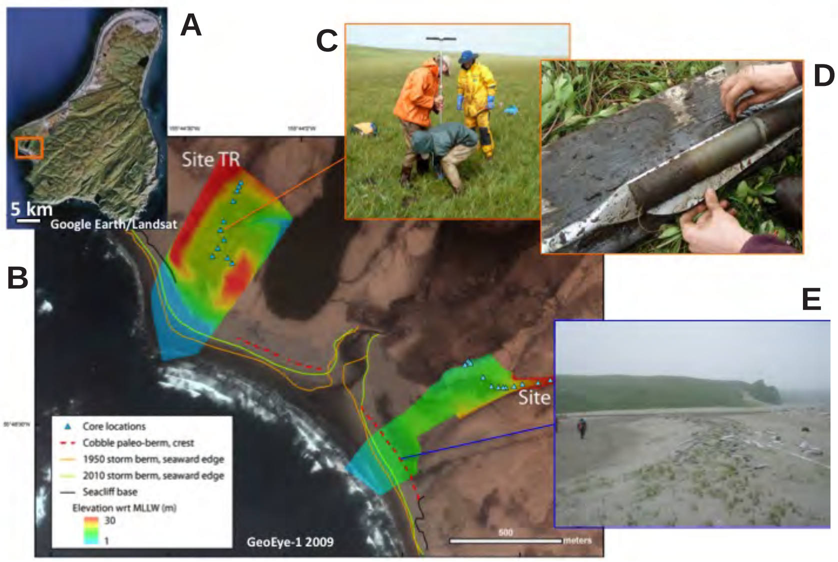

Figure 2. Reconnaisance studies of tsunami frequency and inundation and interseismic land-level changes on Chirikof Island (August 2010). A) Chirikof Island with study area marked by rectangle. B) Elevations, core sites, and geomorphic features at two study sites on the southwest coast of the island. C) USGS team collects a core in a peat bog at 13 m elevation. D) Thick sand and silty sand bed in core deposited by a tsunami about 10.5 ka. E) Beach berms that have moved landward in the past century and other shoreline features suggest that Chirikof Island is currently submerging.

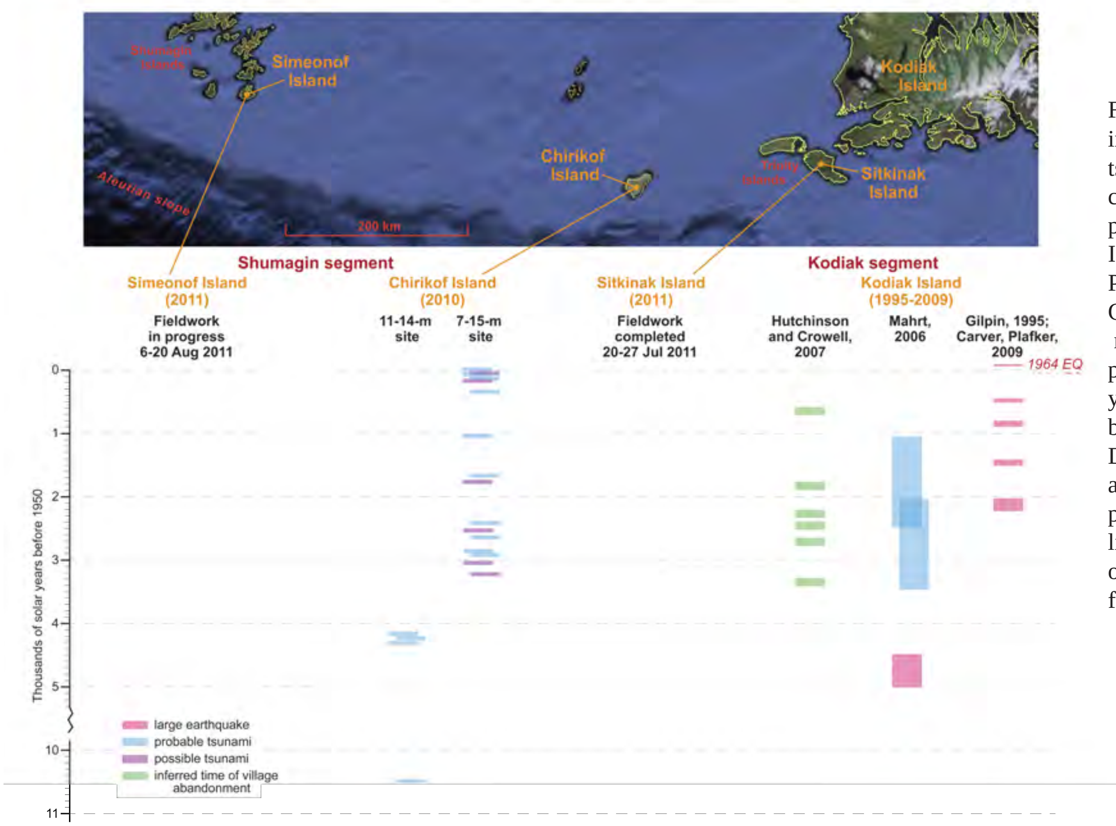

Figure 3. Initial USGS reconnaisance investigations of great earthquake and tsunami history of the past year compared with results of earlier paleoseismic investigations on Kodiak Island east of the area shown on the map. Preliminary 14C ages from two sites on Chirikof Island show an intermittent record of sand bed deposition in freshwater peat bogs over the past 4-10 thousand years. Many of these beds may have been deposited by Aleutian tsunamis. During fieldwork completed a few weeks ago on Sitkinak Island we found sand beds probably deposited by 3-5 tsunamis and lithologic evidence of rapid emergence or submergence of tidal marshes. Similar fieldwork is in progress on Simeonof Island.

GeoPRISMS Planning Workshop for the Alaska Primary Site White Paper: An Aleutian Seismological Observatory

(Previously submitted to USArray and EarthScope Science in Alaska Workshop)

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The Aleutian Islands are an attractive target for dense small-aperture USArray Flexible Array deployments, as volcanic and subduction zone seismicity rates are high but island geography severely limits sub-aerial geophysical data coverage. Akutan and Unalaska Islands are ideal sites for USArray to reach into the Aleutians for six principal reasons: 1. The area has a rich variety of seismic sources at a variety of depths with both tectonic and volcanic origins, 2. The islands are located at the transition between subduction of continental and oceanic lithosphere, near the eastern edge of 1957 M8.6 megathrust rupture zone, 3. Dense array studies would compliment ongoing USGS, AEIC, and PBO monitoring efforts in the region and could potentially dovetail with other multidisciplinary GeoPRISMS and EarthScope projects, 4. Akutan and Makushin are among the most frequently active volcanoes in the United States and are defined as 'very high threat' volcanoes by Ewert et al. (2005), 5. Unalaska is the most populated Aleutian Island, and current development of a new airport and geothermal power plant in the region promises continuing growth of critical north Pacific infrastructure here, 6. Unlike some islands in the Aleutians, the field logistics here are tenable, and land use permitting is relatively straight forward as these islands are not classified as wilderness areas.

Dense small-aperture seismic arrays installed on Akutan and Unalaska Islands could potentially have multiple targets. The subduction zone beneath Akutan and Unalaska Islands has been the most prolific producer of detectable deep non-volcanic tremor (NVT) in the Aleutian arc in the past decade (Brown et al., 2011., Peterson et al., 2005). NVT generally locates at the down-dip edge of the 1957 rupture zone (Figure 1). A spectacular case of triggered tremor occurred in this region during the surface wave arrivals of the M 9.0 Tohoku-Oki earthquake (Rubenstein et al., 2011). Despite recent progress in our understanding of NVT in this region, its temporal and spatial extent and relationship to earthquakes and slow slip is not well resolved. Attractive volcanic targets exist in this area as well, which offer excellent opportunities to partner with GeoPRISMS to study the interplay between the subduction zone and volcanic processes in the crust and upper mantle. For example data from dense arrays could be used to refine the velocity tomography of Syracuse et al. (2010). Akutan volcano had the largest seismic response to magmatic intrusion of any Alaskan volcano in the history of local monitoring, when more than 200 earthquakes ≤ M 3.5 (M_{max} 5.1) occurred during a shallow magmatic intrusion in 1996 (Lu et al., 2005). Akutan and Makushin volcanoes are a persistent source of deep (10-45 km) volcanic long-period (LPs) earthquakes as well (Power et al., 2004). The source process and locations of deep LPs are difficult to constrain with data from current seismic networks, yet these events are thought to be related to magma transport. Further study of deep LP's with dense seismic arrays, particularly if tied to geochemical studies, would further our understanding of magma generation and ascent in a volume of crust where these processes are poorly resolved. Deep LPs have the potential to be used as intermediate term precursors to volcanic eruptions.

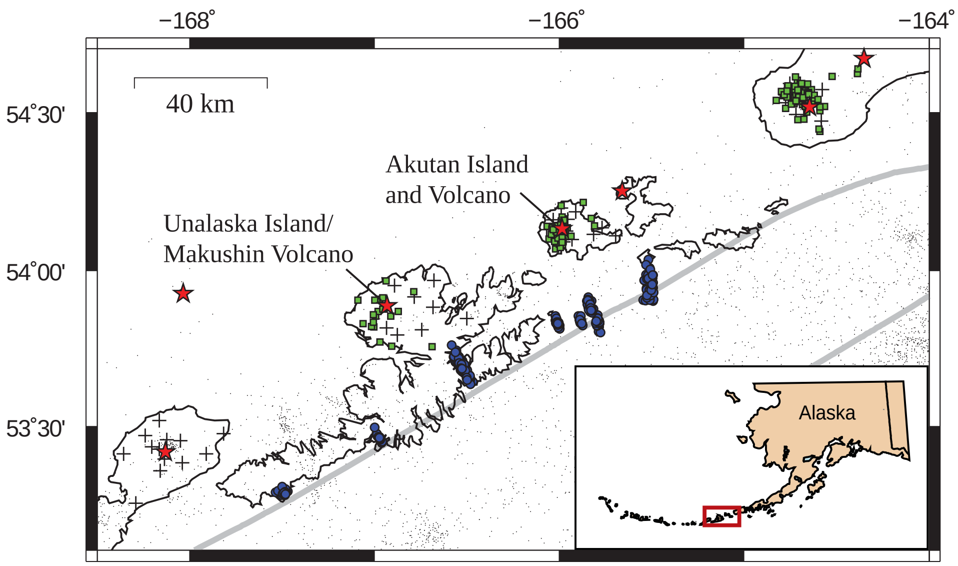

Figure 1 – *Target events for small-aperture arrays. Blue circles are locations of low-frequency events within NVT (Brown et al., 2010). Green squares are deep (10-45 km) long period earthquakes. Crosses are existing seismic stations. Red stars are volcano summits. Gray line shows M8.6 1957 rupture zone. Dots show ANSS catalog M2+ earthquake locations 2002-2010. Red box in inset map shows location in Alaska.*

Given this suite of seismic targets and following Ghosh et al. (2009, 2011), data from several dense seismic arrays on Akutan and Makushin Islands could potentially refine our understanding of the spatial and temporal characteristics of NVT near the end of a rupture zone, illuminate volcanic system structure and earthquake sources at Akutan and Makushin volcanoes, and constrain the relationship between earthquakes, subducted slab composition and structure, and magma genesis and transport. One advantage of the multi-beam back projection method is that it can track the migrating source, volcanic or non-volcanic, in high resolution over different time scales. We suggest that a suitable Flexible Array deployment in this region could consist of four or more 10-15 sensor arrays located above known NVT and deep LP sources.

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Effects of spatial and temporal variation in sediment flux on the Aleutian subduction zone

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SCD Themes Addressed: *4.1 (Size, location and frequency of subduction zone EQs)*
4.2 (Evolution of plate boundary deformation in space and time)
4.7 (Climate/surface/tectonic feedbacks)

The understanding of sedimentary input to a subduction zone is key to the interpretation of long-term behavior of the subduction cycle. The complex tectonic relationships created by the Yakutat terrane collision with North America and strong glacial-climate signal in the Gulf of Alaska margin create multiple point and distributed sediment sources that create a significant feedback between surface and tectonic processes in the region. Field studies strongly suggest that subduction zone and orogenic dynamics are influenced by surficial processes and the sediment delivery rates to subduction zones (Brocklehurst and Whipple, 2002; Lamb and Davis, 2003; Whipple and Meade, 2004). Climate, in turn, directly affects precipitation rates and types, thus controlling the rate and timing of sediment production. Glacial advance-retreat cycles provide the primary climate forcing that may affect structural evolution of the Gulf of Alaska margin. Recent thermochronologic studies in the area provide evidence for intensified exhumation and uplift onshore in response to focused erosion by glaciers (Berger et al., 2008; Enkelmann et al., 2010); offshore drilling shows that terrigenous flux throughout the Gulf more than doubles at ~1 Ma (Lagoe et al., 1993; Rea and Snoeckx, 1995). These data make a strong case for an increased effect of sediment flux on Aleutian subduction since ~5 Ma. A five-fold increase in sediment delivery to the Aleutian Trench during the Pleistocene (Piper et al., 1973) may have altered subduction zone dynamics through significant along strike and temporal variations in the incoming sedimentary section as well as sediment loading within forearc basins (e.g., Simpson, 2010).

Three major sediment bodies atop the Pacific Plate are currently subducting at the Aleutian Trench. The first is the Surveyor Fan, the terrigenous outwash body that comprises the majority of the Alaska Abyssal Plain and thickens into the Yakutat shelf. The Kodiak-Bowie Seamount Chain is the southern boundary of the Surveyor Fan, beyond which lies the second sediment body, the inactive Zodiac Fan (Fig. 1) (Reece et al., 2011; Stevenson and Embley, 1987). The third deposit is an axially-deposited wedge of sediments that lies within the Aleutian Trench and atop the subducting Surveyor and Zodiac Fans. Herein we refer to this wedge of sediments as the Aleutian Trench fill.

The St. Elias Range glacial systems feed the modern Surveyor Fan as multiple point sources from the Yakutat shelf edge. While both the Surveyor Fan and Aleutian Trench fill deposits decrease in thickness overall away from the Yakutat margin, the Aleutian Trench fill receives sediment from a few prominent point sources along its extent, likely creating local increases in trench fill sediment thickness. Perhaps the two greatest sources of trench fill are the Bering glacial system at the trench head, and the end of the Surveyor Channel, which terminates at the trench between the Kodiak Bowie and Patton Murray Seamount Chain. Additionally, Chugach Range glaciers are a source for trench fill, perhaps most notably those that feed the Copper River and Cook Inlet systems. The majority of sediment in the Fan and Trench is supplied during glacial maxima due to an abundance of accommodation space on the Aleutian foreland and the ~100 km wide Yakutat shelf and no major mechanism for cross-shelf transport during highstand (Reece et al., 2011; Worthington et al., 2010). A thin, distal Surveyor Fan abuts the Patton-Murray Seamount Chain, south of which is a much thicker section of the older Zodiac Fan (Fig. 1). This boundary between fans creates the single increase in fan-type sediment along the axis of the trench. The narrow focusing of the point sources within the trench fill allows this sediment body to exert an influence on subduction beyond the boundaries of the Surveyor Fan to at least as far southwest as the Zodiac Fan.

These sediment bodies drive growth of the Alaskan-Aleutian accretionary prism to a first order. The along strike variation of sediment thickness arriving at the Trench has clearly affected the size and shape of the accretionary prism and forearc; the width and thickness of the prism decreases substantially towards the distal Aleutians. Any increase in sedimentation to these systems could potentially extend the transition from an accretionary to a non-accretionary/erosional subduction system.

The configuration and nature of the subducting and accreting sediment in the Gulf of Alaska lead us to ask some key questions about the effect of sediment on the Aleutian subduction zone:

1- How do spatial and temporal variations in sediment thickness affect taper of the prism, fault vergence, width of the prism, location of forearc basins, development of out of sequence thrusts, and the potential for backthrusts and/or splay faults?

2- What are controls on the formation of the décollement and how do they vary along strike, especially with regards to point source sediment input and the boundary between the Zodiac and Surveyor Fans? How does this relationship affect the amount of sediment underplating versus accretion to the front of the prism?

3- What is the extent of the Aleutian Trench fill sediment body and how far along strike does it exert an influence on subduction? Where does the subduction process fundamentally change along strike from an accretionary to non-accretionary margin?

4- How do significant amounts of sedimentation affect the length of seismogenic zone segments, namely, what is the potential for sediments to overtop basement topography, effectively smoothing out the subducting plate and removing potential asperities?

5- Do existing locked and creeping zones correspond to differences in 1) sedimentary inputs 2) sediment loading on the shelf in forearc basins and/or 3) sediment interaction with subducting basement topography?

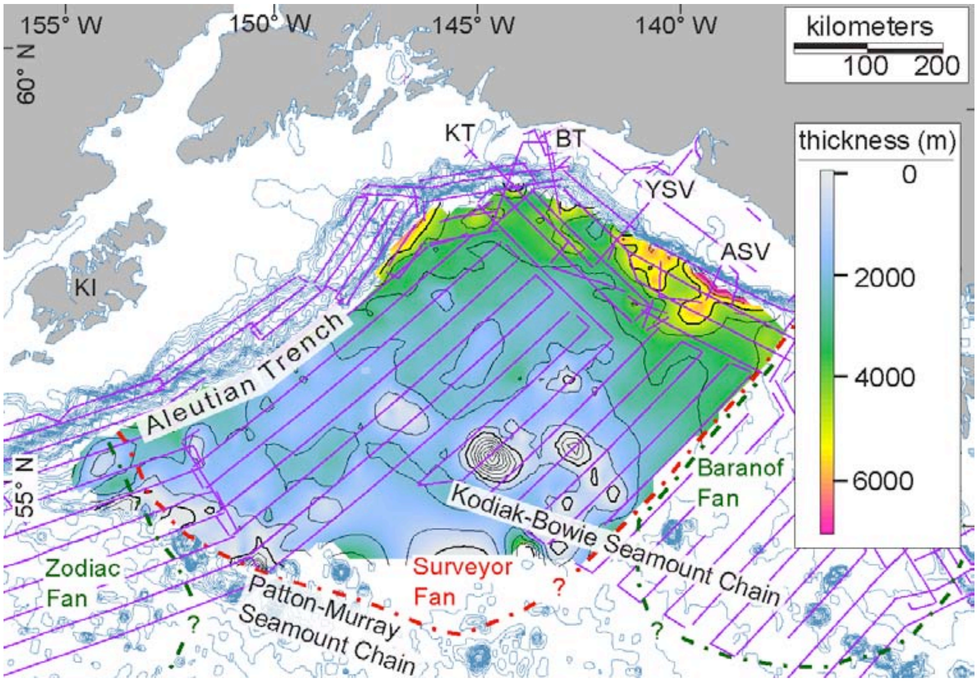

Figure 1. Two-way travel time thickness map of the Surveyor Fan. Seismic reflection data tracklines used in calculation shown in purple. Estimated boundaries of the Surveyor, Zodiac, and Baranof Fans shown in red and green dashed lines, respectively. ASV- Alsek Sea Valley; BT- Bering Trough; KI- Kodiak Island; KT- Kayak Trough; YSV- Yakutat Sea Valley. (Reece et al., 2011).

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White Paper for GeoPrisms Alaska Meeting: September 2011

From the Slab to the Surface: Origin, Storage, Ascent and Eruption of Volatile-Bearing Magmas

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Proposed Sites: Unimak-to-Cleveland corridor; Cook Inlet (Augustine-to-Spurr) corridor (Fig. 1)

Related SCD Themes: This white paper directly supports the primary theme from the SCD Implementation Plan:
C. How are melts delivered from the mantle to the arc crust and out the volcano? What is the relationship between magmas that erupt and those that freeze in the crust?

Key Existing Data/Infrastructure*:
- PBO Volcanoes (AK, AU, OK, UN)
- AVO Intensive Mapping efforts (AU, AK, FI, MK, OK, RD, SH, SP)
- AVO/PBO Seismic Arrays (AK, AU, IL, MK, OK, RD, SH, SP, UN)
- Zimmer et al. (2010) baseline study of volatile contents (AK, AU, MK, OK, SH)
- Completed studies of precursory and non-eruptive volcanic earthquake swarms (AK, AU, IL, RD, SH, SP)

*Akutan (AK), Augustine (AU), Fisher (FI), Iliamna (IL), Makushin (MK), Okmok (OK), Redoubt (RD), Shishaldin (SH), Spurr (SP), Unimak Island (UN)

1. From the Slab to the Surface:

Volatiles (H_2O and CO_2) fuel volcanic eruptions, but what processes deliver different quantities of fuel to each volcano? How do volatiles leak out of magmas during ascent? And how do magma compositions and degassing processes affect the ascent, storage and eruption of magmas? At a convergent margin like Alaska, these questions are likely related all the way down to the devolatilization reactions in the subducting slab. One of the discoveries made by the MARGINS program is that volcanic plumbing systems may be imaged seismically down into the mantle. For example, a low Vp/Vs column beneath Nicaragua connects the volcanic system in the crust to the dehydrating system in the subducting slab (Syracuse et al., 2008). EarthScope researchers have discovered that volcanoes respire geodetically and speak seismically, revealing the depths of magma storage and degassing and the mechanisms of magma ascent. Connecting shallow and deep magmatic systems is a new challenge to GeoPrisms, but one that holds promise for linking - for the first time - subduction processes to eruptions and shallow intrusions.

Volatile Cycling - The deep-Earth volatile cycle contains 75-90% of Earth's water and carbon, yet its characteristics are poorly understood when compared with the surface cycle. The most significant interface between the surface and deep-Earth volatile cycles is the global subduction zone system; >99% of volatile input into the Earth's interior, >50% of volatile degassing, >90% of great earthquakes, and half of the Earth's volcanic activity occurs within 200km of a subduction trench. Volatile cycling between the surficial and deep-Earth cycles is initiated by transport of water-rich sediments and altered oceanic crust to the Earth's interior in subduction zones, where earthquakes testify to the processes of slab dehydration and deformation. Volcanoes deliver important volatile-bearing compounds from the deep Earth and vent gases (including greenhouse gases) into the atmosphere on timescales that are important to Earth's long-term climate variability. Yet the balance of delivery and return between the Earth's surface and interior is so poorly known that we don't even know whether the net flux of water or carbon is into - or out of - the Earth's interior, which is a key constraint on its evolution.

From the slab to the Moho - Combined geodynamic-petrological models now make predictions as to the flux of volatiles released from the subducting plate (van Keken et al., 2011) and seismic images can now illuminate the melting region in the mantle wedge, but these source regions have yet to be linked to volatile fluxes at the surface. Aleutian magmas record a link between water and other slab tracers (Fig. 2), but do higher erupted water contents reflect a wetter slab, more efficient recycling, or different mantle melting conditions?

From the Moho to midcrustal storage reservoirs - Magmas form storage reservoirs by stalling in the deep- to mid-crust, but it is not known whether the control is intrinsic (magma buoyancy, viscosity and volatile content) or extrinsic (regional stress regimes). The depth and duration of magma storage may set the mode of crustal evolution and the vigor of eruption. Geodetic, seismological and petrologic observations can be used in tandem to test models of magma ascent, stalling and freezing. Deep long period (LP) earthquakes (Power et al., 2004) occur at >10 km depth, and are thought to be linked with deep crustal magma storage and transport systems. For example, in Alaska, deep LPs are recorded both in association with eruptive activity, and in the absence of eruptions, at many volcanoes including Spurr, Redoubt, Iliamna, Akutan, and Makushin. A careful synthesis of geophysical and petrological data can potentially reveal melt and fluid transport pathways in the deep crust.

From storage to eruption - Imaging of reservoir-to-surface magma plumbing systems is possible through analysis of geodetic, seismic, and petrologic data. Melt inclusion studies not only provide information on arc volatile budgets, but can also be used to estimate storage conditions and conditions of dynamic crystallization during ascent. Pressure increases in midcrustal magma storage and transport systems are commonly signaled by an onset or increase in microseismic activity beneath the volcano, but only a fraction of these episodes of unrest proceed to eruption – is the fate of a batch of magma ascending through the shallow crust somehow linked to tectonic setting, magma volume and/or ascent rate, magma composition, or volatile contents (Fig. 3)?

2. Opportunities in Alaska:

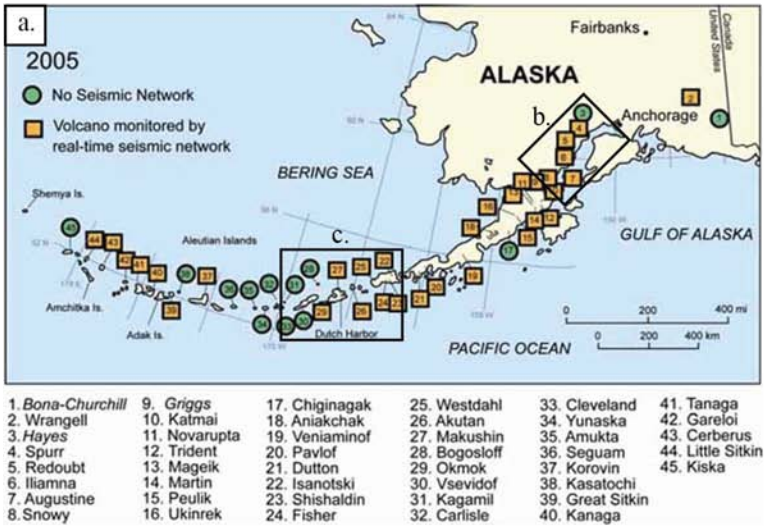
Focusing of the GeoPRISMS effort on two specific Aleutian arc "discovery corridors", the Cook Inlet corridor and the Shishaldin-to-Cleveland corridor (Fig. 1), will provide an unprecedented opportunity to study relationships between tectonic setting, earthquakes, magmatic volatile transport, magma composition/rheology, and volcanism.

The Cook Inlet corridor extends for 200km from Mt. Spurr to Augustine Volcano at the easternmost terminus of the Aleutian arc, and is located on young continental crust. The Cook Inlet corridor is just south of the locus of the 2nd largest earthquake in recorded history (M9.2, Prince William Sound 1964), and just north of the largest volcanic eruption of the past century (1912 Katmai). The Cook Inlet corridor itself has experienced only a single >M7 earthquake over the past century (1909 M7.4 Kenai), indicating the presence of an actively slipping subduction megathrust. Cook Inlet corridor magmas are generally volatile- and crystal-rich andesites and dacite, and include the most water-rich volcanic system in the entire Aleutian arc (Augustine volcano). Geophysical and petrological evidence indicates short-term storage or hybridization occurring at about 4-10 km depth (Spurr, Redoubt, and Augustine: Gardner et al. 1998; Lahr et al., 1994; Roman et al., 2006; Larsen et al., 2010), fed by deeper sources (e.g., 20-40 km; Power et al., 2004). At Augustine volcano, syntheses of petrological, geochemical, and geophysical data indicate a conspicuous lack of long-term shallow magma storage, with magma stalling in a complex series of dikes 4-6 km beneath the summit (Roman et al., 2006), and remobilized by new inputs of basalt from depth (Larsen et al., 2010). Cook Inlet magmas may be especially prone to arrested transport through degassing-related crystallization, as seen in 1992 and 2004 at Mt. Spurr (Gardner et al., 1998; Coombs et al. 2006) and in 1996 at Iliamna Volcano (Roman et al., 2004), suggesting that the formation of plutons below arc volcanoes, and thus continental crust formation, is related to degassing-induced crystallization (Fig. 3).

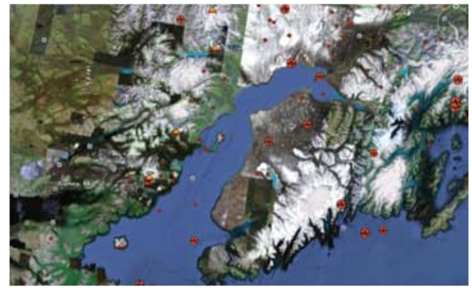
The Unimak-to-Cleveland corridor extends for 500km from Cleveland volcano in the west to Shishaldin volcano in the east. This corridor straddles the continent-ocean boundary in the arc by equal amounts, and encompasses volcanoes with a range of pre-eruptive H_2O contents that span half the range observed in the Aleutian arc, including the lowest-H_2O volcano (Shishaldin) and is thus highly complementary to the extent of magma hydration observed in the Cook Inlet corridor. In addition, this corridor has experienced almost a dozen >M7 earthquakes over the past century, and was the site of a recent (2010) large earthquake swarm located just to the southeast of Cleveland. Magmas in the Unimak-to-Cleveland corridor are typically mafic (basaltic andesite) and remarkably phenocryst-poor. Okmok maintains a relatively long-lived shallow storage region between 3-5 km depth, based on geophysical and petrological evidence (e.g., Masterlark et al., 2010; Izbekovet al., 2005). The reservoir is almost constantly re-filled, as shown by geodetic observations over the past ~15 years, punctuated by two eruptions in 1997 and 2008. Although evidence for deeper supply exists, all data indicate that the shallow crustal reservoir is the main control on Okmok's frequent eruptive activity. Although less-well-understood, the occurrence of a sustained high rate of shallow LP seismicity beneath Shishaldin (Petersen et al., 2006) suggests a similar set of controls on Shishaldin's eruptive activity.

Together, the Cook Inlet and Unimak-to-Cleveland corridors capture nearly the entire spectrum of tectonic, seismic, petrologic, and volcanic activity displayed in the Aleutian arc, as well as the full range of magma storage depths and water contents. This diversity is contained within a combined arc length of 700km, less than 1/4th of the length of the arc. Although this represents a significant geographical area, it is an arc length that is similar to that of the Central American arc that was a focus site of the previous MARGINS program. The causes of the significant differences in the character of magma systems within the two corridors is an open question. A fundamental question that could be addressed within the GeoPRISMS themes would be the extent to which the differences in magmas between the Unimak-to-Cleveland and Cook Inlet corridors originate from a fundamental difference in their parental compositions, due to differences in volatile flux from the slab. Community-scale projects focused on these two corridors would be poised to answer questions about volatile budgets, formation of continental crust, how magmas and fluids are transported through the crust, and the relationship between magmas that freeze and those that erupt.

Figure 1



b. Cook Inlet Corridor



c. Unimak to Cleveland corridor

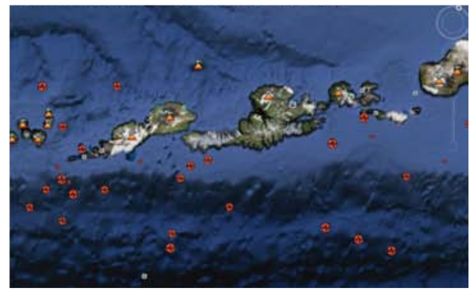
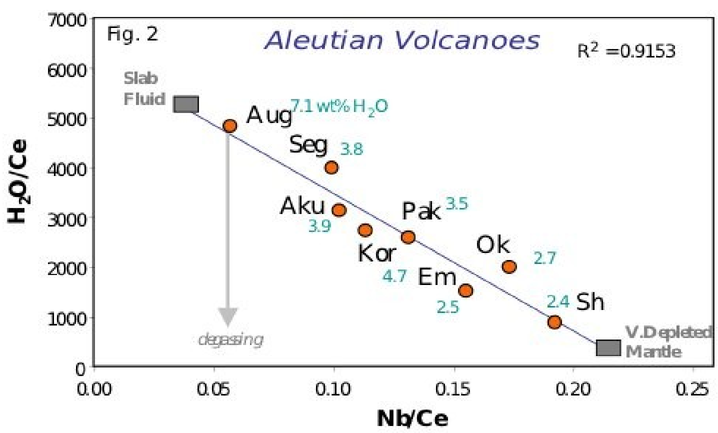


Figure 1. a) Location of seismically monitored volcanoes along the Aleutian arc (after Dixon et al., 2006). b) The Cook Inlet and c) Unimak-to-Cleveland corridors, showing the locations of major recent earthquakes.



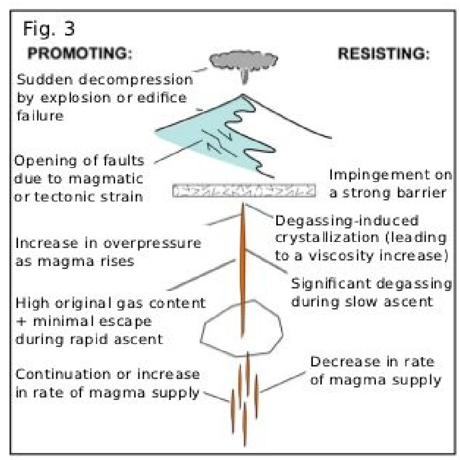


Figure 2. H_2O/Ce - Nb/Ce correlations in Aleutian volcanoes is consistent with a link between maximum pre-erupted H_2O (values in blue) and the amount of slab fluid added to the mantle. Zimmer et al. (2010; 2009).
Figure 3. (after Moran et al. 2011) Cartoon of forces promoting and resisting eruption of ascending magma.

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The Aleutian-Alaska Subduction Zone Is Prone to Rupture in Great and Giant Megathrust Earthquakes—How Scientific Information Can Mitigate Consequences

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THE FIELD SETTINGS OF LARGE SUBDUCTION ZONE EARTHQUAKES

Great (Mw8.0 and larger) and giant (Mw8.5 and larger) megathrust earthquakes occur repeatedly along certain subduction zones and uncommonly or unkown at others. Why this circumstance should exist has long been the focus of study, wonderment, and debate. But, based on observational information, it seems clear that the nucleation sites and hallmark lengthy, trench-parallel ruptures of great and giant megathrust earthquakes are significantly influenced by physical field relations and settings. Important among these are:

A) For the underthrusting ocean plate:
1) Subducted high bathymetric relief, in particular ridges, fracture zones, and large seamounts, and seafloor roughness generally, and
2) Subducted thick sequences (>1-2 km) of trench sediment, and

B) For the upper plate of the forearc:
1) Forearc structural highs, and
2) Large, forearc basins or plateaus

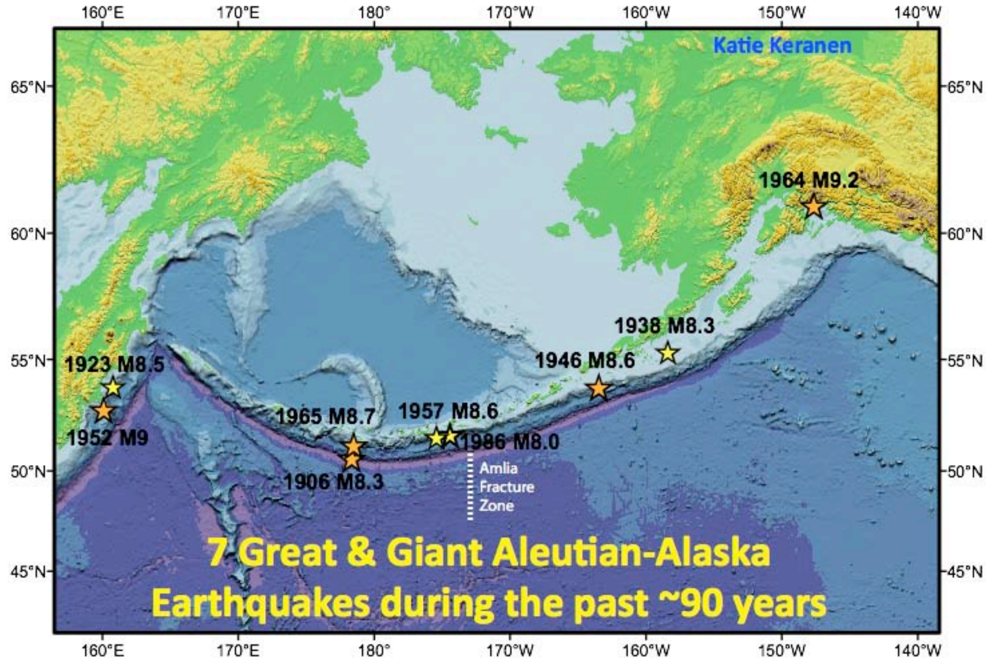
Great and giant megathrust earthquakes characteristically nucleate below a forearc structural high, or atop a subducted ridge or large seamount, and rupture laterally away for distances of 300-1200 km. Rupturing commonly terminates at a subducted ridge, fracture zone, or large seamount. As the table below shows for the best-documented instrumentally and geologically recorded (Cascadia, 1700) great and giant events (23 total--including the 2011 Tohoku Mw9.0), trench sectors with laterally continuous axial deposits thicker than 1.0 km are associated with the occurrence of:

52 % of Mw8.0 and larger megathrust earthquakes (12 of 23)
57 % of Mw8.3 and larger megathrust earthquakes (8 of 14)
67 % of Mw8.5 and larger megathrust earthquakes (8 of 12)
71 % of Mw8.8 and larger megathrust earthquakes (5 of 7)
67 % of Mw9.0 and larger megathrust earthquakes (4 of 6)
100 % of Mw larger than 9.0 (3 of 3).

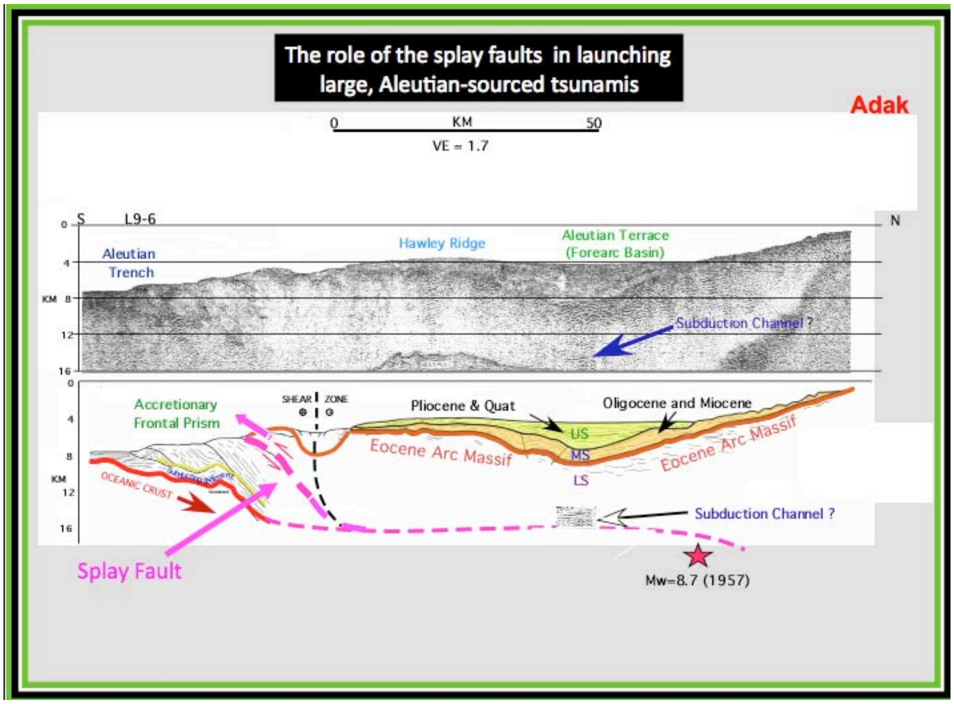
The reason for this relation, as hypothesized by Ruff (1989), is that subduction of a thick section of trench-floor sediment inserts a laterally homogenous layer of material into the subduction channel separating the two plates of the submerged forearc. The interplate surface of rupture probably runs along the top of the subduction channel. A sediment-packed subduction channel mechanically smoothes the roughness of subducted sea-floor relief. During a megathrust earthquake, an even, lateral distribution of interplate strength or coupling would favor lengthy trench-parallel rupturing. Smoothing can also be effected by basal subduction erosion that mechanically inserts upper plate crustal debris into the subduction channel. The setting of the giant Tohoku megathrust, which is not associated with a thick section of subducted sediment, exhibits a subduction channel charged with a >1.0 km-thick layer of tectonically eroded debris overlying an exceptionally smooth, underthrusting sector of Pacific plate.

THE ALEUTIAN-ALASKA MEGATHRUST SETTING

The Aleutian-Alaska subduction zone is one of the world's most seismically active and also the home of repeated great and giant earthquakes and matching tsunamis. Many factors are involved in setting up this reality, but those that promote long run-out megathrust events and rapid seaward interplate slipping can be linked to the observations that:



1) Subducted, high-standing ridges and large seamounts are widely spaced beneath the Aleutian-Alaska forearc—a circumstance favoring long run out ruptures.
2) The trench axis from Middleton Island, eastern Gulf of Alaska, 3200 km westward to Attu Island is, except for the Shumagin sector thickly charged (~2 km) with sediment shed from glaciated Alaskan drainages—a circumstance favoring lateral rupture continuation.
3) Much of the length of the submerged Aleutian-Alaska forearc is underlain by a wide, structurally deep forearc basins or platform—a circumstance that localizes rapid trenchward slip beneath them and the generation of regional and areally larger tsunamis (Wells et al, 2003).
4) Aleutian outer forearc is sheared by splay fault systems (but apparently not everywhere), a circumstance favoring the launching of large near field and/or trans-oceanic tsunamis.

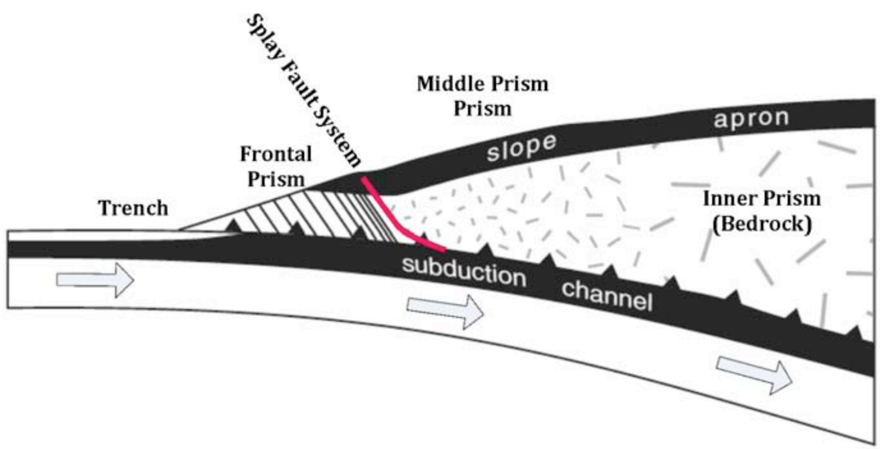

The role of the splay faults in launching large, Aleutian-sourced tsunamis
Adak
0 KM 50
VE = 1.7
S L9-6
N
Aleutian Trench
Hawley Ridge
Aleutian Terrace (Forearc Basin)
Subduction Channel ?
KM
Accretionary Frontal Prism
SHEAR ZONE
Pliocene & Quat
Oligocene and Miocene
US
MS
LS
Eocene Arc Massif
Eocene Arc Massif
OCEANIC CRUST
Subduction Channel ?
Splay Fault
Mw=8.7 (1957)

INFORMATION NEED TO MITIGATE CONSEQUENCES OF SEISMIC GEOHAZARDS

To mitigate the consequence of marine geohazards generated at the Aleutian-Alaska subduction zone, in particular large tsunamis, field knowledge is needed to make probabilistic estimates (forecasts) of their likely future occurrence and source regions. This essential information, which is largely or wholly missing, can be acquired by a blend of coastal and offshore studies to reveal the late Cenozoic paleoseismic and -tsunamic record and to regionally map the location, continuity, and geometry of forearc fault systems.

Specifically, what is needed for the entire length and width of the submerged forearc is:

1) High-resolution, multibeam bathymetric maps adequate, for example, to laterally trace fault scarps, identify middle and frontal prisms and splay faults separating them, slope failures, debris flows, and paths of subducted relief.



2) Information about when and where great and giant megathrust earthquakes nucleated.
3) Information about when, where, and source-cause of local, extra-regional, and trans-oceanic tsunamis.
4) Information about the geometry and shape of the interplate surface and locations of significant along-strike changes.
5) Information about the location, geometry, and lateral continuity of high-angle reverse, splay, and strike slip fault systems.
6) Information about the causes of rupture segmentation (limits and termination).

7) Information about the thickness of sediment and tectonically eroded debris within the subduction channel with respect to the underthrusting seafloor relief and roughness.

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Heat flow measurements and the thermal state of the Alaska convergent margin

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Subduction zone thermal models are important to understanding subduction dynamics [e.g., *van Keken et al.*, 2002], dehydration reactions [e.g., *Moore and Saffer*, 2001], metamorphic reaction progress [e.g., *Peacock*, 2003; *Hacker et al.*, 2003], serpentinization in the forearc [*Abers et al*., 2006], and estimates of temperature limits for interplate seismicity [e.g., *Hyndman and Wang*, 1993; *Oleskevich et al*., 1999]. Dehydration reactions have also been implicated in episodic tremor and slip events [*Schwartz and Rokosky*, 2007]. Making progress toward many of the goals in the *GeoPRISMS -- Suduction Cycles and Deformation* science plan requires well-determined thermal models.

In the seismogenic zone, the thermal structure of subduction thrust strongly depends on the thermal state of the incoming oceanic lithosphere, the convergence rate, and plate geometry. In contrast to the convergence rate and slab geometry that are confidently known from plate motion data and seismology, the incoming plate geotherm is less well known. In the absence of heat flow data, models are commonly idealized using conductive cooling models that are parameterized in terms of plate age [*Parsons and Sclater*, 1977; *Stein and Stein*, 1992]. In fact, uncertainties in these generic models lead to significant uncertainties in the position of isotherms along the plate interface. At subduction zones with plentiful heat flow observations, the data commonly require significant departures from predicted geotherms. Uncertainties in the initial geotherm are can be larger if hydrothermal circulation within the incoming crust has been important. Seafloor probe measurements offer an economical method for obtaining transects of heat flow across the margin and along strike. At subduction zones where plentiful heat flow data exist, significant departures from conductive conditions, rapid changes in heat flow along strike (e.g. Costa Rica), and continuing hydrothermal circulation within the downgoing plate (e.g., Muroto, Costa Rica), have been documented.

Of the convergent margins with historic M9.0 megathrust earthquakes only a few have adequate heat flow to constrain thermal models of the shallow subduction zone (Table 1).

Table 1: Characteristics of subduction zones with M9.0+ earthquakes and Nankai margin

Subduction Zone	Largest Magnitude Earthquake	Well-defined Seismogenic Zone?	Slow Earthquakes and Tremor Observed?	Well-Defined Thermal State?
S. Chile	9.5	Yes	No	No
Alaska	**9.2**	**Yes**	**Yes**	**No**
Sumatra	9.1	Yes	No	No
N. Japan	9.0	Yes	No	No
Kamchatka	9.0	Yes	No	No
N. Chile/Peru	9.0	No	No	No
Cascadia	9.0	No	Yes	Yes
Nankai	8.1	Yes	Yes	Yes

The Alaska margin provides a link between the Nankai and Cascadia margins. It has had a magnitude 9.0 or larger earthquake; it has a well-defined seismogenic zone, and it has had observed slow slip and tremor events. Previous thermal models of the Alaska subduction zone [e.g. *Ponko and Peacock*, 1995; *Oleskevich et al*., 1999; *Gutscher and Peacock*, 2003] have been hampered by the lack of heat flow data to initialize models and validate model results. Along the entire >3200 km length of the Alaska-Aleutian subduction zone, there are only 32 heat flux observations on the incoming plate (Figure 1). In contrast, on the Nankai margin, more than 100 surface heat flux observations were used to constrain the thermal state along one trench-perpendicular transect. The existing thermal models for the Alaska subduction zone are not adequately constrained (Figure 2); to date, no thermal models have been published for the Aleutian portion of the subduction zone.

Thermally important targets for GeoPRISMS research includes documenting 1) the thermal state of the Pacific plate prior to subduction. Is hydrothermal circulation ongoing and has it removed significant quantities of heat? 2) Documenting fluid flow along plate bending normal faults. Is fluid flow along plate bending normal faults significant and does its magnitude correlate with along-strike variations in arc volcanism and seismic attenuation anomalies in the upper mantle? 3) Do along strike variations in the thermally predicted distance between the 100° and 350° C isotherm correlate with observed changes in the width of the interplate seismogenic zone? 4) What is the thermal regime in the forearc and where does the trend in heat flow change from decreasing due to the subducting slab to increasing due to mantle wedge flow [e.g., *Wada et al.*, 2008; *Wada and Wang*, 2009]. Does this change correlate with patterns of seismic attenunation in the upper mantle.

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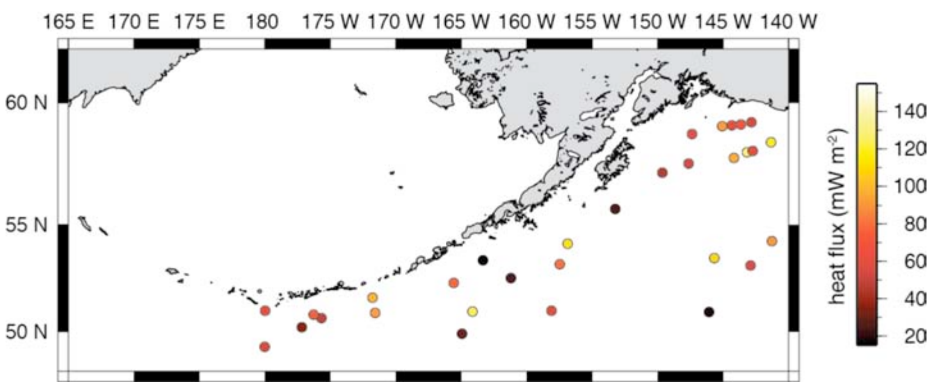

Figure 1. Existing heat flow observations along the Aleutian convergent margin.

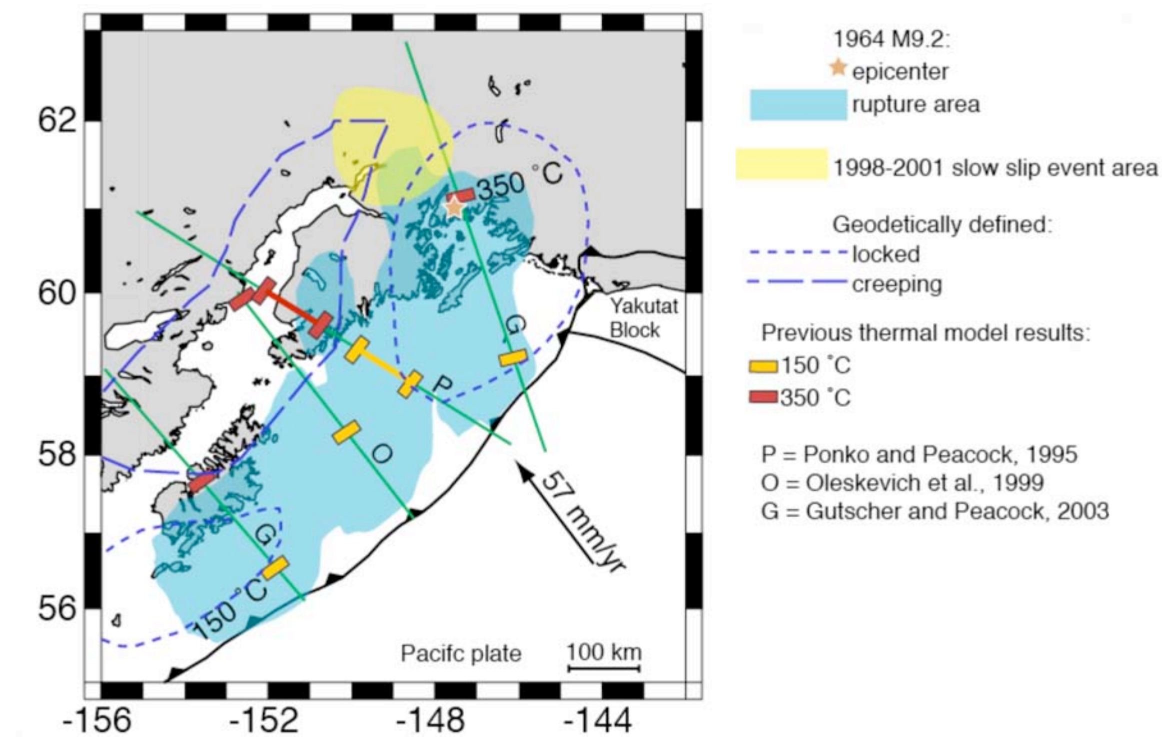

Figure 2: Location and summary of results for previous thermal models for the Alaska margin. The thermal models are 2-D cross-sections along the transects shown (P = *Ponko and Peacock*, 1995; O = *Oleskevich et al*., 1999; G = *Gutscher and Peacock*, 2003). Yellow ticks on the transects show the modeled position of 150 ˚C on the plate boundary fault; red ticks show the modeled position of 350 ˚C on the plate boundary fault. Ranges of locations on line P reflect uncertainty in degree of frictional and radiogenic heating. Blue shading shows 1964 M9.2 earthquake rupture area – assumed to be the full extent of the megathrust seismogenic zone.

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Linking arc volcanic fluxes and growth rates with Pleistocene climate change: Marine tephrostratigraphy of the Aleutian-Alaska volcanic arc

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The long-standing observation that the frequency of arc volcanism changes periodically in intensity has led to many hypotheses and models as to cause-and-effect relationships and feedbacks mechanisms with the global climate (Cambray and Cadet, 1994; Jegen et al., 2010; Jicha et al., 2009; Kennett and Thunell, 1975; Prueher and Rea, 1998; Prueher and Rea, 2001). For example, global cooling has been proposed to follow the enhanced injection of climatically-active gases and aerosols into the atmosphere (Jicha et al., 2009; Kennett and Thunell, 1975; Prueher and Rea, 1998; Prueher and Rea, 2001), that may possibly be followed by positive feedbacks, such as an increased albedo of snow covers and ice sheets, or the biological drawdown of CO_2 driven by the release of nutrients from dissolving ash into the oceans (e.g. Jones and Gislason, 2008). In a recent study, Huybers and Langmuir (2009) proposed that glacially induced volcanism, triggered by the depressurization of the upper mantle increased the frequency of volcanic eruptions worldwide, and thus plays a key role in the atmospheric CO_2 balance and ice-age cycles. A link between arc volcanism and the 41 ka Milankovitch periodicity also emerges from a statistical evaluation of macroscopically visible marine tephra deposits near circum-Pacific arcs (Jegen et al., 2010). On a more immediate scale, Tuffen (2010) concluded that ongoing glacier recession likely will result in intensification of eruptions worldwide, with a corresponding increase in associated hazards.

While these studies suggest causal links between volcanic frequency and climate change, the global approaches remain inconclusive as to magnitude, causes and feedback mechanisms. Testing time-cause relationships between arc volcanism and climate needs an integrated approach where reliable data on the frequency of arc volcanism can be combined with data on volcanic emissions of climatically active volatiles and arc growth rates, and in addition can be directly related to the other parameters of climate change, such as ice volume data, IRD (ice-rafted debris) input, etc.. We propose that the Pleistocene Aleutian-Alaska arc system provides these characteristics and therefore represents an ideal system for addressing a key question of the GeoPRISMS Draft Science Plan (Subduction and Deformation cycles): '*How do surface processes and climate modulate volatile inputs and outputs at subducting margins and vice versa*' (p. 4-15).

Fig. 1 shows the distribution of tephra-bearing ODP/IODP drill cores and piston corers in the proximity of the Aleutian-Alaska arc. ODP Leg 145 drill sites 882, 883 and 887 provide clear evidence for increase in volcanicity at the onset of the Quaternary glaciation (Prueher and Rea, 1998; Prueher and Rea, 2001), despite the incomplete core recovery rate. The recently completed IODP Leg 323 provides an ideal set of sediment drill cores from the Bering Sea. Tephra bed frequency is also high in IODP Leg 323 drill sites in the Bering Sea (drill sites U1340-45) that have a 100% recovery rate (Ravelo et al., 2011). The analyses of drill cores from ODP Leg 145 and IOPD Leg 323 can be complemented by piston cores recently recovered as part of the INOPEX program during the R/V SONNE 202 cruise (INOPEX, 2009) which provide additional information on the Quaternary tephra distribution of the Aleutian-Alaska arc. Clearly, the available marine tephra beds allow for establishing a time-precise and temporally highly resolved record of the Pleistocene Aleutian-Alaska arc volcancity that can be correlated with the marine archives of climate change (Ravelo et al., 2011).

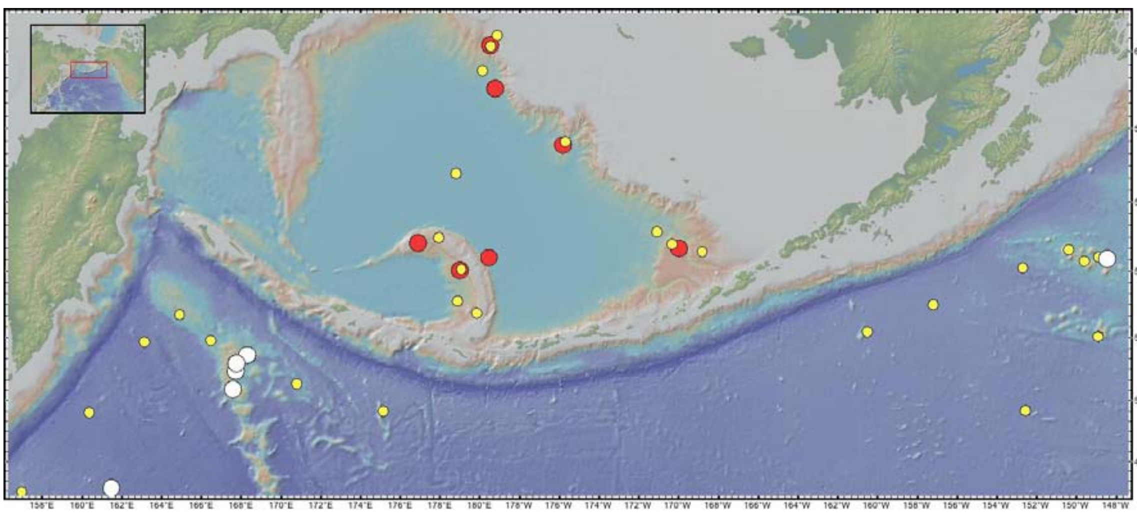

Figure 1: Tephra-bearing drill cores from IOPDP Leg 323 (red), ODO Leg 145 (white) and piston cores from INOPEX-SO202 cruise (yellow) in the Bering Sea and Subarctic North Pacific.

As part of the research of the GeoPRISMS Primary Site ‘Alaska/Aleutian Margin’, we propose to integrate the information from the marine tephra beds in order to address the following science questions:

(i) Testing the connection between arc volcanic frequency and glaciation as proposed by Huybers and Langmuir (2009) and Jegen et al. (2010).

This connection should be most pronounced at high latitudes, and as northernmost arc on Earth, the Aleutian-Alaska arc is ideally suited for this project. We propose to focus on cores from IODP Leg 323 in the Bering Sea and complement those where needed with piston cores from the INOPEX/SO-202 cruise, south of the arc system. The information on arc volcanic frequency can be obtained from these marine sediment cores whereby the studies must comprise a systematic evaluation of the distribution of both discrete (macroscopic visible) and disperse (tephra camouflaged by non-volcanic sediment) tephra. To reconstruct the climate change signal in these cores, we will combine information from ongoing paleoceanographic studies of the IODP Leg 323 and SO202 cores (Asahi et al., 2011; Schlung et al., 2011) and additional stable isotope and isotope geochemical analyses.

(ii) Connecting the marine tephra record with the volcanic record of the Alaskan-Aleutian arc.

As significant output take the form of tephra far from volcanic sources (Kutterolf et al., 2008b; Kutterolf et al., 2008a; Kutterolf et al., 2008c), the marine tephra record of the Alaskan-Aleutian arc provides important information for characterizing the rate of arc growth (see also pg. 4-17 of GeoPRISMS Draft Science Plan). In addition, the distal tephra may best record high-silica arc volcanism that preferentially erupts explosively and is less well preserved on land. The comprehensive evaluation of composition and volcanic volumes are essential data input for the dedicated GeoPRISMS goal of material transfer through subduction zones (Key Question 3) and arc crustal growth (Key Question 3).

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FlexArray Alaska: Basin-to-slab seismic imaging of subduction tectonics

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Abstract

Forearc basins are fundamental components of convergent margins, both accretionary and erosive. However, crustal, slab, and upper mantle structure in the vicinity of these basins are not well imaged by traditional seismic techniques, because the basins trap seismic waves, thereby obscuring subtle signals that originate from target structures below. We propose a deployment of 30 FlexArray broadband seismic stations in the vicinity of Cook Inlet basin to image a slab-normal subduction profile that extends from the locked zone of the 1964 M_{w} 9.2 earthquake, through the Cook Inlet forearc basin, through the active volcanic arc (Redoubt), and 100 km into the backarc region. Our seismic imaging technique utilizes spectral-element and adjoint methods which rely on highly accurate wavefield simulations within three-dimensional models. These techniques should allow us to better image the extreme structural complexity of this region, as manifested in full-length, three-component seismograms. Motivated by the striking spatial patterns in shear-wave splitting from previous deployments in Alaska (BEAAR, MOOS), we will broaden these observations to help understand how the anisotropic fabric changes across the subduction zone. Our overarching question is:

> What are the relationships among basin formation, active crustal faults, slab geometry, and mantle dynamics in subduction systems? Specifically, how is the formation of Cook Inlet forearc basin related to the dynamics of the Alaska-Aleutian subduction zone?

A targeted broadband array of stations, combined with seismic wavefield modeling, could exploit the phenomenal slab and crustal seismicity, and would provide a golden opportunity for producing a detailed structural model of the subduction zone. Such a model could serve as a basis for geodynamical and geochemical models.

The project would provide promising targets for complementary 2D and 3D active-source marine experiments within Cook Inlet and oceanward of Seward Peninsula toward the trench.

Fundamental objectives

1. What is the 3D structure of the subduction zone (basin, slab, crust, arc, upper mantle) in the region of Cook Inlet forearc basin (Figure 1)?
2. What is the anisotropic structure: (1) below the slab, (2) within the slab, and (3) above the slab?
3. What are the modes of deformation inferred from source mechanisms of local intraslab and crustal earthquakes?
4. How does sub-arc and sub-basin seismicity (Figure 1) connect to the slab below and the surface geological deformation above?
5. How is the formation of the forearc basin related to the surface and subsurface dynamics of the subduction zone?

Scientific tasks

1. Build an initial 3D upper mantle and crustal model of the subduction zone in Alaska.

2. Build an initial high-resolution 3D model of the crust and upper mantle in the vicinity of Cook Inlet forearc basin.

3. Collect 2–3 years of waveform data from 30 temporary broadband stations and ~20 permanent broadband stations in the Cook Inlet region.

4. Use spectral-element and adjoint methods within a tomographic inversion to iteratively improve the high-resolution 3D models (*Tape et al.*, 2009).

5. Use local shear-wave splitting to determine anisotropic structure in the mantle wedge or crust. Compare with previous SKS splitting results (*Christensen and Abers*, 2010).

6. Use generalized radon transform or receiver function analysis to identify primary interfaces (Moho, slab), in addition to those within the upper mantle and crust. Such techniques have proven successful on Alaska data sets (*Ferris et al.*, 2003).

7. Investigate the relationships among slab seismicity, crustal seismicity, gravity anomalies, and the formation of the basins (e.g., *Wells et al.*, 2003; *Haeussler and Saltus*, 2011).

8. Relocate crustal and uppermost mantle seismicity in order to refine the deformation zones below forearc basin and arc.

9. Perform targeted 2D and 3D imaging of the Cook Inlet subducting slab (e.g., *Rondenay et al.*, 2008). What can the images (in combination with seismicity) tell us about the compositional and thermal structure of the slab?

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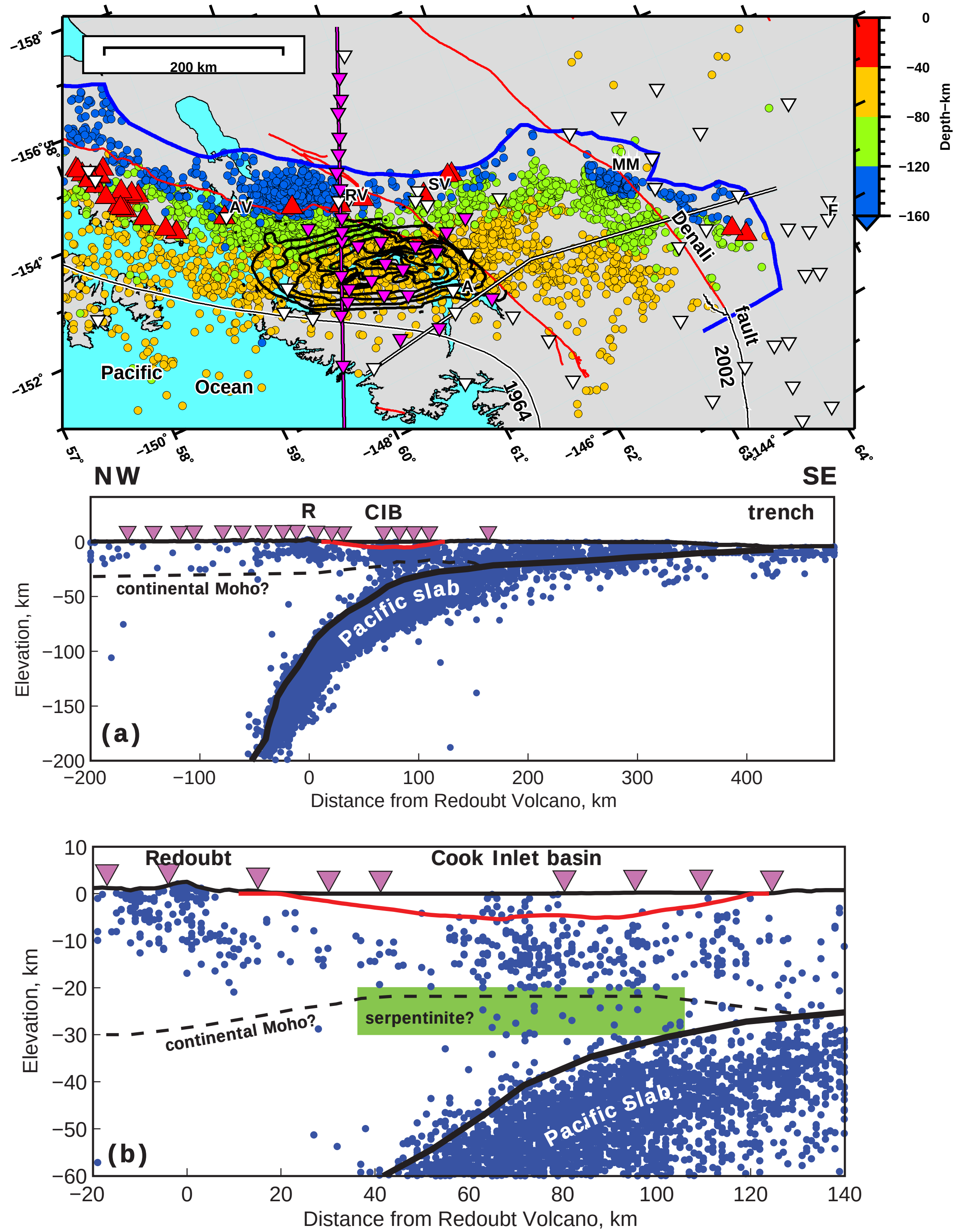

Figure 1: Proposed FlexArray seismic deployment in the Cook Inlet region, southern Alaska. **(top)** Slab seismicity (depth > 40 km, $M > 3$, 1990–2010) illuminates the subducting Pacific plate; active volcanos are plotted as red triangles. In this oblique perspective, north points to upper right. Permanent broadband seismic stations are plotted as solid inverted triangles; proposed FlexArray stations are plotted as open inverted triangles. Target subduction profile contains Redoubt volcano and Cook Inlet basin, whose basement contours are plotted in black (max depth = 7.6 km). Labels: AV = Augustine volcano, RV = Redoubt volcano, SV = Spurr volcano, MM = Mt. McKinley, A = Anchorage, F = Fairbanks. Aftershock zones for the 1964 M_w 9.2 and 2002 M_w 7.9 earthquakes are plotted. The two segments show the approximate trend of previous PASSCAL arrays (MOOS, BEAAR). **(a)** One-to-one perspective of the full profile. **(b)** One-to-one perspective of the section emphasized in this proposal. Notice the seismicity within and below Cook Inlet basin, in addition to pervasive seismicity beneath Redoubt volcano and within the Pacific slab. Proposed serpentinite body is based on gravity and magnetic modeling.

3D geodynamic and geomorphic modelling of the Alaska/Aleutian Margin – STEEP and GeoPRISMS

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Key SCD questions addressed:
(2) How does deformation across the subduction plate boundary evolve in space and time, through the seismic cycle and beyond?
(7) What are the feedbacks between surface processes and subduction zone mechanics and dynamics?

Key types of data/infrastructure: coupled three-dimensional geodynamic and geomorphic modelling, topography, seismic stratigraphy, geochronology.

Overview – The Alaska/Aleutian Margin is a premier location in which to investigate subduction related deformation and surface processes:subduction zone feedbacks. Much of what will be investigated here also has direct implications for the Cascadia and the Hikurangi margins, the two other GeoPRISMS SCD focus sites. The Continental Dynamics funded STEEP (ST Elias Erosion-tectonics Project) has already significantly influenced thinking on both deformation styles of flat-slab subduction and interactions between tectonics and erosion at this boundary (Berger et al., 2008; Koons et al., 2010). The GeoPRISMS initiative and the choice of the Alaska/Aleutian Margin as one of the focus sites give us the opportunity to build on the results of STEEP, focusing on higher resolution spatial scales and shorter temporal scales such as a glacial advance and retreat cycles.

Previous results – 3D models of the southern Alaskan orogen (Koons et al., 2010) make robust first-order predictions of style and time of deformation, and illustrate connections between an inlet orogen (the Chugach-St. Elias Mountains), an outlet orogen (Alaska Range), an obliquely convergent lateral orogen (Fairweather Ranges), and subduction basins (Cook Inlet-Copper River basin system) (Fig. 1). The models suggest all of these elements are related to the flat-slab, corner geometry of the Yakutat collision. Additionally, subduction quenching due to rapid advection of cooler material into the orogen produces a high-strength frictional sliver along the subduction interface that controls the position of the inlet orogen. Separation of the inlet and outlet orogens is enhanced by increasing the differences between their respective thermal regimes. At the mesoscale (< 50 km^2), models constrained by observations capture most of the variance in the signal of accretionary tectonics in the southern Alaska plate corner. They predict the formation of strain maxima in the tectonic corner, spatially associated with the Seward Glacier area. Inclusion of natural surface topography and erosion alter these tectonically developed strain patterns and capture the evolution of local topography, observed fault zones, and cooling age patterns. In particular, the models reveal focused uplift that perturbs the thermal structure in the tectonic corner to the east of the present high topography. This pattern of focused strain demonstrates the dominant control of the tectonic geometry on the focusing of strain and the secondary influence of topographic load and erosion.

Opportunities – 3D geodynamic modelling has the potential to bring together a variety of geological and geophysical data and interpretations into an overarching framework that can then be used to constrain ideas and make testable predictions. We identify three topics where geodynamic and coupled geomorphic modelling can address key SCD science questions.

a) *Evolution of deformation in space and time* – With increasingly high resolution data to constrain our models we can expand upon macro- and meso-scale models of the Alaska/Aleutian Margin. Possible modelling targets include the rheological characteristics of the megathrust, thermal evolution of the down going slab and overriding plate, long-term evolution (>10 Ma) of the plate boundary and developing embedded models with higher resolution geological, geophysical and topographic inputs to explore components of the system. We can also now use mesoscale atmospheric models to condition the surface boundary.

b) *Feedbacks between tectonic driven processes and surface processes* – Sophisticated models are available for both crustal and surface processes, however, a complete description of an active landscape requires coupling between them (Koons et al., 2011). At present, available coupling is rudimentary at best. Consideration of temporal and spatial variability in material erodibility is currently lacking in most surface process models. Application of strain-softening material to lithosphere-scale models of the central Southern Alps of New Zealand (Fig. 2) and Namche Barwa in the Eastern Syntaxis of the Himalayan collision illustrate the time dependent variability of material strength fields within actively deforming regions (Koons et al., 2011). Application of strain-softening materials coupled to glacially driven erosion should be a next step in geodynamic/geomorphological models of the SE Alaska margin, facilitated by our established working relationship with the Community Surface Dynamics Modelling System (CSDMS) Group.

c) *Short term vs long term strain* Identification of long period great earthquakes is problematic as on many margins the last event occurred prior to reliable historic records. Although some structures are clearly evident through transitional paleoseismic studies, the signals of many structures reside in the permanent strain fields over the past 10 kyr. As a community we must add to our tools that aid identification of characteristic geological/topographic signals in the landscape that can be used to identify locations of great earthquakes that have occurred outside the historic record. Linking kinematics of the permanent strain field to high-frequency topography using the evolving geomorphic theory of tectonic:surface coupling can provide constraints on timing and location of low-frequency, great earthquakes.

Conclusion – 3D coupled geodynamic/geomorphic modelling will be an important tool for GeoPRISMS to utilise at all three of its focus sites. Models of the Alaska/Aleutian Margin will build on the significant body of modelling work carried out by STEEP. They will focus on shorter spatial and temporal scales, constrained by the large volume of geological and geophysical data available for this margin and be guided by the evolving geomorphic theory.

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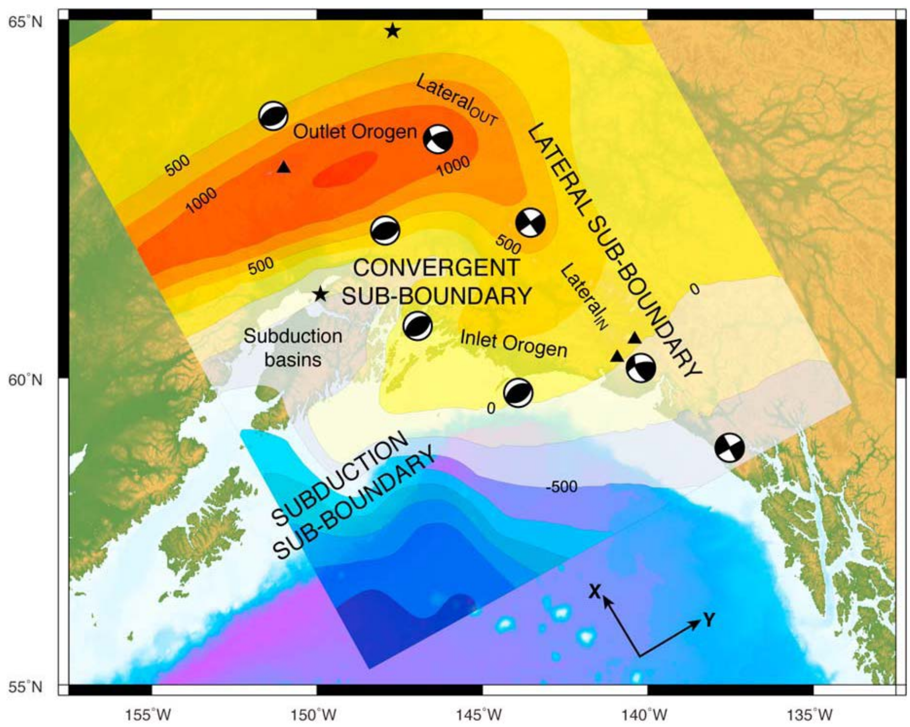

Fig. 1. Diagrammatic sketch of kinematic elements from a 3D geodyanamic model of SE Alaska (Koons et al., 2010). Contours of vertical displacement field in metres. Two orogens form, the Outlet, corresponds to the Alaska Range, and the Inlet, corresponds to the Chugach/St Elias Mountains.

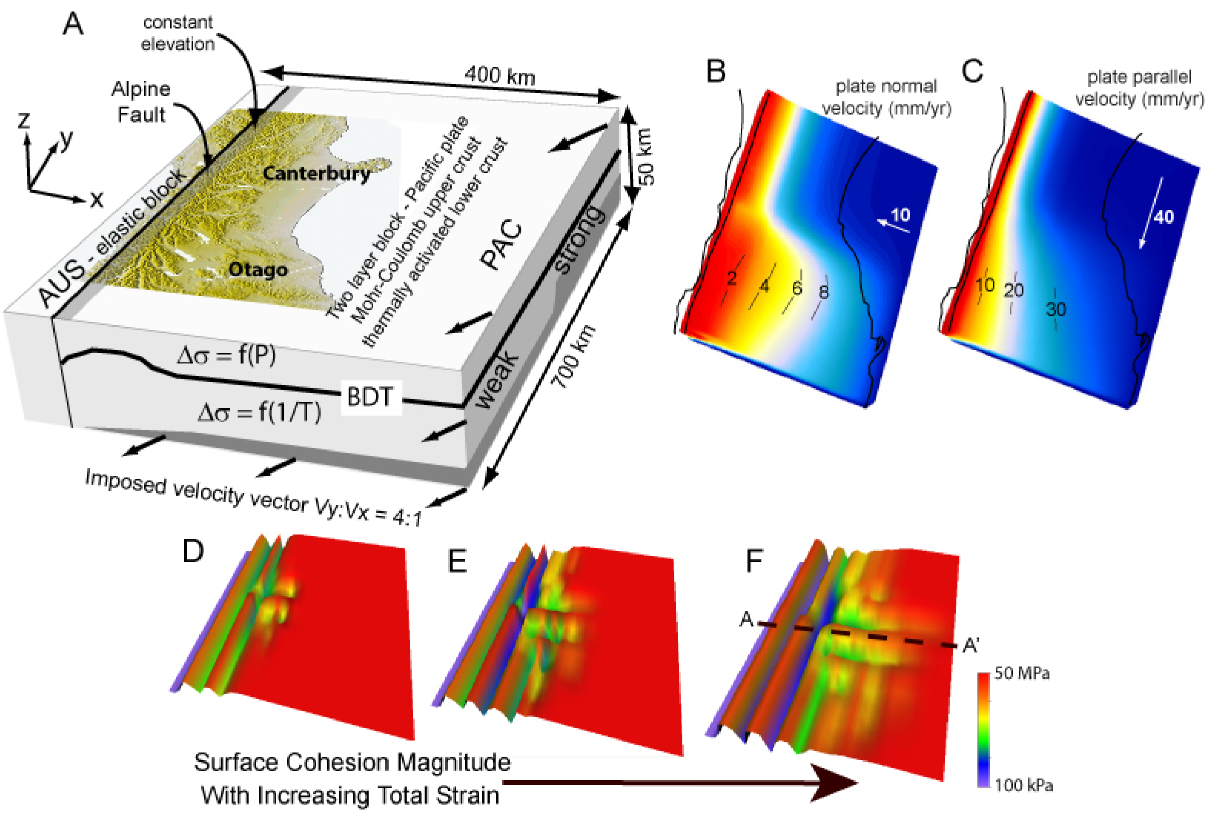

Fig. 2: From Koons et al. (2011). A: Geometry and boundary conditions of Southern Alps model after Upton et al. (2009). B & C: plate normal and perpendicular velocity for model with a time-invariant upper crust. D, E, F: Cohesion with increasing strain for model with time-variant friction and cohesion-softening upper crust (red is intact rock with ϕ=35°C=50 MPa, purple is weakened rock mass with ϕ=15° and C=100 kPa at 3% shear strain).

Toward a Synoptic View of Alaska-Aleutian Volcanic Rock Geochemistry: The Rationale for a Campaign of Isotope Data Acquisition on Existing Samples

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Introduction

The Alaska-Aleutian arc (Fig. 1) provides a prime opportunity to understand how the magmatic output of a subduction system responds to variations in the physical parameters of subduction. The region though, is immense and remote, and so presents a daunting challenge to investigators whose aim is to develop a synoptic view of the system as an approach to moving forward on key scientific issues. For those of us in petrology-geochemistry-volcanology, it is therefore fortunate that so much fieldwork has already been done, and that so many high-quality geochemical analyses have already been acquired. The point of this white paper is therefore to summarize the existing data sets that are relevant to the use of volcanic rock geochemistry to understand subduction systems, and to highlight some recent work as one approach to moving forward by first by taking advantage of work that has already been done.

Existing Sample Collections and Data

Large collections of Quaternary-age Aleutian lavas exist at several universities (e.g., Columbia, Cornell, Johns Hopkins, Wisconsin, Wyoming). Geochemical data from more than 2000 samples from these sources have been published and/or compiled and made available through review studies (Kelemen et al., 2003) and online databases. These data were generated over decades in many different laboratories and by diverse methods. A much larger, more geographically extensive sample set and more complete geochemical database is held by the Alaska Volcano Observatory (AVO). This database includes approximately 3600 fully modern XRF and ICPMS whole-rock analyses from a single laboratory (Washington State University). The largest part of this collection is from volcanoes along the Alaska Peninsula and in southern Alaska. This is important because it means that the AVO collection and related data are largely complementary to the above-mentioned university collections, which are primarily from the Aleutians.

In addition to the 5000+ samples mentioned above, which were collected entirely from on-land sites, there is now a complimentary sample set, which has been collected by dredging of seafloor volcanoes in the Aleutians. These samples were collected beginning in the late 1980's by the Russian *R/V Vulkanolog* (Yogodzinski et al., 1994), and more recently during the 2005 Western Aleutian Volcano Expedition on the *R/V Thompson* (White et al., 2007; Wyatt et al., 2007; Yogodzinski et al., 2007) and during two cruises of the German *R/V Sonne* as part of the German-Russian KALMAR project (http://kalmar.ifm-geomar.de). Most of the mapping and related dredging on these cruises has been focused in the western Aleutians, from Buldir to Piip Seamount, but seafloor volcanoes located throughout much of the Aleutian system, from Buldir to Unalaska, have now also been sampled (Fig 1).

Despite the widespread availability of samples and decades of study, there are still relatively few places where fully complete and modern geochemical data sets are available. The main shortfall is in the area of isotopic data. In the Aleutian part of the system, the availability of isotopic data is relatively good. For example, a database of 2000 samples includes approximately 260 Pb, Sr and Nd isotope measurements, published over many years, from widely scattered locations along the arc. These data, combined with unpublished data from active studies of mostly seafloor lavas, provide a clear view of systematic changes in the geochemistry of Aleutian lavas over the full length of the arc (Fig. 2). Further east, for volcanoes along the Alaska Peninsula and in southern Alaska, the availability of isotopic data is poor and insufficient to provide anything beyond the most basic conclusions about geochemical variability in the continental part of the Alaska-Aleutian system. In addition, data for the Lu-Hf isotopic systems and modern measurements of oxygen isotopes on mineral separates are only available in small numbers from very few places anywhere in the Alaska-Aleutian system.

More Isotopes

With the samples and data described above, it is easy to imagine a campaign of isotope data acquisition designed to test ideas about the geochemical products of subduction, and their relationship to the creation of continental crust. In particular, new isotopic data for volcanoes on the Alaska Peninsula and in southern Alaska will provide a basis for detailed comparison between the continental and oceanic parts of the Alaska-Aleutian arc. It is interesting that despite broad differences in crustal thickness of the over-riding plate and parameters such as arc-trench gap (width of the outer arc), existing data suggest that there are not large-scale isotopic differences between the oceanic and continental parts of the system (George et al., 2004). It is very likely though, that acquisition of a large quantity of high-quality isotopic data over the whole Alaska part of the arc (for Pb, Sr, Nd and Hf), combined with existing major and trace element data, will reveal systematic differences from the Aleutian part of the arc that will be interpretable in the context of key questions about subduction magma genesis.

For example, the presence of abundant seamounts in the Gulf of Alaska and in front of the Alaska portion of the arc (Fig. 3) provides a basis for hypothesizing that certain aspects of OIB geochemistry might be transferred to arc magmas in southern Alaska but not in the Aleutians. An approach to identifying a subducted OIB end-member could be based on recent results from dredging and geochemical studies, which have highlighted the presence of a high-Sr geochemical source end-member in seafloor volcanoes in the western Aleutians. This end-member has some characteristics of a MORB fluid (Class et al., 2000; Miller et al., 1994), and although the details of its origin remain uncertain, it seems clear that its source must be predominantly in subducted basalt (Fig. 4). This is important, because it provides a basis for quantifying the role of subducted basalt in controlling the geochemistry of arc lavas from other parts of the Aleutians and other arc systems worldwide. If subducted seamounts are contributing to the source of arc magmas in southern Alaska, we might expect the geochemical character of OIB to be expressed in the form of a high-Sr end-member with elevated $^{206}Pb/^{204}Pb$ (Keller et al., 1997) and possibly low ε_{Hf} relative to ε_{Nd} (Yogodzinski et al., 2010). This is one way that by developing a synoptic view of Alaska-Aleutian volcanic rock geochemistry, we can provide an improved basis on which mass flux through subduction systems may be quantified and related to the genesis of continental crust.

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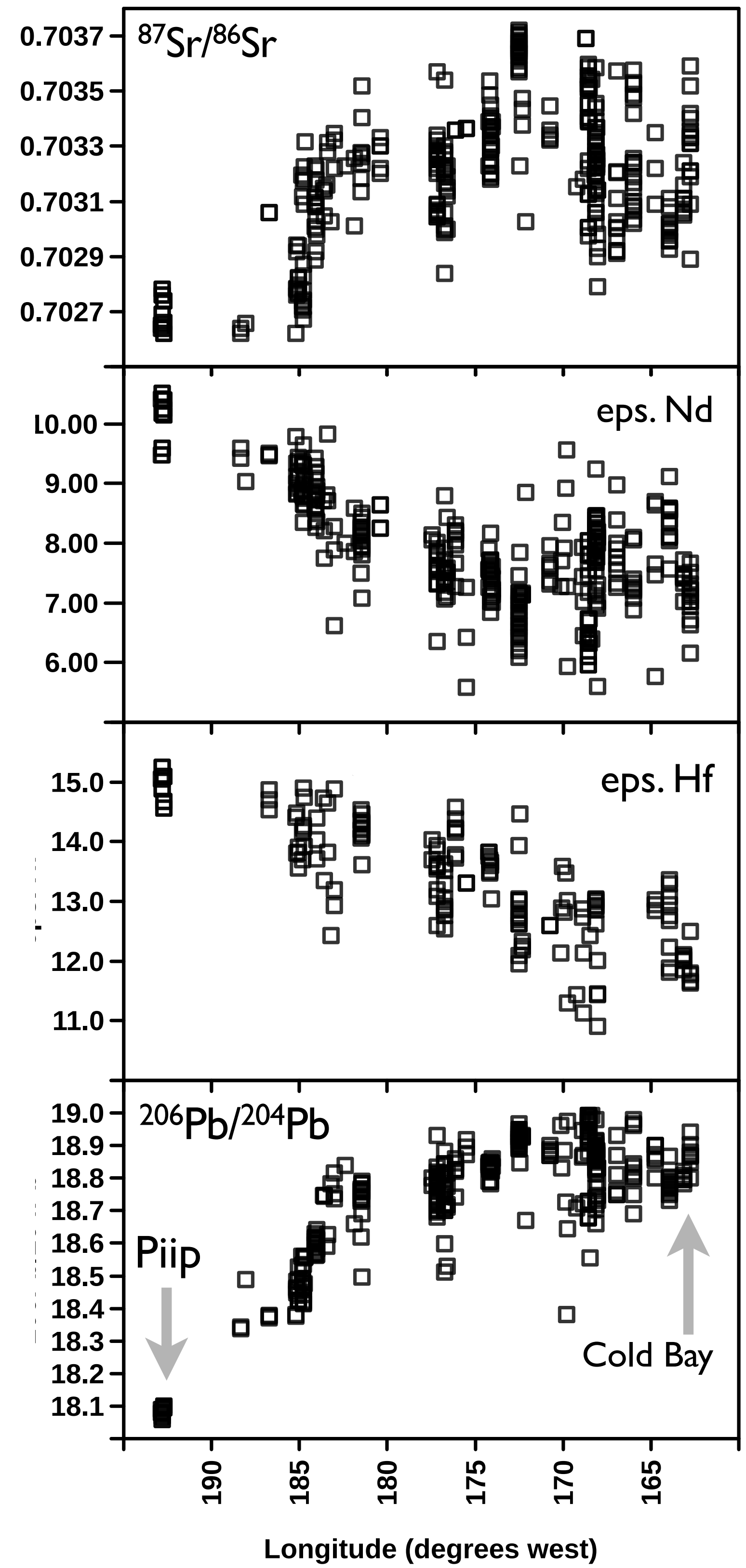


Fig. 2 Along-arc isotopic variability for Quaternary Aleutian lavas.

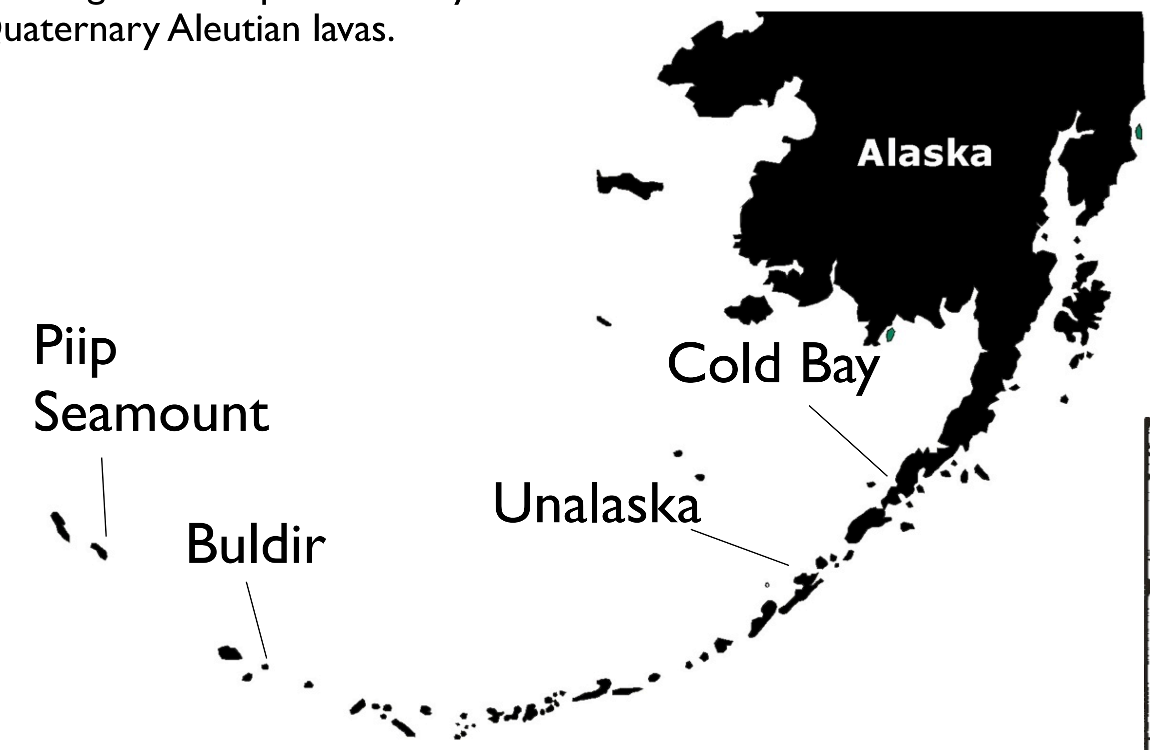


Fig. 1 Map of Alaska-Aleutian subduction system

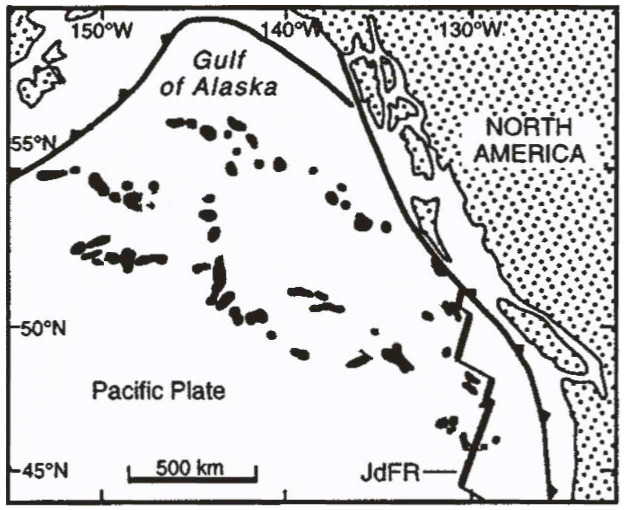
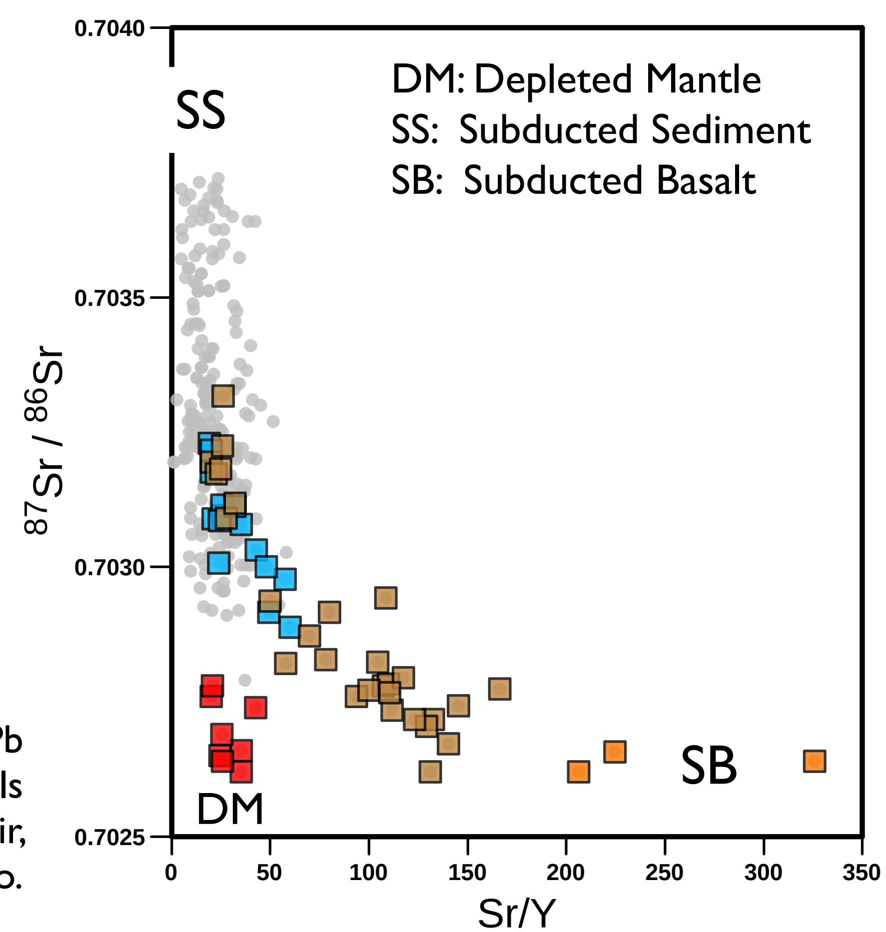


Fig. 4 Map of northeast Pacific seamounts and Gulf of Alaska, from Keller et al., (1997)



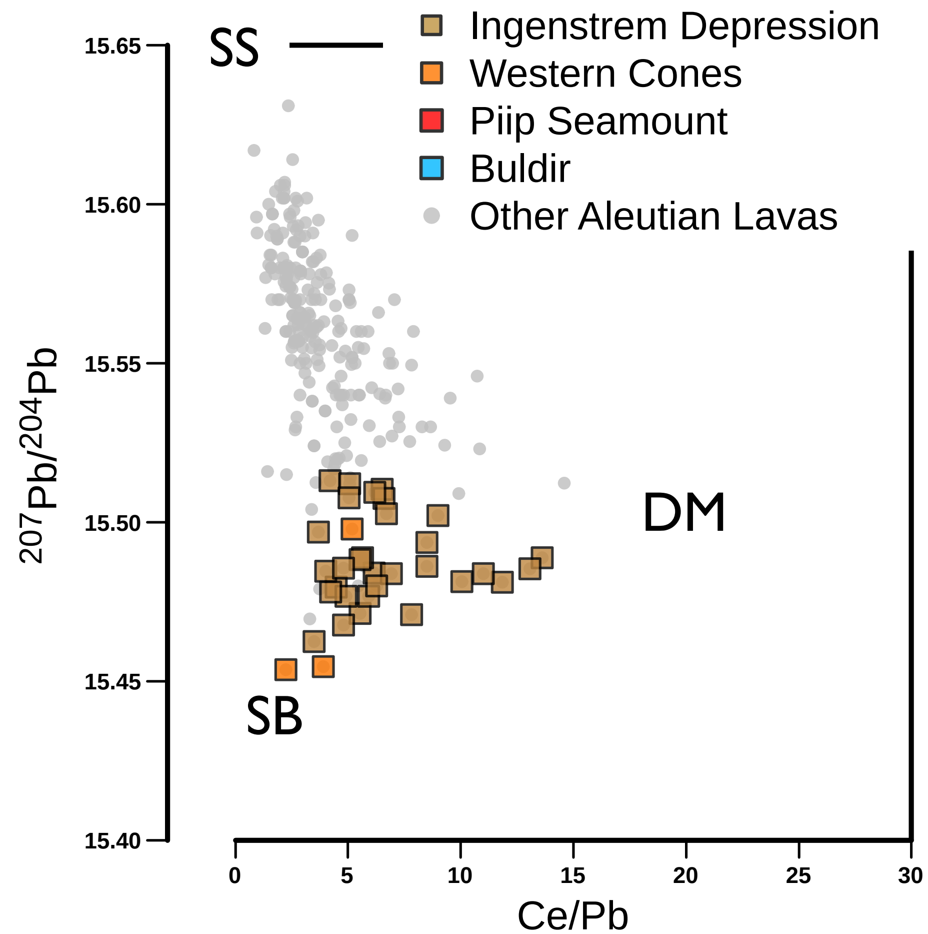


Fig. 4 Sr isotopes vs Sr/Y and Pb isotopes vs Ce/Pb adopted from Miller et al., (1994). Colored symbols are lavas from western Aleutian seamounts and Buldir, the westernmost emergent volcano.