2.2. Alaska/Aleutian Margin – Primary Site

(Replaced March 24, 2012)

2.2.1. Background and Motivation: Relationships to SCD questions

The Aleutian-Alaska subduction zone (AASZ) and associated volcanic arcs define the most tectonically active region in North America (Figure 2.1). It is an ideal location to study arc magmatism, structure and the contributions of arc volcanism to the development of continental crust. The AASZ is also ideal for study of earthquake processes and the seismic cycle. The margin is seismically active at a range of temporal and spatial scales, with segments in various stages of the earthquake cycle and showing different modes of slip. Examples include megathrust events (e.g., M_W 9.2 1964 Prince William Sound earthquake), freely slipping zones (e.g., Shumagin Gap), and apparently locked sections (Figure 2.2). Important factors potentially controlling both seismogenesis and volcanism vary systematically along strike and properties of both the seismogenic zone (Figure 2.2) and arc volcanism (Figure 2.3) vary as well, so that along-arc studies and/or comparisons of different segments of the arc have the potential to reveal the causes for the observed variations in behavior.

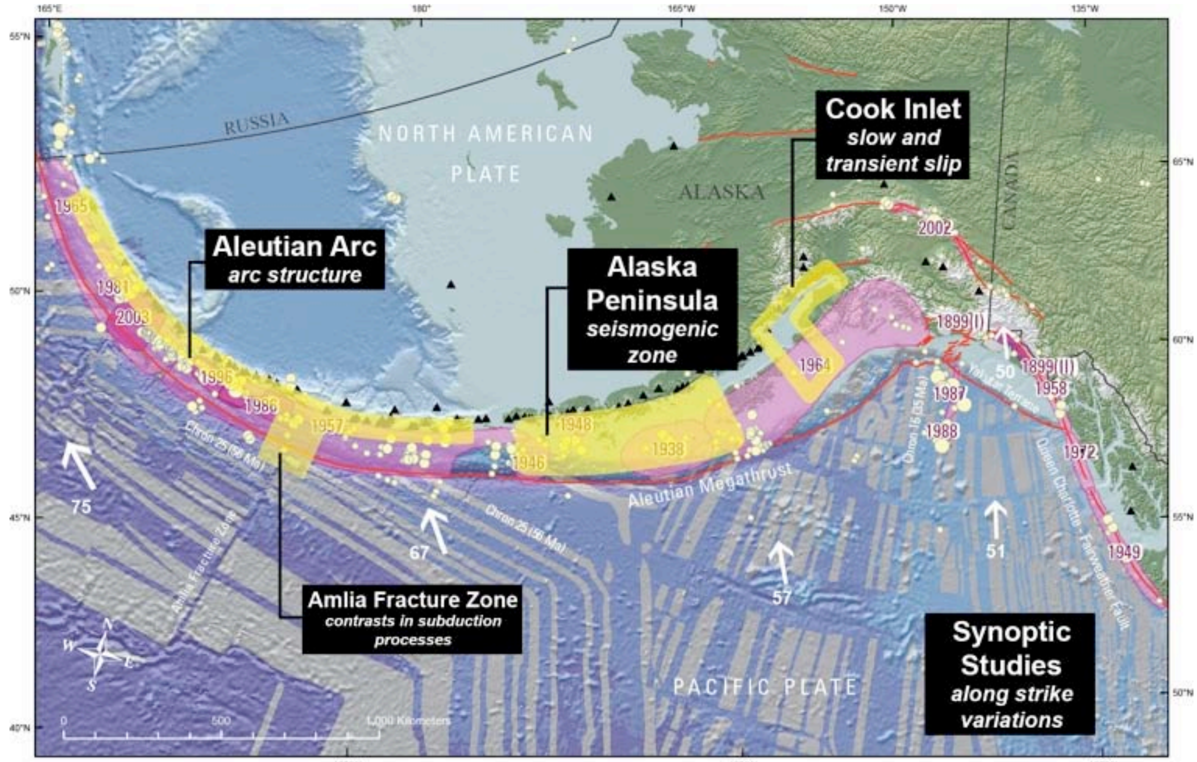


Figure 2.1. Tectonics of Alaska and proposed Geographic Focus Areas. The three regions shown in yellow are the Aleutian Island Arc, the Alaskan Peninsula, and Cook Inlet. Subduction along the Alaska-Aleutian subduction zone (AASZ) transitions into strike-slip motion along the Queen Charlotte-Fairweather fault. Holocene volcanoes (black triangles) extend along the entire subduction plate boundary. Red lines are major active faults. Significant earthquakes (white circles, scaled to size) since 1980 and large to great megathrust earthquake aftershock areas (pink) are shown and marked by year. White arrows indicate the Pacific-North America (using HS3-Nuvel1A model) and Yakutat Terrane-North America relative motions (Elliott et al., 2010.); associated numbers indicate relative velocities in mm/yr. Magnetic anomalies of the incoming Pacific plate from the map of Atwater and Severinghaus (1989).

2.2.1.1. Background and Science Questions

Subduction has been active beneath the Alaskan margin since Triassic time, but the Aleutian arc formed relatively recently, ~50 Myr ago. It exhibits no backarc extension and the lack of intra-arc rifting enables the time-integrated magma flux and the bulk composition of the arc to be measured directly by seismic methods. The age of the subducting oceanic lithosphere changes moderately along the arc, but obliquity and associated rates of subduction, crustal thickness in the hanging wall, sediment flux to the trench, forearc, and arc, width of the accretionary complex (arc-trench gap), the composition of volcanic rocks, and occurrence of subducting topography, all change markedly along the arc.

The characteristics of the volcanic arc change systematically along strike. Although eastern Aleutian arc lavas are tholeiitic on average, western Aleutian volcanic rocks – and intermediate to felsic plutons throughout the oceanic arc – are the most compositionally similar to bulk continental crust of any intra-oceanic arc. However, western Aleutian volcanic rocks also have the smallest contribution of recycled components derived from subducting continental sediments (Figure 2.3); they represent the isotopically depleted end-member for arc lavas worldwide. This provides an unmatched opportunity to address how continental crust is created from volcanic arcs, enabling a definitive hypothesis test of the "andesite paradox."

The general along-arc (east to west) decrease in the size of Aleutian volcanoes suggests that volcanic production rates are linked to trench-normal subduction rates, resulting in large and predominantly basaltic volcanoes in the eastern Aleutians, shifting to smaller and more calc-alkaline volcanoes with greater abundances of andesite and dacite in the west. A slightly different pattern is seen along the continental part of the arc, where smaller calc-alkaline systems are found at a variety of locations, but the large basaltic systems are confined to the eastern part of the oceanic arc and the western part of the continental arc. Along-arc changes in isotopic compositions of Aleutian lavas indicate that significant recycling of sediment/continental materials occurs in the eastern part of the arc, but not in the west. Where large fracture zones are being subducted (Amlia Fracture Zone), the compositions of basalt may reflect an increased role of serpentine dehydration into the mantle wedge, further linking subduction inputs and arc processes.

Megathrust slip behavior may be influenced by sediment influx or by changes in other subduction parameters, such as plate age, convergence rate, slab dip, and obliquity. The largest known megathrust event in the AASZ, the 1964 M_W 9.2 Prince William Sound earthquake, occurred in 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. This part of the subduction zone also features the shallowest slab dip within the seismogenic zone. However, the second and third largest historic events (M_W 8.7 1965 Rat Islands and M_W 8.6 1957 Central Aleutians) occurred in the oceanic part of the arc. Great earthquakes ($M_W > 8.0$) occur every 13-14 years on average, and have been observed or inferred on almost all segments of the AASZ. In the east, along the Alaska Peninsula, convergence is nearly orthogonal to the trench with a rate of ~6 cm/year. Moving to the west, subduction becomes increasingly oblique, reaching nearly 90º, and a slightly faster convergence rate of 7 cm/year. The dip angle of the slab at depths < 50 km varies significantly along strike, as does the dip angle and length of the deep slab. Other evidence suggests that geometric features within the subduction zone (e.g., fracture zones, upper plate segmentation, etc.) strongly influence the rupture areas of great earthquakes, although dramatic along-strike changes in seismogenic properties have been observed that have not yet been correlated with such features. Significant along-strike changes make the AASZ an ideal laboratory for studying what controls the slip behavior and segmentation of the seismogenic zone.

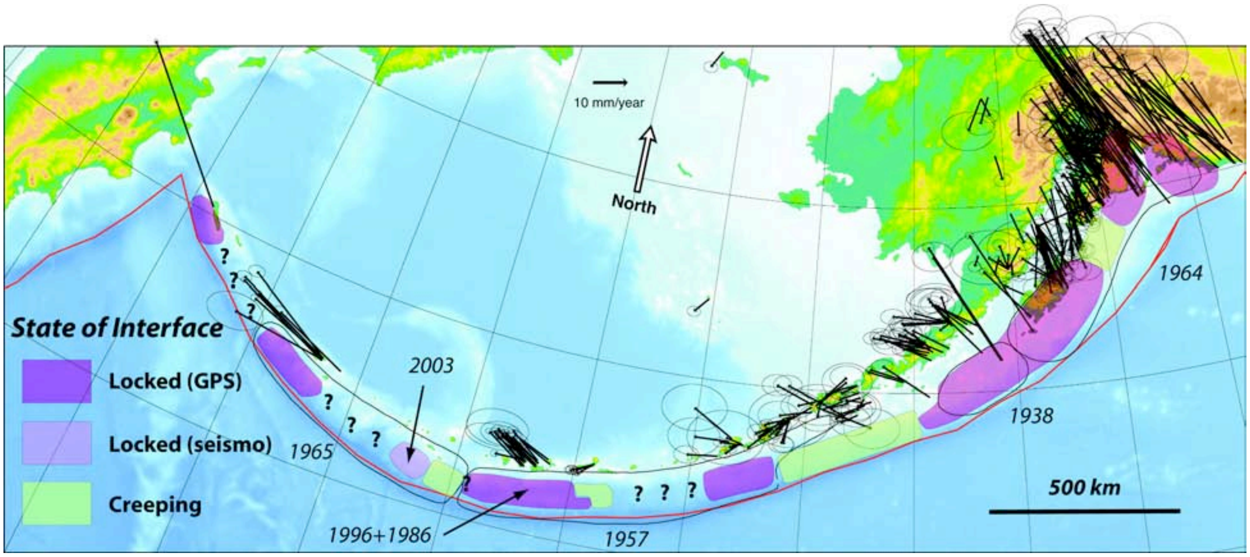


Figure 2.2. Plate coupling variations along the arc. Colored regions indicated the state of the plate interface, with dark areas indicating locked regions (significant slip deficit). Darker shading indicates the locked region is based on GPS data, while lighter shading indicates an assessment based on seismic ruptures alone. Regions shaded in yellow are inferred to creep, while areas shown with question marks do not have enough data to determine the state of the plate interface.

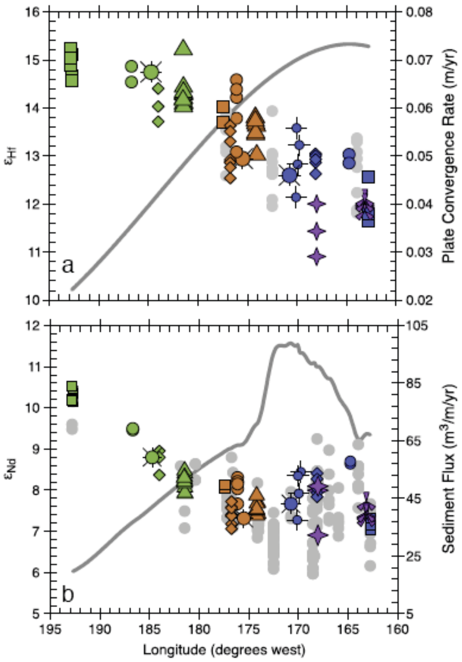


Figure 2.3. Along-arc changes in Aleutian lavas for Hf and Nd isotopes plotted with convergence rate and sediment flux. The eastern end of the graph is located at the western tip of the Alaska Peninsula. The western end is in the far western Aleutian Komandorsky area (see also Figure 2.1). Along-arc changes are inferred to reflect decreasing rates of sediment subduction from east-to-west along the arc. From Yogodzinski et al. (2010 – Figure 3).

The GeoPRISMS community, through a series of planning workshops, identified the AASZ as the highest priority setting in which all of the SCD science topics can be addressed. Research targets for these topics may include:

- *Along-strike variations in earthquake cycle style and magnitude:* Overall contrast in earthquake cycle (i.e., creeping, locked) and earthquake magnitudes from east to west related to changes in upper plate composition (continental – oceanic), changes in obliquity of convergence (normal – extremely oblique), incoming plate features (sediment thickness and composition, seamounts, ridges, etc).

- *Spectrum of fault behavior:* Determine the relation of tremor and slow-slip with the seismogenic zone and within the earthquake cycles, and evaluate changes in locking depth through time. Study along-strike variations in the seismogenic zone, and the causes for the abrupt along-strike changes between dominantly locked and dominantly creeping segments.

- *History of multiple earthquake cycles:* Determine the paleoseismic history along the subduction zone to evaluate their relationship to historical ruptures and to other kinds of fault slip, such as areas of slow slip.

- *Relationship between long-term deformation and earthquake cycle:* Establish how upper plate and accretionary prism structures (thrust sheets; forearc basins and highs; marine terraces) behave during the seismic cycle and their influence on rupture behavior and the overall strain budget.

- *Storage, transfer & release of volatiles, melts & fluids:* Establish how along-strike variability in sediment thickness, crustal age, hydration, and deformation of subducting slab relate to magmatic end-members (mafic vs. intermediate/felsic) and magma flux/activity.

- *Geochemical products of subduction and creation of continental crust:* Use along-arc geophysical surveys and associated geochemical analyses to determine crustal structure and composition, fractionation processes in oceanic portion of subduction zone

- *Shallow/crustal controls on volcanism:* Document how a volcano is constructed through intensive geophysical and geological mapping at a few key volcanoes.

- *Mass fluxes (sediment, ice) and the control on evolution and architecture of the subduction margin and effects on subduction dynamics:* Investigate the role that differences in sediment character along-strike have in megathrust behavior (e.g. Surveyor and Zodiac fans and sediment-starved western Aleutians) and geochemical fluxes and volcanism (e.g. roles of clay, opal). Explore the response of the geometry and seismicity of the forearc wedge responded as the sediment mass balance and ice cover fluctuated throughout the Plio-Pleistocene.

- *Subduction initiation beneath the Alaska Peninsula and the Aleutian Arc*: Determine timing of subduction zone initiation and relationship to Pacific-wide tectonic processes versus more local tectonic processes.

GeoPRISMS studies in the AASZ have high societal relevance, primarily due to the impact of earthquakes, tsunamis and volcanic eruptions. The largest U.S. subduction earthquake on record, the M_W 9.2 1964 Prince William Sound event, ruptured the eastern portion of the subduction megathrust, an area that continues to pose significant seismic hazard for the growing populations in Anchorage and along the Kenai Peninsula. Subduction zone earthquakes are highly tsunamigenic, and large events along the AASZ pose a grave risk to the entire Pacific basin, in particular to Hawaii and the US west coast. Moreover, the Aleutian arc is among the most active volcanic regions on the planet, with the potential to disrupt a critical air transport pathway between Asia, North America, and Europe. This is not a hypothetical hazard: for example, in 1989 a KLM passenger jet was forced to make an emergency landing in Anchorage after volcanic ash disabled all four engines. In addition to earthquake and volcanic hazards, the oceanic Aleutian arc is the site of massive undersea landslides, some with extents of more than ~400 km^2, with km-sized individual blocks. The largest of these slides were certainly tsunamigenic. In addition to delineating seafloor landslide debris, an important focus of future studies will be to identify and quantify the hazard utilizing tsunami deposits that likely ring the Bering Sea and Gulf of Alaska. The high potential impact of AASZ geohazards opens the door for educational and outreach opportunities, both nationally and locally.

Logistically, the AASZ can be a challenging environment to work because of its large size, severe climate, and small, dispersed population centers. However, several key features allow GeoPRISMS to move forward in this region. There has been substantial on-land mapping and sample collection that can be analyzed for geochemistry and geochronology. There are legacy and recent marine surveys (e.g., seismic, bathymetry, dredging) that can help identify geographic areas for study. Scientific oceanic drilling, both past and future, provides coarse constraints on subduction inputs. There are numerous potential statewide, national, and international partners, providing an opportunity for leveraging of resources. These include the Alaska Volcano Observatory (AVO), a joint program of the United States Geological Survey (USGS), the Geophysical Institute of the University of Alaska Fairbanks (UAFGI), and the State of Alaska Division of Geological and Geophysical Surveys (ADGGS), and the Alaska Earthquake Information Center (AEIC). Other programs within the USGS are potential partners. International partners active in the westernmost Aleutians include Japan, Russia, and Germany, and Canada is actively exploring the consequences of subduction in the easternmost part of the region. EarthScope is currently active in the region through the 139 Plate Boundary Observatory (PBO) continuous GPS stations that have been operating in Alaska since 2008, and the USArray Transportable Array will be deployed across Alaska beginning in 2014 onward. Redeployment of the Amphibious Array (OBS, GPS) is possible after conclusion of its initial program in Cascadia. Although, there are logistical challenges for new research, workshop participants highlighted that these can be overcome through proper planning, communication, coordination, and cooperation among government agencies and academic scientists, and community efforts and experiments can maximize science returns.

2.2.1.2. Geographic Focus Areas

The community has identified key geographic regions within the AASZ in which individual SCD questions can best be addressed (Figure 2.1); this leads naturally to particular kinds of research studies being focused on these key regions. The community concluded that a strict focus on a few small focus sites would miss the key opportunities afforded by the along-strike variability of the AASZ. Instead, the community supported an approach in which three broader geographic regions were chosen, with each having a focused science questions and a limited scope of investigations. Detailed plans for proposed investigations should identify opportunities for synergy across the entire SCD program. In addition, the community concluded that some questions are best addressed through synoptic-scale studies that compare processes along the entire subduction zone. These are studies that ought to be carried out wherever possible to capture the along-strike variations in inputs or outputs of the subduction system, although they do not necessarily require new data collection. To avoid repetition, topics best suited for synoptic studies are combined together in a separate section. The next sections of this plan are organized geographically, and highlight the scientific rationale and possible studies in each region in turn, followed by the synoptic studies. Timing, staging and partnership opportunities are described in later sections.

In the following sections, bulleted lists indicate the primary SCD key topics that can be addressed in each region, with those in ***bold*** being the main priorities for that region.

2.2.2. Aleutian Island Arc

SCD Key Topics

- ***Geochemical products of subduction and creation of continental crust***
- ***Subduction zone initiation and arc system formation***
- *Storage, transfer, and release of volatiles through subduction systems*
- *Controls on size, frequency and slip behavior of subduction plate boundaries*

The primary GeoPRISMS focus in the Aleutians is on the structure, history and composition of the arc crust through the study of Miocene-and-older volcanic and plutonic rocks, combined with geophysical imaging of the arc lithosphere. Studies of lavas from the modern volcanoes are important for the storage, transfer, and release of volatiles through subduction systems, and will be discussed in the section on synoptic studies. Study of along-strike segmentation of the seismogenic zone across the Amlia fracture zone would address important questions in that key topic, and would be complementary to geophysical studies of the arc crust and structure.

Crustal genesis is a central theme for GeoPRISMS research in the oceanic part of the Alaska-Aleutian subduction system. This theme unites several SCD key topics, especially those related to subduction zone initiation and the geochemical products of subduction and their role in the creation of continental crust. Seismic and geochemical observations indicate that the composition of continental crust is similar in most respects to subduction-related andesite. These observations present a significant challenge to our understanding of crustal genesis, because mantle-derived magmas in subduction zones are generally interpreted to be basaltic – not andesitic. The central question then becomes, how can the genesis of continental crust that is andesitic be understood in the context of magmatism in island arcs that is largely basaltic? A particular advantage for crustal genesis studies in the Aleutians stems from the fact that the arc was never rifted, so the products of ~50 million years of subduction-related crustal growth are intact and available for study. The physical character of Aleutian crust, which may be inferred from its seismic properties, is therefore the product of magmatic and tectonic processes over the lifetime of the arc, combined with the oceanic foundation upon which the arc was constructed.

The mid-crust of some arcs is seismically slow, and has been inferred to be tonalitic and therefore to have a composition consistent with that of primitive continental crust (Figure 2.4). Calc-alkaline plutons (those with Mg#>0.50 at intermediate SiO_2 contents) are particularly important because they are relatively felsic (Figure 2.5) and therefore buoyant and because they are emplaced as massive bodies at depth, and so are more likely to be preserved during collision and amalgamation of larger crustal masses than are volcanic rocks of similar age. The Aleutians are likely the best active island arc on earth for investigating the relationships between the plutonic rocks of the arc (magmas that did not erupt) and their coeval volcanic rocks (magmas that did erupt). Volcanic and plutonic masses produced in the early and intermediate stages of Aleutian arc growth, which are accessible on islands and by dredging of the seafloor, provide key opportunities to quantify magmatic production rates, and to investigate the timing and nature of subduction initiation in the Aleutians. A better understanding of pluton genesis, in particular a better understanding of the high-SiO_2 end-members in Aleutian plutons, is also key to understanding the nature and evolution of the deep crust, which can be observed geophysically, but is difficult to sample for geochemical studies.

Volcanoes of the western-most Aleutians produce lavas that have major and trace element characteristics of continental crust, even though their isotopic compositions indicate that they contain virtually no recycled continental material. This means that the western Aleutians (Adak area and west) provide an opportunity to investigate the idea that andesitic crust, with major and trace element characteristics of continental crust, may be produced largely out of mantle and subducted oceanic lithosphere, with only a minor role for recycled continental material. If large blocks of western Aleutian crust were produced by primitive andesitic magmatism, they will be readily distinguished from the seismically fast and apparently mafic compositions that dominate crust that underlies the eastern parts of the arc (Figure 2.4a). Anticipated high water contents of primitive andesitic magmas indicate that subduction-related volatile cycling and pre-eruptive volatile contents of arc magmas may also be important in models for arc crust formation.

The oceanic arc displays along-strike variations in the behavior of the seismogenic zone, and the intersection with the Amlia Fracture Zone (AFZ) is of particular interest. There is an abrupt change in the pattern of seismicity at the intersection of the arc and the AFZ, and the 1986 Andreanof Islands earthquake terminated at or near there. GPS data and modeling suggest that this represents a transition from a locked region to the west and a freely slipping region to the east. Although the 1957 earthquake ruptured across this segment, a lack of aftershocks in the zone immediately east of the AFZ suggest that the rupture may have jumped the segment with little strain release. 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, slab dip, mantle wedge, and upper-plate structure/properties between the segments of the margin that display varying seismogenic behavior. Terrigenous sediment input to the trench stops at the AFZ due to a bathymetric barrier to westward sediment flow (Figure 2.3b). 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.

2.2.2.2. Existing Datasets and Studies in the Area and Data Gaps

Geophysical constraints on the crustal structure of the Aleutian arc come primarily from an onshore/offshore seismic reflection/refraction study in 1994 that acquired an along-arc profile and two cross-arc profiles. The along-arc profile covered the eastern part of the oceanic arc from Atka Island to the oceanic-continental transition at Unimak Island. The refraction dataset is sparse, with only 15 instruments deployed onshore and offshore along this 800-km-long section of the arc. No geophysical data are currently available on arc crustal structure west of Atka Island. Bathymetric data for most of the oceanic arc is limited to 1980s GLORIA data. Seismic and geodetic data comes mainly from dense networks on currently active volcanoes, augmented by stations in the villages and logistical hubs (Dutch Harbor, Nikolski, Atka, Adak, Amchitka, and Attu).

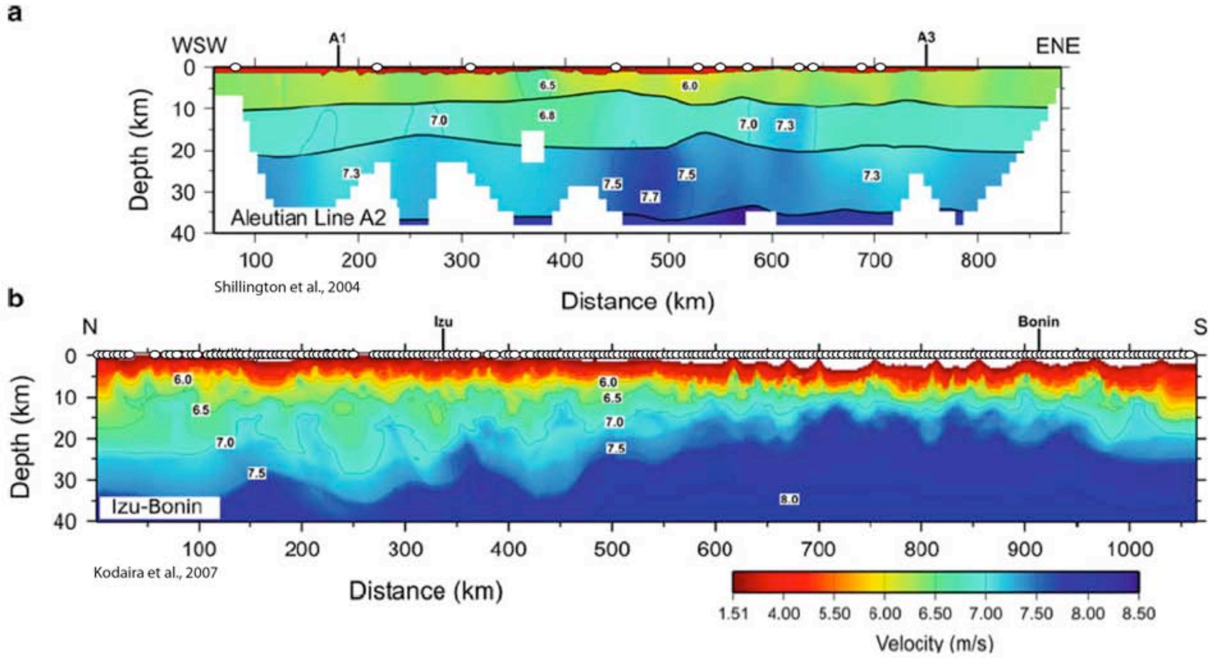


Figure 2.4 Comparison of crustal P-wave velocity structure along (a) the central Aleutian island arc (Shillington et al., 2004) and (b) the IBM arc (Kodaira et al., 2007) from wide-angle seismic reflection/refraction data (figure modified from Calvert et al., 2011). White dots indicate approximate locations of seismometers along each line. Note the sparse spacing of instruments along the Aleutians compared with recent datasets along the IBM (spaced at ~5 km). Dense data in IBM reveal changes in crustal thickness and velocity structure that can be correlated with volcanoes at the surface. Minimal data in the Aleutians hint at possible along-strike changes in velocity structure, but are too sparse to constrain variations at ~20-50 km scale.

Studies based on the existing profiles (Figure 2.4a) showed that the crust in the oceanic arc crust near Seguam island is 30 km thick, with relatively high P-wave velocities in the middle to lower crust (~6.9-7.2 km/s), indicating an average basaltic composition. Importantly, these data do not provide evidence for significant volumes of andesitic material observed in other island arcs (e.g., the Izu-Bonin arc). A ~7-km-thick layer in the middle crust with velocities of 6.8 km/s is interpreted as the Kula plate, upon which the arc was built. The transition from oceanic to continental arc has a more complicated structure, interpreted to arise from deformation of the Kula plate. P-wave velocities of 7+ km/s in the fore-arc lower crust/upper mantle are interpreted to represent serpentinization of the mantle wedge. The along-arc profile displays a relatively thick (32-35 km) and mafic crust from the vicinity of Atka Island in the west to Unimak Pass in the east. Although the dataset is sparse, significant along-strike variations in velocity structure are observed, particularly in the lower crust, and hint at a correlation with along-strike variations in the composition of volcanism at the surface. But these data are far too sparse to determine if along-strike changes in crustal velocity structure and thickness comparable to those observed in the IBM arc are present (Figure 2.4). Recent reprocessing of seismic reflection data along the arc also reveals considerable variability in the reflective structure of the deep crust.

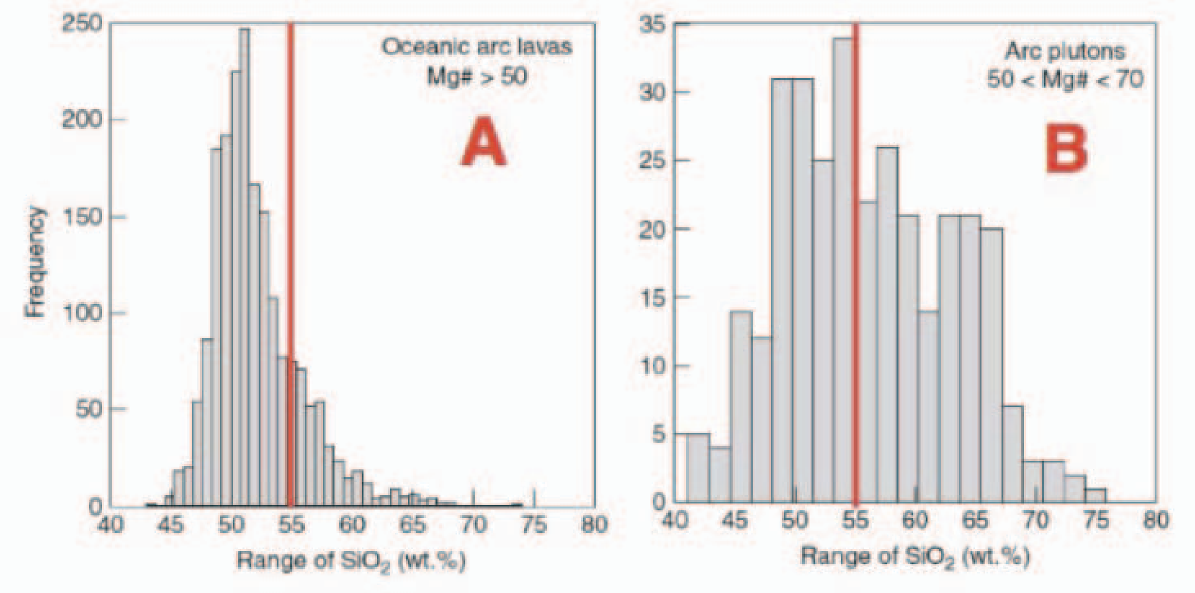


Figure 2.5 Comparison of whole-rock compositions showing systematically higher SiO_2 contents for arc plutons compared to island arc lavas. Data from arc lavas are compiled from locations worldwide. Arc plutons data are mainly from the Aleutians, Talkeetna, Kohistan, Ladakh, Mt. Stuart, Peninsular Ranges and Tanzawa. Compilation and figure from Kelemen et al., Treatise on Geochemistry (2003 – Figure 5).

Geochemical studies of the modern volcanoes provide a starting point for constraining the nature of Aleutian crustal genesis. What is missing is a thorough characterization and understanding of the Miocene-and-older parts of the arc – both volcanic and plutonic – which are critical to establishing a chronology of crustal growth and evolution, and which provide the basis for calculation of rates and for understanding key topics such as subduction initiation and lower crust formation and evolution. Subsequent to reconnaissance work by the USGS in the years following World War II, geochemical and geochronological studies of Miocene-and-older rocks in the Aleutians have focused primarily on a few easily accessible islands, especially Adak, Unalaska, Amlia and Attu. In general, the Miocene-and-older volcanic and plutonic rocks are geochemically similar to the Quaternary lavas, although many appear to be somewhat less enriched in the most incompatible elements (higher Ba, Th, U relative to La). The highly depleted and primitive boninites and island arc tholeiites that are observed in the early histories of some western Pacific arcs have not been observed among Miocene-and-older Aleutian lavas collected either on land or among the small number of submarine samples – are such rocks a characteristic feature of the earliest phases of arc magmatism? Isotopic data on Miocene-and-older volcanic and plutonic rocks are only sparsely available and whole-rock trace element measurements by modern ICPMS methods are nearly non-existent. Available data indicate that the average Aleutian plutonic rock from the eastern part of the arc (Adak area and east) is granodioritic, with 60-66% SiO2 and 1-3% K2O. This is significantly more felsic and more potassic than the average of Quaternary lavas from the same part of the arc (average SiO2 <54%, K2O<1%). These differences in major element abundances mean that Aleutian plutons may have geophysical characteristics that more closely resemble continental crust than those of the average volcanic rock.

2.2.2.3. Potential GeoPRISMS Studies

New constraints from along-strike geophysical imaging of the Aleutian lithosphere combined with geochronological and geochemical studies of Miocene-and-older volcanic and plutonic rocks are needed to better understand the role of island arcs in the formation of continental crust. Geochemical and geochronological studies of this type also provide an opportunity to determine the timing and nature of subduction initiation in the Aleutians, and its relation to subduction initiation in other Pacific island arcs. Focused studies in each of the western and eastern parts of the arc would complement work to characterize the arc along-strike. Cross-arc geophysical imaging in key locations with existing geochemistry and geochronology can further illuminate arc crustal genesis and evolution, and can image properties related to the seismogenic zone and inputs to the subduction system (sediments). The community identified the Amlia fracture zone and immediate surroundings as a high-priority corridor for such cross-arc studies. Examples of potential research approaches to address AASZ SCD research topics in this geographic focus area could include, but are not limited to:

Geophysical Imaging: The backbone of this effort could include geophysical imaging of along-strike variations in arc crustal structure at length scales of ~20 km that would provide comparable constraints on crustal structure to the active-source seismic imaging along the IBM arc (Figure 2.4). Cross-arc imaging will also be needed in key locations in the eastern and western arc to understand variations in structure across the arc platform, which could arise from changes in temperature and composition; these cross-arc lines may enable studies of other SCD key topics at those locations. Examples of data sets that could address these goals include: 1) dense active-source refraction data to constrain along- and across arc patterns in crustal structure; 2) seismic reflection imaging of crustal and upper mantle reflectivity in combination with Moho and slab topography beneath the arc along and across strike; 3) passive seismic studies or other geophysical imaging along the arc that will provide pointwise estimates of the thickness and velocity structure of the arc crust as well as information on variations in mantle conditions beneath the arc, including the possible presence of ultra-mafic cumulates below the Moho and the temperature structure and distribution of melt beneath the arc.

Electromagnetic methods offer a complementary view to seismic approaches. The electrical conductivity is very sensitive to the presence of fluids (aqueous or melt) and has been used increasingly in subduction zone settings to identify fluids entering the system, fluids released from the downgoing slab and the generation and transport of melt to the arc. Resistivity images of the incoming plate could address issues of hydration, particularly as plate bending opens pathways through the crust and into the upper-mantle. Variations in the degree of upper-mantle hydration as a function of subduction obliquity could be tested in Alaska where there is a strong gradient in subduction orientation along the length of the arc. The interaction of the Amlia fracture zone and the trench, and how fluids are introduced into the system through this collision, would be a possible target. Variations in along strike fluid input, related to variations in orientation of faults with the trench could also be a target. Imaging variations across the arc would require a combination of marine CSEM and MT experiments, with the potential to place some land stations on islands along the Aleutian chain.

Geochronological and Geochemical Investigations: Geophysical imaging of the arc could be coupled to geochronological and geochemical investigations into the nature and timing of Miocene-and-older magmatism that constructed the Aleutian crust. High-priority targets for campaigns of rock sample collection could include locations along the arc where prior studies indicate that Miocene-and-older volcanic and plutonic basement rocks are well exposed (e.g., Unalaska, Amlia, Atka, Adak, Amchitka and Kiska islands). Offshore sampling of basement outcrops by dredging and ROV could complement onshore efforts and might include submerged areas of the Aleutian fore-arc, which may be particularly fruitful from the Adak area west, where the arc massif has been broken into crustal blocks and displaced by clockwise rotation to produce steep-sided submarine canyons and fault-bounded summit basins at several locations along the arc. Offshore sampling could be aided through international collaborations with the German-Russian KALMAR project. Additional discussion of this topic is presented below in section 2.2.7.6.

Geochronological (40Ar/39Ar, U-Pb) and geochemical studies of new and existing samples could provide a basis for quantifying the geochemical evolution of the arc crust and its rate of growth. Detailed characterization of arc basement age and composition at several locations along the east-west extent of the arc would make it possible to link along-arc changes in arc basement geochemistry and geochronology to changes in the geophysical character of the arc, which will be observed in along-arc and cross-arc lines. Studies of this type also provide a basis for evaluating the timing and nature of subduction initiation. Coupling geochemical and geochronological data to geophysical observations of the lithospheric-scale structure of the arc would make it possible to produce a fully quantitative accounting of the crustal growth over the entire ~50 Ma history of subduction.

Geodetic Studies and Passive-source Seismology: Properties of the seismogenic zone could be assessed from estimates of plate coupling based on geodetic data, and from seismicity and structural variations, measured by passive-source seismology. Potential changes in these properties across the Amlia Fracture Zone are a particular priority within the oceanic arc, especially if integrated with structural and mapping investigations. More general studies of this type within the oceanic arc fall into the category of synoptic studies, and potential scientific objectives and methods are discussed in Section 2.2.5.

Heat Flow Studies: Quantifying variations in the thermal state of in the Pacific plate prior to subduction, along the subduction thrust and across the arc is important to understanding subduction zone processes. Along strike variations in heat flow unrelated to variations in crustal age can provide essential constraints for understanding thermally mediated hydration and dehydration processes along the subduction thrust and deeper subduction zone. Heat flow transects across the arc can delineate mantle wedge flow patterns. These data are complementary to seismic, geodetic, and electromagnetic data that link surface observations with processes at depth. Heatflow data would be particularly interesting in the oceanic part of the arc, but could also be fruitfully undertaken along the Alaska Peninsula and Cook Inlet area of southern Alaska.

2.2.3. Alaska Peninsula

SCD Key Topics

- ***Controls on size, frequency and slip behavior of subduction plate boundaries***
- ***Spatial-temporal deformation patterns during seismic cycle***
- ***Feedbacks between surface processes and subduction dynamics***
- *Storage, transfer, and release of volatiles through subduction systems*

> *The Alaska Peninsula focus region extends from approximately Kodiak Island to Unimak Island, the first of the Aleutian islands (but separated from the mainland by a narrow and shallow channel). The primary GeoPRISMS focus within the Alaska Peninsula region is to determine the processes controlling the spatial and temporal patterns of megathrust earthquakes and the extent of megathrust earthquake ruptures. The Alaska Peninsula region should be the focal point for studies of the feedbacks between surface processes and subduction dynamics, in particular how surface processes are affecting the forearc and seismogenic zone, and vice versa. The general question of the role of sediment flux into the subduction zone impacts the entire arc, and falls under synoptic studies.*

The Alaska Peninsula region includes multiple historical megathrust earthquake ruptures. Large or great earthquakes occurred in 1938, 1957 and 1964, and smaller earthquakes occurred in 1946 and 1948 (Figures 2.1, 2.2). A large or great megathrust event occurred in 1788, although the details of the event are poorly known. The Alaska Peninsula segment encompasses a complete range in locking and slip behavior. The observed range in slip behavior, from completely locked in some areas to freely slipping in others, begs to be explained. Geodesy, seismology, paleoseismology, and crustal imaging all can contribute to a better understanding of megathrust slip behavior. The region includes the most volcanically productive part of the continental arc, as well as a transition from calc-alkaline to tholeiitic volcanism. Although studies of magma processes from slab to surface are discussed under Synoptic Studies, this is the best place in the continental arc for such studies. There are significant variations in sediment input and structure along the subduction zone (Surveyor Fan, Zodiac Fan, Shelikof Strait, Aja Fracture Zone, Patton Murray Seamounts, Figure 2.6), which likely affect a broad range of subduction zone and magmatic behavior. The region was a depocenter for massive glaciers emanating from the Shelikof Strait - Cook Inlet region (Figure 2.7), and an examination of these inputs can address the impact of glaciers and climate cycles on subduction dynamics.

Due to the geometry of the margin, tsunamis generated by great earthquakes in the Alaska Peninsula pose an extra hazard to Hawaii and the west coast of the U.S. The April 1, 1946 earthquake (Figure 2.1) and tsunami was one of the most puzzling and controversial events anywhere. The earthquake had a conventional magnitude (M_S) of only 7.4, but modern reinterpretations put the moment magnitude (M_W) at 8.6. The earthquake apparently had exceptionally slow rupture and exceptionally large shallow slip. It produced a tsunami with local run-up of 42 m at Scotch Cap on Unimak Island that crossed the Pacific and killed 159 people in Hawaii. This earthquake occurred within a section of the subduction zone that shows very little coupling according to GPS results, and it is the only significant case of a mismatch between geodetic and seismic estimates of segmentation. These puzzles of the 1946 event might be explained if it resulted from extreme slip at very shallow depth near the trench, such as was observed in the March 2011 Tohoku-oki earthquake. The consequences of a similarly tsunamigenic earthquake with a much longer rupture length, comparable to those of historic great earthquakes, could be devastating. A record of prehistoric tsunamis from the region needs to be developed to assess their frequency, and how they relate to the megathrust earthquake record.

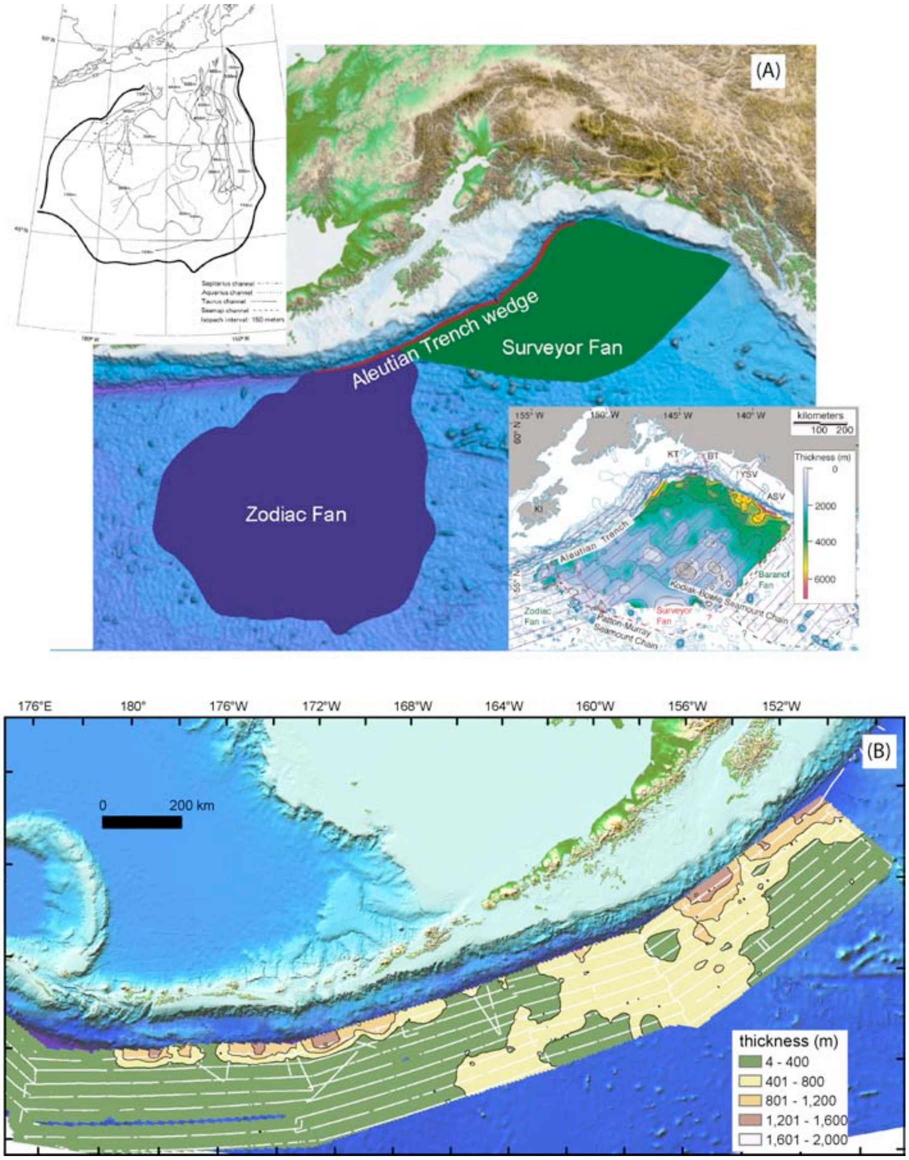


Figure 2.6. Thickness of sediment on the subducting Pacific plate based on MCS and single-channel reflection profiles. Thicknesses are in meters assuming a sediment velocity of 2 km/s (A) Sediment bodies and isopachs in the Gulf of Alaska. The spatial extent and thickness of the Zodiac Fan is after Stevenson et al. (1983) and the Surveyor Fan from Reece et al (2011). Background image courtesy of Robert Reece. (B) Thickness of sediment west of Kodiak Island, including the trench and incoming plate from Ryan et al. (in review). Note different isopach color scale between A and B.

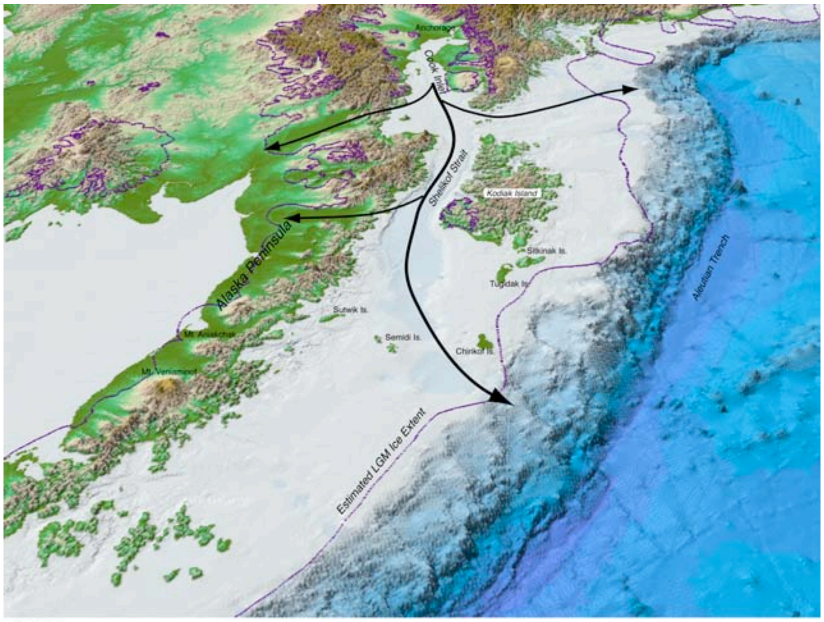


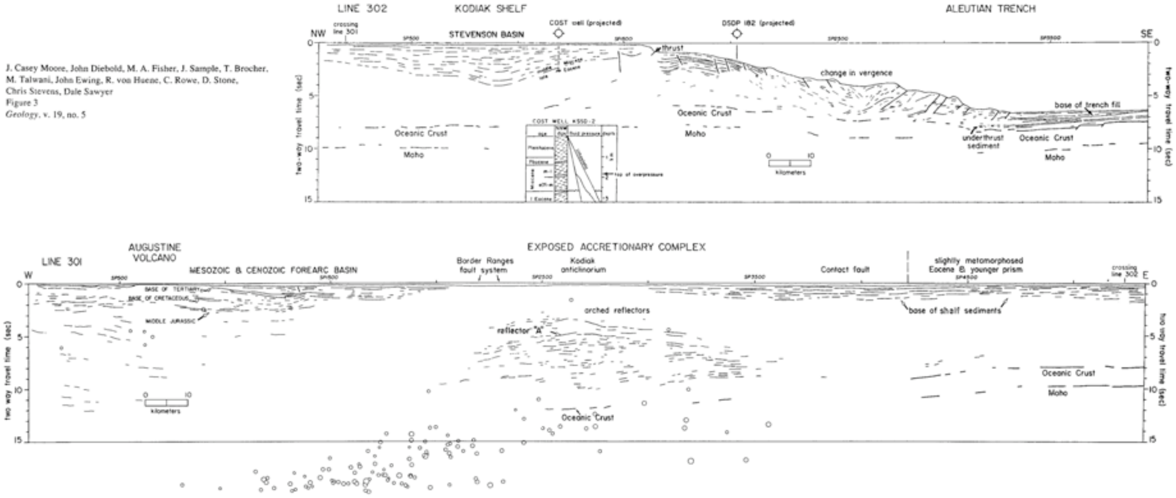
Figure 3.2

Figure 2.7. Bathymetry and topography of Alaskan Peninsula annotated with Late Wisconsin (Last Glacial Maximum) glacial coverage shown in purple. A large lobe of the Alaskan Cordilleran Ice sheet flowed from Cook Inlet through Shelikof Strait over the Alaskan Peninsula and adjacent Pacific continental shelf (hypothetical flow paths shown by arrows). Topography from GLOBE dataset and Alaska Region Bathymetric DEM from Danielson et al. (2008). Glacial extent from Manley and Kaufman (2002). Horizontal scale varies with distance; vertical exaggeration is 6x.

Because of the dominance of Pleistocene glacial coverage in the region, there is no better location to study how mass fluxes (sediment, ice) control the evolution and architecture of a subduction margin. Kinematic models and observations from the eastern Gulf of Alaska margin document how step increases in sediment flux to an orogenic wedge can lead to a broad temporal and spatial transition of deformation within the wedge. A large ice tongue sourced in the Alaska Range and Upper Cook Inlet likely led to a massive transfer of sediment from the arc to forearc and trench in Plio-Pleistocene time (Figure 2.7). Thus, it is the ideal location in Alaska to explore if the geometry and seismicity of the forearc wedge has responded as the sediment mass balance and ice cover fluctuated throughout the Plio-Pleistocene. Glacial erosion and changes in glacial loads can affect tectonic strain localization, seismicity, and potentially volcanic productivity, making glaciers a potentially critical feedback between surface processes and subduction zone mechanics and dynamics. Thus, the evolution of ice cover over time and quantitative estimates of erosion are needed to understand and model this feedback.

2.2.3.2. Existing Datasets and Studies in the Area and Data Gaps

Pre-existing data and an existing framework of geological and geophysical studies provide a strong foundation for focused studies. Islands between the peninsula and the trench allow on-land geologic investigations and the opportunity to provide ground-truth for observations made offshore through geophysical studies. Shore-based seismic and geodetic studies also can be carried out at substantially lower cost than marine studies. Much of the area has been mapped geologically, with accompanying stratigraphic and geochronology studies; intensive geological studies of the accretionary prism have been carried out; new and legacy seismic reflection data have been collected on both sides of the arc (Figure 2.8); geodetic and seismic monitoring networks exist across the region, including on several volcanoes. Moreover, there have been intensive studies of the bedrock of the accretionary prism on Kodiak and some of the adjacent islands. A substantial data gap exists for the paleoseismic and paleotsunami record for the region, for which there is no published information.



J. Casey Moore, John Diebold, M. A. Fisher, J. Sample, T. Brocher,
M. Talwani, John Ewing, R. von Huene, C. Rowe, D. Stone,
Chris Stevens, Dale Sawyer
Figure 3
Geology, v. 19, no. 5

Figure 2.8. Line drawing of migrated EDGE seismic line showing projected earthquakes and COST and DSDP wells. From Moore et al. (1991).

Marine seismic reflection data exist on both sides of the arc, but recent multi-channel data are limited to the 2011 ALEUT project. Lower quality legacy USGS and oil industry data exist, along with exploration boreholes on the north side of the Alaska Peninsula. The incoming trench and slope were drilled during DSDP Leg 18 north of this region, but no boreholes or long cores exist for the region. A significant data gap is in bathymetry data; high-resolution mulitbeam data are available in a few places along the slope and trench near Kodiak (collected by Geomar) and along the ALEUT shiptrack; however, there is very little detailed bathymetry away from the shorelines south of Kodiak.

Both campaign GPS sites and PBO continuous GPS sites span the entire region, with a concentration on the islands south of the Alaska Peninsula and on the volcanoes of Unimak Island. PBO provides a sparse but complete backbone network across the region (station spacing generally ~60-150 km), with a dense cluster of sites around Westdahl and Shishaldin volcanoes on Unimak Island. The permanent seismic network consists of a sparse backbone and several volcano networks, with a few key sites on islands near the trench. The EarthScope USArray transportable array (TA), to be deployed starting in 2014 will provide a significant, if temporary, enhancement to the network.

There is also a shortfall of potential fields data. Regional, low frequency gravity data exist from satellite altimetry, however, land and marine data are lacking. Moreover, there are almost no aeromagnetic data, which would be useful for deciphering crustal structure and interpreting regional geotherms.

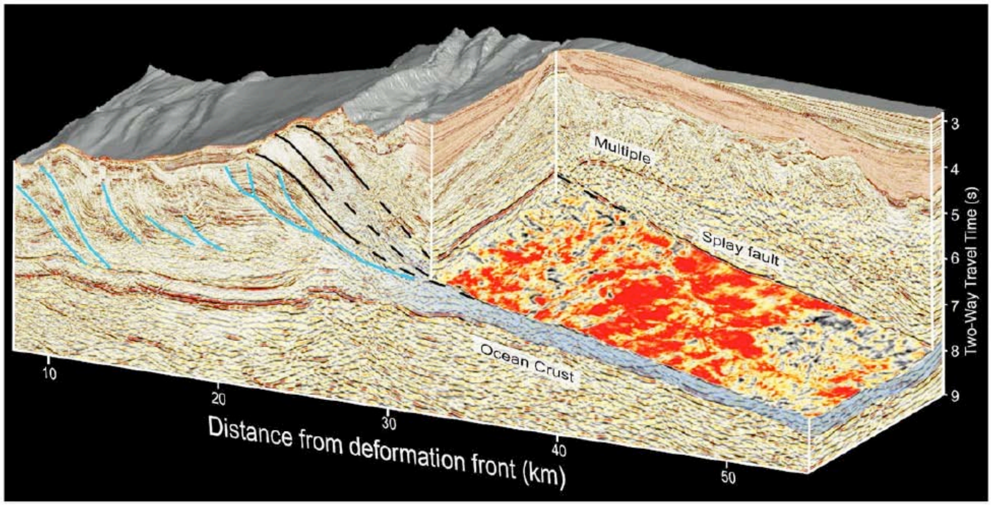


Figure 2.9. Example of 3-D seismic reflection volume that could be collected within Alaskan Peninsula geographic focus area. Image is a perspective view from Bangs et al. (2009) of the Nankai 3-D seismic volume with cut-out to show high-amplitude, reversed-polarity seismic reflection from the deep splay fault (red areas). Cube is 12 km wide by 50 km long..

2.2.3.3. Potential GeoPRISMS Studies

Examples of potential research approaches to address AASZ SCD research topics in this geographic focus area could include, but are not limited to:

Geophysical imaging of the megathrust – Legacy 2D USGS seismic reflection data and the recent (2011) ALEUT project deep active-source reflection and refraction data provide crucial crustal-scale framework data, however data coverage is limited. In order to make fundamental observations of changes in megathrust character along and across strike, additional seismic experiments will be needed. High priority targets for imaging include transitions in locking at the plate boundary, such as the transition from the locked 1938 rupture area to the narrow locked zone in the Shumagin Islands and the apparently creeping segment to the west at the end of the Alaska Peninsula. This latter segment includes the presumed 1946 rupture area, and study of this region offshore may reveal insights into the puzzling earthquake and tsunami generation there. High-resolution geophysical imaging (e.g., Figure 2.9) could identify the location and nature of surface deformation associated with that event, including possible landslides, the presence of active splay faults, and how deformation is manifest offshore. Forearc deformation may also be influenced by patterns of sediment deposition, e.g., derived from ice streams originating from Shelikof Straight, and depositing southwest of Kodiak (Figure 2.7). Examples of geophysical datasets that could address these goals include bathymetric mapping and seismic reflection imaging. Deep imaging (e.g., passive seismic studies) can provide complementary information to the active-source studies. e.g., better constraining the deep configuration of the slab, overriding plate and mantle wedge beneath the Alaska Peninsula. Given the high rate of seismicity, tomography could improve understanding of processes from slab to surface. The map pattern of seismicity in the forearc is similar to the Tohoku region of Japan, where onshore/offshore passive seismic networks have enabled successful tomographic inversions that have imaged the slab, interface and overriding plate. Moreover, shear-wave splitting studies would help to reveal the character and role of mantle flow across the entire width of the subduction zone.

The deployment of dense networks in conjunction with the USArray TA is an obvious opportunity for synergy with EarthScope. The redeployment of the Cascadia Initiative Amphibious Array (AA), after its demobilization in the Pacific Northwest, represents a great opportunity to better understand crustal structure and seismic processes in this area. The timing of such a deployment also would influence the ideal sequencing of studies. Optimally, the AA deployment would coincide with the USArray deployment, along with other broadband seismometers.

Active deformation – Geodetic studies are needed to assess variations in locking and slip behavior along the length of the megathrust, as well as deformation associated with arc volcanoes. The campaign GPS sites in the area have not been surveyed for more than a decade, and most have not been visited for more than 15 years. A repeat survey would dramatically improve the number of sites with usable data and provide a high-precision data set for modeling. Additional sites could be focused on the along-strike transition zones between wide locked zones and creeping zones. Higher spatial resolution is needed for interseismic models in these areas, and continuous GPS sites could show whether these boundaries remain stable with time or if slip transients are responsible for some of the along-strike variation. Ideally, such GPS sites should be established early during GeoPRISMS studies in the area to recognize temporal changes over a meaningful period of time. Sections of the megathrust that are dominated by creep are particularly promising targets for seafloor geodesy. These measurements are the only way to determine if creep extends to the trench, or if the near-trench region is locked and potentially seismogenic. Seismicity studies would help to define earthquake activity, tremor patches, and loci of deformation. More careful studies of historical seismicity (for example, relocations using updated 3D velocity models) may better define rupture areas for the historical events, cumulative moment release, and invite a comparison to geodetic inversions. As described above, the deployment of dense networks in conjunction with the USArray TA is an obvious opportunity for synergy with EarthScope, and Alaska would be an excellent target for the Amphibious Array.

Paleoseismology and paleotsunamis – One high priority in this region is to define the paleoearthquake and paleotsunami history of the region, to evaluate if the historical rupture boundaries repeat or change through time. Moreover, it is vital to establish how often megathrust ruptures generate significant tsunamis. Submarine paleoseismic records should also be developed, and methodologies will need to be honed for this task. Some of the offshore islands, such as Chirikof Island (Figure 2.7), show a wealth of useful geomorphic features and have sites that are promising for further paleoseismic and paleotsunami research.

Mass flux studies – Comprehensive thermochronology studies would establish the history and rates of rock exhumation, and allow linkages between tectonic, collisional, or climatic events. Moreover, structural mechanisms of exhumation could be examined through bedrock structural or seismic reflection studies. The transfer and accumulation of sediment derived from erosion must be determined across the forearc and trench. Geophysical imaging studies may define high-priority coring and drilling targets. After collection and interpretation of seismic reflection data, a sequence of scientific boreholes can be proposed to characterize the physical characteristics of the incoming sediment, structural development of the toe of the accretionary prism, fluid escape from deforming sediments, and the timing and evolution of slope basins. A drilling transect of the toe of the prism (e.g., ODP Leg 171; NanTroSEIZE) may be desired.

2.2.4. Cook Inlet

SCD Key Topics

- ***Controls on size, frequency and slip behavior of subduction plate boundaries***
- ***Spatial-temporal deformation patterns during seismic cycle***
- *Volatile storage, transfer, and release in subduction systems*
- *Feedbacks between surface processes and subduction dynamics*

The Cook Inlet focus region extends from Prince William Sound approximately to Kodiak Island, and includes the rupture zone of the great 1964 M_W 9.2 earthquake. The primary GeoPRISMS focus within the Cook Inlet region is on slip behavior of the megathrust, and in particular transient slip. This region provides the opportunity to study large and small slow slip events and their associated tremor, transient postseismic deformation following the 1964 earthquake, and a dramatic along-strike boundary in the slip behavior of the plate interface that appears to correlate with the edge of the subducted Yakutat terrane. This region is also the source of most of the trench sediment for the entire AASZ, and for the sediment deposited in the forearc in the adjacent Alaska Peninsula. The greater land area in this focus region, also means that EarthScope will have a greater presence here. Given the complementary science goals, The Cook Inlet focus region is an excellent target for joint GeoPRISMS-EarthScope projects. and for leveraging EarthScope data.

The Cook Inlet region experienced a watershed seismic event in 1964, triggering long-lived postseismic deformation transients that provide an opportunity to study the mechanics of the lithosphere and asthenosphere and improve models of the seismic cycle. Measurements of surface deformation and improved 3D models of structure and anisotropy are needed to determine the stress distribution and rheology of the fault zone, and of the lithosphere and asthenosphere. Multiple slow-slip transients have now been observed in this region, including a very large ($M > 7$) slow slip event, transient variations in the width of the locked zone, and what appear to be small and short-lived events perhaps similar to Cascadia ETS events. More detailed observations and models are needed to understand the stress evolution and slip mechanisms controlling these events.

The Yakutat terrane is subducting under and colliding with southern Alaska at the eastern end of the AASZ, with the transition from subduction to collision occurring east of the eastern end of the 1964 earthquake rupture (Figure 2.10). The Yakutat terrane crust is thick and buoyant, and is probably composed of continental sediments deposited on top of an oceanic plateau. Subduction of this buoyant crust has affected the margin strongly for at least the last 6 million years and possibly as long as 20-30 million years. It results in a very shallow slab dip (essentially a flat slab), enhanced deformation of the overriding plate, and a gap in the volcanic arc. The subducted Yakutat slab extends to the northwest under the Cook Inlet region, and the SW edge of the subducted Yakutat crust correlates roughly with the edge of the Prince William Sound asperity of the 1964 rupture, and a transition from a very wide seismogenic locked zone to a segment dominated by creep (Figure 2.2). The Yakutat slab edge offers a chance to study the effects of a dramatic change in properties of the subducted crust on the seismogenic zone and arc volcanism.

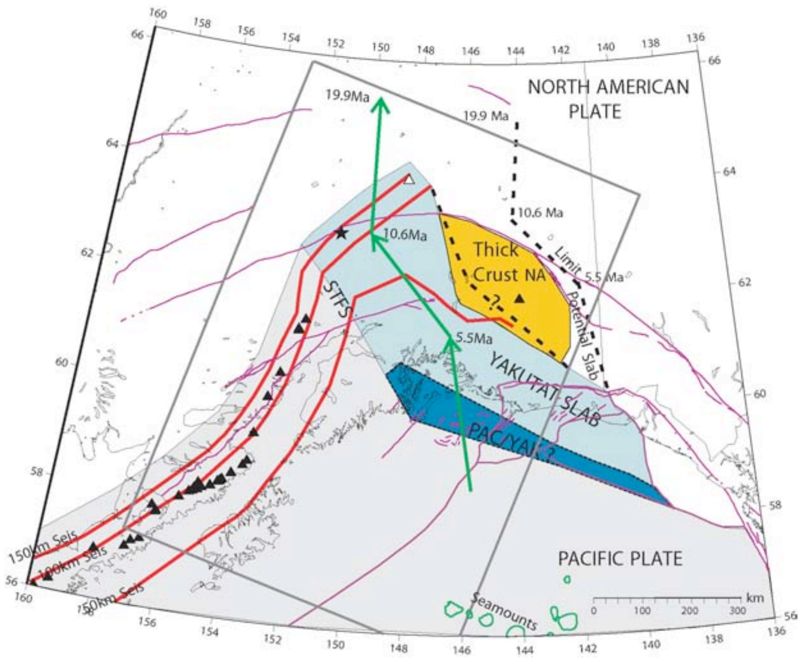


Figure 2.10 Subducting plate as inferred by Eberhart-Phillips et al. (2006), gray = Pacific, light blue = Yakutat, dark blue = schematic region of Pacific underthrust Yakutat (actual amount not certain). Thick crust east of the slab is in the overlying plate. Red lines show slab depth as defined by seismicity. Seamounts from bathymetry. Green arrows show cumulative plate motions for the last 20 Ma for a spot on the Pacific plate. For the hypothetical case of zero Pacific-Yakutat displacement and a dipping slab, the dashed line shows cumulative motion for a point at the surficial edge of the oceanic Yakutat terrane, and thus limits the potential 'missing' slab. The plate motions are from Stock and Molnar (1988), and the 19.9 Ma vector is approximate.

The very high seismicity rate of the region provides sources that can be used in tomographic and other imaging, if seismometers are installed to record them. The effectiveness of seismic imaging depends on the number of intermediate magnitude earthquakes that are large enough to be recorded well over a large area, but small enough to have very simple sources. The slab beneath Cook Inlet and southern Alaska is a particularly rich seismic source, generating hundreds of earthquakes per year that would be broadly recorded in the overlying region. Frequent seismicity also allows for studying the physical properties that control and/or are diagnostic of the slip behavior of the interface. Slow slip phenomena (geodetic transients, tremor, etc.) could be useful for examining these coupling questions (Figure 2.11).

The Cook Inlet region is the continental end-member for the AASZ, providing a strong contrast to SCD processes active along the oceanic Aleutian Arc. This part of the subduction zone has the largest distance globally from a trench to an arc, with magma generation through relatively thick continental crust. Neotectonic exhumation and Quaternary glaciation in southern Alaska results in large terrigenous sediment fluxes across the region and into the subduction zone. The volatile-rich eruptions from volcanoes in Cook Inlet may be driven by the combination of these conditions. The prevalence of Pleistocene ice cover in Cook Inlet results in strong surface process signals, and this region has the potential for the strongest climatic/glacial influence on volcanism and seismogenesis in Alaska.

2.2.4.2. Existing Datasets and Studies in the Area and Data Gaps

A tangible benefit of the Cook Inlet region is the greater amount of existing data relative to the Alaska-Aleutian subduction system to the west. In addition, EarthScope plans include deployment of a large number of USArray TA stations across the region (Figure 2.11). The greater accessibility of the Cook Inlet region has allowed for longer-term volcanic and geophysical monitoring through the AVO and PBO. The denser spatial coverage of existing geodetic measurements and vertical motion data in this region allows modeling of megathrust slip events, although data on the recurrence of megathrust events remains limited. Geophysical data are available at moderately dense spatial coverage that resolve deep-to-shallow structures and ‘slow’ slip phenomena (geodetic transients, tremor, etc.).

Deep seismic reflection data exists in Cook Inlet and Prince William Sound from 1980s and 1990s projects, including EDGE and TACT. Cook Inlet is home to Alaska's oldest producing oil and gas basin, and both industry and public domain map, core, seismic reflection and well log data exist for potential interpretation of neotectonic deformation and the Neogene sedimentation (Figure 2.10). Additional deep seismic reflection lines in Cook Inlet are unlikely due to permitting restrictions, and future work of that type is most likely limited to the area offshore the Pacific coast. Past OBS deployments were very limited, which means there are great opportunities for acquiring fundamental new data given the high seismicity rate and limits to past information.

Pre-existing campaign GPS networks cover most of the region, especially along the road system, with sparser coverage on the NW side of Cook Inlet and other more remote regions. PBO operates continuous GPS sites across the region, with a typical station spacing of ~80 km. For comparison, this is similar to the station coverage in the northern part of Cascadia prior to PBO (current Cascadia PBO station spacing is ~40 km). Greater densification in targeted areas would be justified. Data from a few additional sites, mostly located on the road system, are available from the University of Alaska Fairbanks and various other station operators.

AVO plays a key role on the study of Cook Inlet volcanoes. It has a program of real-time seismic monitoring at the four active Cook Inlet volcanoes — Spurr, Redoubt, Iliamna, and Augustine — plus the recently active Fourpeaked Mountain at the NE end of the Alaska Peninsula. AVO has 4-station GPS networks on Redoubt and Spurr. For some volcanoes, AVO has remote, real-time video capability and obtains intermittent airborne sulfur dioxide and carbon dioxide measurements. AVO also oversees a regional tephra laboratory to systematically measure and catalog tephra-producing eruptions, establish radiocarbon-controlled tephrostratigraphic frameworks, and to evaluate the magnitude and frequency of tephra-producing eruptions. This tephra catalog has the potential to enable long-distance correlation of tephras, provide greater detail on the chronology of eruptions, and establish a longer-term context for tephra hazards.

Quaternary sedimentation is likely dominated by glacial processes interacting with active deformation in the forearc and volcanic arc, but quantification of mass flux is still in early stages; uplift and exhumation are relatively well understood, but how this translates to mass transfer and timing of sediment delivery to forearc and trench is still poorly known. A significant amount of sediment from this region exited through Shelikof Strait, contributing sediment to the trench in adjacent segments of the subduction zone. This region also has been examined using three-dimensional numerical geodynamic models of both crustal and mantle processes to investigate the mechanical evolution of the southern Alaskan plate corner where the Yakutat and the Pacific plates converge on the North American plate. These models allow for hypothesis testing linking geodynamic and surface processes.

2.2.4.3. Potential GeoPRISMS Studies

Many GeoPRISMS science targets within the Cook Inlet region could be addressed by exploiting existing and planned on-land infrastructure, augmented by targeted offshore data. GeoPRISMS and EarthScope have common scientific goals that can be met collaboratively and synergistically in this region. For example, densification of the EarthScope USArray TA and PBO facilities with focused FlexArray and GPS deployments would provide data that could be used to resolve the plate interface and mantle flow, deep-to-shallow structures, slow-slip events, and volcanic activity. Such efforts could be supported by a combination of GeoPRISMS and EarthScope funding. The key scientific targets within the region are to record data needed to develop models of deformation throughout the seismic cycle, focusing on slow and transient slip the effects of the 1964 event, and the subducted Yakutat slab and its impacts. The largest known slow slip event in Cook Inlet (Figure 2.11) was studied primarily through campaign GPS surveys, which was possible only because of the event's enormous size. Analysis of existing continuous GPS data is needed to identify and determine the slip history of smaller events, and additional continuous GPS sites would provide further data for study of these events, and their spatial relationship. Ideally, these studies would benefit from complementary geodynamic modeling over geologic and earthquake cycle timescales and exhumation rate measurements to better relate short-term geodetic and seismological measurements to longer-term Quaternary deformation and mass fluxes.

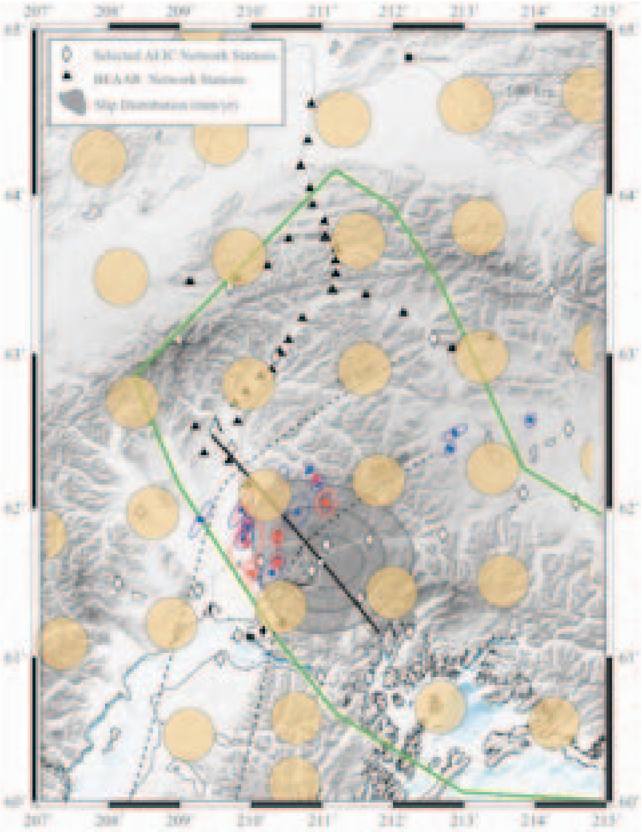


Figure 2.11. Locations of nonvolcanic tremor from Peterson and Christensen (2009). Summer of 1999 (red circles) and summer of 2000 (blue circles). Note that all but three events are located in the region of the slow slip event. BEAAR stations are mapped as black triangles; selected AEIC stations are mapped as white diamonds. Orange circles delineate 20-km footprint of potential EarthScope Transportable Array deployment. Slip distribution [Ohta et al., 2006] from the 1998–2001 slow slip event is shown by dark gray solid lines with rates in mm/a and one GPS station, ATW2, used in the Ohta et al. [2006] model is shown by the white circle in the center of the slip region. The green outline shows the subducted Yakutat terrane as modeled by Eberhart-Phillips et al. [2006]. The 30 km and 50 km contours of the subducting Pacific plate are shown by the dashed lines.

Determining the extent and geometry of subducting Pacific Plate, especially near the western edge of the subducted Yakutat terrane, is a priority for this focus area because of the profound changes in interseismic deformation and arc volcanism observed. The details of the subducted Yakutat slab are broadly known from tomographic inversion and at shallower levels, a prominent magnetic anomaly. It's impact on mantle wedge properties are not known, although there is a clear gap in eruptive arc volcanism above the Yakutat slab, and shear-wave splitting directions are parallel to the strike of the slab in the mangle wedge. Better characterization of the seismic, electrical, and thermal properties of the mantle wedge are needed, as are models of mantle flow. A combination of land-based and OBS seismic deployments could provide the data needed for such images. Densified GPS deployments could improve the resolution of geodetic models.

2.2.5. Synoptic Studies

SCD Key Topics

- ***Controls on size, frequency and slip behavior of subduction plate boundaries***
- ***Spatial-temporal deformation patterns during seismic cycle***
- ***Volatile storage, transfer, and release in subduction systems***
- ***Feedbacks between surface processes and subduction dynamics***

The dramatic change along strike of many basic subduction parameters is one of the most important features of the AASZ. Synoptic studies that encompass the entire arc are needed to capture the effects of variations in these parameters. Synoptic studies provide essential data sets or analyses needed to understand variations in the inputs or outputs of subduction cycles and deformation. Knowledge of along-strike trends, variation or segmentation in the quantities measured by these studies will allow more robust conclusions to be drawn from the more focused investigations that will be done at a much smaller number of sites along the arc.

Five categories of synoptic studies are needed to complement the more targeted studies envisioned by GeoPRISMS: geology and geochemistry; geodesy; paleoseismology and paleotsunami; sediment flux; and broadband seismology. Such synoptic studies may not, in general, require systematic and expensive new data collection along the entire arc. In many cases, they will rely on a synthesis of existing data, reanalysis of existing samples, exploitation of data collected by the EarthScope facilities, or data collected by community experiments or community expeditions (defined in Section 2.2.7). Specific areas where significant data gaps exist may be targeted for new data. In the case of paleoseismic and paleotsunami studies, the number of high quality sites for carrying out studies will be limited, but spread out over the length of the arc.

2.2.5.1. Geology and Geochemistry

The AASZ provides a prime opportunity to understand how the magmatic output of a subduction system responds to along-strike variations in the physical parameters of subduction. The primary targets of synoptic studies in this disciplinary area are to determine the causes of along-arc variations in magma chemistry including pre-eruptive volatile contents.

The existing rock sample collection is extensive and provides the opportunity to develop a fully synoptic geochemical view of volcanic output for the AASZ. Large collections of Quaternary-age Aleutian lavas exist at several universities (e.g., Columbia, Cornell, Johns Hopkins, South Carolina, Wisconsin, Wyoming). Geochemical data from more than 2000 of these samples have been published or compiled in reviews and are publically available. The Alaska Volcano Observatory (AVO) holds a larger, more geographically extensive sample set, covering the whole arc with greatest focus on the Alaska Peninsula and Cook Inlet. The AVO collection includes approximately 3600 fully modern XRF and ICPMS whole-rock analyses from a single laboratory.

Despite the widespread availability of samples and decades of study, there remains a great opportunity to exploit the existing samples and gain new insights, especially for new isotopic studies. Available Pb, Sr, Nd and Hf isotopic data provide a clear view of geochemical changes to lavas along the Aleutian part of the AASZ. Further east, for volcanoes on 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 AASZ. New isotopic studies of existing samples will therefore provide a basis for making detailed comparisons between the continental and oceanic parts of the arc, and for assessing the impacts of varying subduction inputs, convergence rate, slab geometry and overriding plate thickness. It is very likely that acquisition of a large quantity of high-quality isotopic data over the whole arc (for Pb, Sr, Nd and Hf), combined with existing major and trace element data, will reveal systematic differences from the Alaskan part of the arc that will be interpretable in the context of key questions about subduction magma genesis.

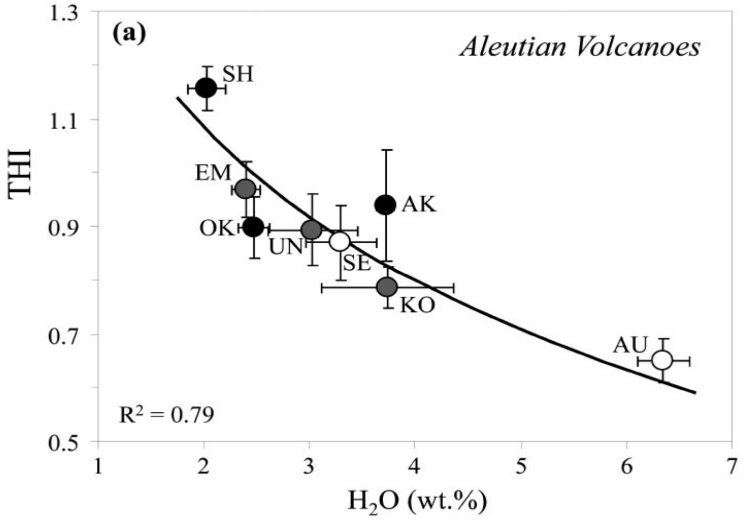


Figure 2.12. Graph of tholeiitic index (THI) versus pre-eruptive water contents from Aleutian melt inclusion samples. The inverse relationship indicates that water contents control whole-rock FeO/MgO variability (THI) and igneous series types (tholeiitic vs. calc-alkaline) expressed at Aleutian volcanoes. Sample locations are Shishaldin (SH), Mt. Emmons (EM), Okmok (OK), Unalaska Island (UN), Seguam (SE), Akutan (AK), Korovin (KO) and Augustine (AU). From Zimmer et al. (2011 – Figure 7a).

Storage, transfer, and release of volatiles through subduction systems were among the key topics motivating GeoPRISMS research in AASZ. Measurement of pre-eruptive volatile contents is therefore an area of disciplinary focus that should be pursued throughout the AASZ, wherever modern measurements have not been made and appropriate samples can be obtained. Volatile contents have long been known to play a central role in the control of subduction magma genesis (Figure 2.12). There has been a significant growth in recent years in the number of direct measurements of pre-eruptive volatile contents in melt inclusion and submarine glass samples from arc and back-arc locations. These results provide a much-improved basis for evaluating the role of water in controlling magmatic production rates and geochemical fluxes of volatile and related soluble metals which are abundant in arc lavas, and which play a central role in our understanding of how arc magmas are produced. Volatiles are one area where the existing sample collection (described above) probably does not represent a sufficient potential source of high quality data. This is because direct measurements of volatiles require well-quenched, melt-inclusion or submarine glass samples that retain their pre-eruptive volatile contents. Additional sampling of volcanic systems may therefore be justified, with the goal of producing a synoptic view of water and related volatile and elemental contents that can be linked to more widely available geochemical parameters which are already known to change systematically along-strike for large segments of the AASZ (Figure 2.12).

2.2.5.2. Geodesy

The primary focus of geodetic synoptic studies is on along-strike variations in the slip behavior of the seismogenic zone. The gross pattern of interseismic slip deficit and stress/strain accumulation is known for many segments of the arc, but data from the central Aleutians are almost completely missing. This leaves the major part of the rupture zone of the great 1957 earthquake unstudied. There are other data gaps in the eastern Aleutians and to a lesser extent along parts of the Alaska Peninsula segment. A more complete assessment of the interseismic strain pattern is needed to test whether or not the along-strike segmentation of present-day slip deficit matches the pattern of high and low slip in the last great earthquakes. The hypothesis that asperities and creeping sections of the interface are persistent features predicts that the interseismic slip deficit and coseismic slip will match each other. Mapping out the development of slip partitioning of oblique subduction in the central and western Aleutians is a secondary goal, a likely side benefit of additional data but not a top community priority by itself.

Individual studies, community experiments, or community expeditions to fill in the data gaps along the arc are needed, in addition to the studies discussed earlier that focus on already-known segmentation boundaries. Except where dense networks can be deployed, the likely spatial resolution for inverse models of variations in the seismogenic zone will be a few tens of km, so the top priority is for along strike sampling at approximately that spacing. Where the distribution of land allows it, it would be highly desirable to have sites at different distances from the trench. Even small trench-normal differences of ~10 km or so allow a measurement of strain that provides new information for models. GPS data already exist for the Bering Sea islands and back-arc areas of the mainland, so new data are needed only along the arc.

Earthquake cycle models are needed to relate surface site velocities to the slip history on the megathrust. The simplest models are elastic, and in that case the site velocity is proportional to the slip deficit distribution on the interface – that is, the strain on the surface is caused by the parts of the plate interface that are locked and building up stress for future earthquakes. To apply these models, the motion of the overriding plate must be known in addition to the relative plate motion. For the entire AASZ, the arc and forearc of the overriding plate move relative to North America, so motion of the arc relative to North America (or relative to the proposed Bering plate) needs to be estimated or accounted for. Data from adjacent segments can aid with this. In addition, the trench-parallel motion of the arc or a forearc sliver due to slip partitioning of oblique subduction needs to be accounted for. Potential effects of postseismic deformation will need to be considered for segments that have ruptured recently, although outside of the 1964 rupture zone there is no clear-cut evidence for ongoing postseismic effects today from any subduction event in Alaska.

Seafloor geodesy provides a complementary and potentially critical measurement to add to GPS observations on land. The limitation of land-based geodesy is that the ability to resolve whether the near-trench part of the interface is locked or creeping is nearly zero due to the shallow depth there and distance from the source to the sites. Seafloor measurements in the outer forearc would resolve this question. The enormous slip near the trench in the March 2011 Tohoku event raises a serious concern that the seismic potential of the near-trench region may have been dramatically underestimated. While the highest priority for seafloor geodetic studies would be in the Alaska Peninsula region, where the 1946 tsunami earthquake already provides evidence for a locked zone near the trench, such studies at any place along the arc would have considerable value and they should be considered at any location where opportunity permits.

2.2.5.3. Paleoseismology and Paleotsunami Studies

The primary focus of synoptic studies of paleoseismology and paleotsunami is to extend the temporal record of great earthquakes over several millennia. The instrumental record lasts only slightly more than 100 years, and the historical record no more than 250 years, and this record is not long enough to capture even a single full earthquake cycle for a great earthquake rupture. Information about past events will tell us if earthquake segment boundaries are persistent, and provide key information on the recurrence intervals. The prehistoric earthquake and tsunami record is needed to tell us whether the earthquakes of the last century are typical, are extreme events, or if much larger earthquakes can happen. This information is critical for accurate geohazards risk assessment, and thus brings with it strong broader impacts. It is likely that the number of potential paleoseismological or paleotsunami sites along the arc is limited, but they should be pursued wherever possible.

Paleoseismology in a subduction zone setting involves finding depositional evidence for abrupt changes in relative sea level caused by great earthquakes. Coastal marshes are generally required for preservation of deposits, and earthquakes smaller than the magnitude 8 range are probably invisible because they do not produce enough vertical coseismic displacement. Most of the Alaska-Aleutian subduction zone lacks paleoseismological data, with the Cook Inlet region being the exception. Paleoseismological data are scarce or absent along the Aleutian arc west of Kodiak Island. Paleoseismology research on the Alaska Peninsula and in the Aleutian Islands has great potential to test the temporal fidelity of spatial correlations between areas of high moment release, or asperities, during large earthquakes and forearc structure, or other competing hypotheses for the cause of asperities. Making precise measurements of the amount of vertical deformation over multiple earthquake cycles is the objective of a relatively new sub-discipline of paleoseismology called paleogeodesy. Along the temperate coast of western North America studies of the change in fossil diatom and foraminiferal assemblages associated with stratigraphic evidence of great earthquakes employ statistical transfer functions that estimate the precise (0.1-0.3 m resolution) amount of coseismic subsidence. This technique has been used for the AD 1700 Cascadia earthquake and the 1964 Alaska earthquake, but not for any part of Alaska outside of Cook Inlet.

Existing paleoseismological data in the Cook Inlet region chronicle nine megathrust earthquakes in the past ~5,000 years in the area of the Prince William Sound asperity of the 1964 earthquake.

At Girdwood and the Copper River Delta, geologic evidence for sudden land-level change and ^{14}C age data indicate a median recurrence interval for great earthquakes of ~560 years with a range of 333–875 years. However, regional correlations of paleoseismological records from Kodiak to Icy Cape reveal that variable recurrence intervals and heterogeneous rupture extents best characterize the history of the Alaska megathrust. For example, evidence from the Kodiak Islands suggests that this segment ruptured alone about 500 years ago. Yet, the penultimate earthquake considered similar in size to the 1964 event occurred 860–900 years ago and may have been larger if it also involved rupture of the Yakutat microplate. Still earlier predecessors, one about ~1480 and another in 2130 years ago, are also considered similar to the 1964 event because evidence of coseismic displacement overlies the Kodiak and PWS segments of the megathrust. The spatial extent of older earthquakes is less certain because of incomplete paleoseismic records in most of the region.

Paleotsunami investigations along shorelines of the Aleutian Islands and the Alaska Peninsula may yield important information on the frequency of large tsunamis, their spatial extent and contribute empirical data that can be used to estimate the hydrodynamic properties of the waves, including flow depth and flow speed. Paleotsunami data can also be used to validate and improve tsunami hydrodynamic models used for hazard mitigation. Paleotsunami investigations along the Alaska-Aleutian arc can provide crucial data to estimate tsunami recurrence intervals, characterize the source mechanisms and assess inundation hazards for vulnerable communities in Alaska and around the Pacific Ocean. The recurrence interval of such outsized tsunamis such as the 1946 event at Unimak Island in the Aleutians is unknown. The 1964 M_w 9.2 Prince William Sound earthquake caused \$430 million in damage and killed 106 people in Alaska, 5 in Oregon and 13 in California. Yet despite these risks, predecessors to these tsunamis are poorly known. In the remainder of the Aleutians, there are no paleostunami data at all, although shoreline sampling by Gary Carver showed evidence for sand beds interpreted as deposition from repeated large tsunamis. This anecdotal evidence suggests that the record of paleotsunamis may be present and a critical first step is to carry out reconnaissance assessments of potential sites, perhaps as part of a community expedition. The most promising sites could then be targeted for focused studies.

2.2.5.4. Sediment Flux

The primary focus of synoptic studies of sediment flux is to characterize the lithological input into the AASZ (Figure 2.6). This is an essential parameter that affects both the physical properties of the subducting slab and the volatile budget of the system. The input of hydrous phases and thermal state constrain the dehydration reactions and subsequent metamorphic reactions. Subduction of a thick section of trench-floor sediment may create a sediment-packed subduction channel that mechanically smooths the subducted sea-floor relief, favoring lengthy trench-parallel rupture during a megathrust earthquake. For all of 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. However, incoming sediment composition is poorly known because there are only three existing DSDP drill sites. Sediment thickness in the trench is known from crustal-scale seismic data at only a few locations. Seismic reflection profiling and swath bathymetry with targeted coring and drilling are the only methods to constrain these parameters. GeoPRISMS geophysical investigations along the arc should include complementary sampling of sediments wherever possible. Targeted studies of sediment properties would ensure a more complete coverage.

Along-arc variability in incoming sediment flux is a dominant characteristic of the AASZ (Figure 2.6). A dominant terrigenous source exists in the northern Gulf of Alaska, whereas hemipelagic and more diatomaceous material accumulates on the Pacific plate towards the western Aleutians. Three major sediment bodies lie atop the subducting Pacific Plate: the Surveyor Fan, the terrigenous outwash body that comprises the majority of the Alaska Abyssal Plain; the Kodiak-Bowie Seamount Chain and the inactive Zodiac Fan; and an axially-deposited wedge of Aleutian Trench fill that lies atop the subducting Surveyor and Zodiac Fans. The along-strike variation of sediment thickness arriving at the Aleutian 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 extend the transition from accretionary to non-accretionary/erosional subduction system. A five-fold increase in sediment delivery to the Aleutian Trench during the Pleistocene may have altered subduction zone dynamics through significant along-strike and temporal variations in the incoming sedimentary section, and sediment loading within forearc basins. Lastly, the AASZ is unique in its incoming lithology, as diatoms comprise a significant portion of the subducting sediments. Whereas the subduction of clays results in a limited number of dehydration steps, diatom dehydration occurs over a range of temperatures that results in more complex patterns of volatile release. Diatoms, if at high concentration, also strongly affect the physical properties of sediments, in particular, the permeability and the porosity reductions with burial depth.

2.2.5.5. Passive Seismology

Synoptic studies involving passive seismology would be aimed at (1) improving information about the distribution of earthquake and tremor sources, (2) mapping the crustal thickness, (3) crust, slab, and mantle wedge velocity and attenuation structure, (4) and shear-wave anisotropy below the arc. By integrating new high-precision earthquake locations for "background" seismicity (and any large earthquakes that do occur) with existing long-term regional and global catalogs, a clear picture of the seismogenic megathrust will emerge. When coupled with tremor and geodetic observations, a more complete picture of the spatial patterns of megathrust behavior will emerge. The seismic velocity structure and thickness of the crust provides critical information for understanding crustal growth. Similarly, down-going slab and mantle wedge structure (velocities and Q) provide insight into initial slab hydration, dehydration processes, and melt generation and migration paths. Shear-wave splitting data are a unique and critical source of information regarding mantle flow patterns.

The standard toolbox of passive seismic imaging will be applied, including body-wave and surface-wave tomography (including ambient noise techniques), attenuation tomography, receiver function imaging/migration, and shear-wave splitting analyses. The application of these passive techniques to explore the structure of the crust and mantle beneath the AASZ is an important complement to active source imaging. For the continental part of the arc, temporary arrays deployed within the backbone of USArray, coordinated with OBS deployments and marine seismic profiling, will extend the length, width, and penetration depth of such profiles. Dense array studies of active volcanoes are also a high priority. Offshore islands, in particular Kodiak, provide excellent opportunities for carrying out large array studies in the forearc. For the marine portion of the arc, the strategies would be similar, but much more emphasis would necessarily be placed on OBS deployments. This is strong motivation for bringing the Amphibious Array to Alaska.

2.2.5.6. Magnetotellurics

Magnetotellurics (MT) is widely recognized as an important component of lithosphere and especially volcano imaging efforts, given that the conductivity of melt is significantly higher than that of the surrounding crust. Melt conductivity is also a function of temperature and composition. Dense networks of 3D broadband MT stations can be used as part of integrated experiments to image the structure inside volcanoes as has been done in other locations. There is a growing pool of instrumentation for land MT operated as a national facility through Oregon State University that would be available for GeoPRISMS field projects.

2.2.6. Numerical and Experimental Studies

Numerical and experimental studies will prove important for the AASZ, as they provide a means to integrate interdisciplinary field observations, test fundamental hypotheses, and constrain critical parameters that govern observed phenomena. Geodynamic modeling can serve as a synthesis activity, bringing together a variety of geological, geophysical, and geochemical data and interpretations into a broader framework that can be used to constrain ideas and make testable predictions.

2.2.6.1. Experimental Studies

Experimental studies are an important means to better constrain material properties and to test hypotheses developed from field observations. Representative studies include laboratory measurements of rock and fault gouge frictional behavior, in order to evaluate the role of rock composition and physical properties, as well as state variables (pressure, fluid chemistry, and temperature) on fault sliding stability, and the origin of specific slip behaviors, including episodic tremor and slow slip. Laboratory experiments can also provide insights into the linkages between surface processes, sediment transport, and accommodation, linked to both field and theoretical studies. Similarly, laboratory experiments provide a direct approach to quantify the effects of hydrous fluids and melts on mantle rheology relevant to the origin of arc volcanoes and volatile fluxes. Experimental studies are also essential for establishing the physical conditions of subduction zone fluid and melt formation and evolution. Without experimental constraints, the significance of volcanic and plutonic rock compositions and their variability through time and space at the earth’s surface cannot be unambiguously understood. A holistic approach involving an experimental component will be particularly important. Fluid and melt formation and migration through subduction zones constitutes a complex problem of reactive transport and heterogeneous equilibria that can only be understood by coupling detailed laboratory constraints (experimental mineralogy, petrology, geochemistry) with observations of bulk physical properties on a lithospheric scale (geophysical data) and with a detailed knowledge of the petrology and geochemistry of volcanic and plutonic rocks, which constitute the end products of subduction crustal genesis. All of the resulting data can be incorporated into geodynamic models that test specific hypotheses for the AASZ, including the dynamics controlling slab dip, anisotropy and flow in the mantle wedge, and the slip behavior of the slab/mantle interface.

2.2.6.2. Numerical Modeling

Regional 3D geodynamic models can be used to investigate several SCD thematic questions, for example:

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. 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. This implies local decoupling of the lithosphere from the mantle, yet the magnitude of this decoupling is poorly constrained. 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.

Evolution of deformation in space and time: Possible modeling 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.

Feedbacks between tectonic and surface processes: Sophisticated models are available for both crustal and surface processes; however, a complete description of an active landscape requires characterization of the interation between these processes. At present, available evidence of such 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 and Namche Barwa in the Eastern Syntaxis of the Himalayan collision illustrate the time dependent variability of material strength fields within actively deforming regions. The addition of similar type strain-softening materials coupled to glacially driven erosion should be a next step in geodynamic/geomorphological models of the Alaskan margin, facilitated by the Community Surface Dynamics Modelling System (CSDMS) Group. Mesoscale atmospheric models now can be used to condition the surface boundary.

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. It is necessary to 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.

2.2.7. Research Strategies and Partnerships

2.2.7.1. Shared Logistical Support for Remote Field Studies - "Community Expeditions"

The costs in time and dollars of moving people and equipment to and from remote locations in the AASZ are substantial, and in many cases place significant limitations on the research goals that can be achieved. One step toward maximizing efficiency and lowering field support costs would be to operate projects in tandem that have similar field support needs, and can therefore be supported from a common, and perhaps mobile, logistical base. One can imagine for example, a helicopter operating from the deck of a ship, moving east-to-west along the arc, supporting a variety of scientific groups at different locations throughout the 3-month Alaska field season. Such an effort might be proposed as a "community expedition", a direct analogue of the community experiments envisioned for the collection of large offshore geophysical imaging data sets. On a smaller scale, centers of logistical support could be established at remote airstrips and in other places where fuel and supplies can be safely cached, and where a common base of field operations could be established and used by diverse groups. This approach to logistical support would require diverse groups, which may or may not have common scientific goals, to collaborate and coordinate their field operations in a detailed way. The potential payoff in terms of cost savings and expanded scientific opportunities would be potentially great.

In order to manage such logistical complications associated with conducting field work in the AASZ, upcoming field activities and community planning events could be announced on a website, facilitating partnerships among investigators. Ideally, the website or wiki page could be hosted by GeoPRISMS and mentioned in any program solicitations from NSF.

2.2.7.2. Community Experiments

Large onshore-offshore geophysical datasets are among the critical observations needed to address the core science questions in some of the geographical focus areas. The GeoPRISMS community and the broader earth science community have embraced the concept of acquiring some large geophysical datasets as community efforts when it's possible and makes sense for a given project. Here we define community experiments as large field efforts planned and executed by the community rather than a small group of PI's; data acquired from these programs would be made publically available immediately. This approach would enable a much larger group of people to benefit quickly from the data, and the use of the data by a broader community will maximize their scientific impact. It would also facilitate the involvement and training of junior scientists and students. The GeoPRISMS community expressed enthusiasm for community experiments in Alaska where possible.

2.2.7.3. Amphibious Array Facility (AAF) in Alaska

There is great scientific potential if the Amphibious Array Facility (AAF) were to move to Alaska. This $10M facility, funded by NSF in 2009 through ARRA (American Recovery and Reinvestment Act) for understanding hazards in the Pacific Northwest, is currently deployed in Cascadia as part of the Cascadia Initiative (CI). The funds, channeled through UNAVCO, IRIS, and OBSIP, were used to improve real-time GPS capabilities, densification of the onshore seismic networks, and to construct ocean-bottom seismometers (OBS) to better record offshore earthquakes in the region. The CI has a finite duration of 4 years, with the expectation that the onshore and offshore components of the AAF will likely move together to other locations following the completion of the CI. In the context of the ongoing EarthScope and GeoPRISMS programs, high priority locations include Alaska and the East Coast of North America. A community workshop in 2014 has been proposed as a venue to decide on the next deployment of the AAF.

There are compelling reasons to redeploy the AAF in Alaska. Alaska is the clear choice in terms of adhering to the earthquake hazards issue that was central to the initial funding of the AAF. There are ~5 times the number of earthquakes within Alaska each year as in all of the lower 48 states combined, and there is significant potential for hazardous high magnitude subduction earthquakes and tsunamis. Alaska was also the top choice of the GeoPRISMS community for subduction zone research. In 2014, USArray is expected to begin deployment in Alaska, subject to funding. Therefore by 2015, USArray should be well established in southern Alaska to provide synergy for AAF deployments. PBO has been fully deployed in Alaska since 2008 and time series are now mature, although there certainly could be opportunities for station upgrades, high-rate, low-latency GPS observations, and targeted station densification. A key aspect of GeoPRISMS efforts in Alaska will be the need for coordinated research efforts with shared logistics, given the short field season and relatively high field costs. This defines a unique opportunity to deploy the AAF in Alaska to take full advantage of the synergy with GeoPRISMS and EarthScope.

2.2.7.4. EarthScope Program

In addition to the collaborative CI Amphibious Array Facility, a variety of current and future EarthScope activities in the AASZ are apparent above, demonstrating the common scientific objectives with GeoPRISMS. Ongoing cooperation between the two programs is anticipated, particularly given the complementary nature of the GeoPRISMS and EarthScope research strategies. The pending deployment of EarthScope's Transportable Array (TA) to Alaska will provide an important framework for more focused onshore-offshore studies, particularly in the Cook Inlet area (Figure 2.11). Geophysical imaging along the Aleutian Arc will augment lithospheric scale studies in continental Alaska. The current recommendation to IRIS is that a single trans-Alaska long-period magnetotelluric profile utilizing the existing road network be carried out as part of Earthscope TA array data collection. This profile would largely follow the TACT line but could include some additional stations closer to the trench, such as on Kodiak Island. EarthScope's PBO facility is already gathering critical geodetic observations relevant to focused studies of megathrust processes, as well as proposed GeoPRISMS synoptic studies. Continued coordination between GeoPRISMS and EarthScope investigators is encouraged and expected to lead to strong synergistic collaborations.

2.2.7.5. USGS and NOAA Cooperation

Addressing GeoPRISMS science objectives in the AASZ can benefit by coordination with other state and national agencies and entities active in southern Alaska.

There are opportunities for partnerships with the USGS. The USGS part of the AVO conducts an extensive volcano monitoring and research program throughout the Alaska-Aleutian arc. AVO welcomes GeoPRISMS research on these volcanoes and related volcanic and tectonic processes. USGS scientists will endeavor to participate in, and facilitate, GeoPRISMS research. Interested researchers should contact AVO staff to discuss collaboration. The USGS also conducts paleoseismology and paleotsunami research along the Alaskan margin. There may be opportunities for collaborative work with this group of researchers as well, because their goals for the Alaska Peninsula region are similar to those in this Implementation Plan. Lastly, the Earthquake Hazards Program of the USGS is encouraging researchers to submit proposals to its external grants program that complement existing or planned GeoPRISMS proposals. There is plenty of overlap in the objectives of GeoPRISMS and this grants program, so this potential source of funding may be useful for some researchers, and collaborative proposals with the USGS may also be developed.

NOAA also has considerable interests along the southern margin of Alaska, in particular for improving tsunami impact forecasts. Any information that leads to better assessment of tsunami generation along the southern Alaska margin is valuable to the tsunami warning centers. In particular, present tsunami inundation models and evacuation plans could be inadequate if giant tsunamis like that generated by the Tohoku event occured in Alaska; paleotsunami studies will be critical for revealing whether or not this is the case. NOAA collects the definitive bathymetric datasets for all US waters, and through the Alaska Interagency Hydrography Working Group, they encourage collection of higher quality bathymetry that may be incorporated into NOAA bathymetry maps, which are then available for all to use. NOAA has volunteered to help with multibeam data acquisition plans, and may be able to provide tide gauges during data collection. Lastly, fisheries researchers within NOAA also collect bathymetry data, and there may be opportunities for collaborating with them for shallow water (<200 m) data acquisition.

2.2.7.6. International Collaborations

Aleutian crustal genesis and subduction-initiation studies described in Section 2 of this document will be closely coordinated with complementary studies that are ongoing under the German-Russian KALMAR Project (http://kalmar.ifm-geomar.de/?Home). All offshore work funded under GeoPRISMS for the sampling of Aleutian basement outcrops should be coordinated with work of the *R/V Sonne* done under KALMAR. The KALMAR work will focus on dredging of the fore-arc in the Adak area and locations further west, where strike-slip faulting and block rotation has produced steep slopes and abundant basement outcrops in the Aleutian fore-arc. Dredging targets for the KALMAR cruises will include Adak Canyon and Murray Canyon – the two major submarine canyons of the Aleutian fore-arc, which have been so far explored only in reconnaissance by prior cruises. Areas of extensive basement outcrop in the fore-arc located by dredging on KALMAR cruises should be investigated in detail by ROV-supported geologic mapping and sampling in follow-up cruises funded under GeoPRISMS. The KALMAR cruises will also focus on dredging of basement outcrops on the incoming Pacific Plate. This work will extend as far east as the Amlia Fracture Zone, but will be focused primarily from the Adak area west. Geochemical studies of rocks from the Pacific side of the trench will provide control over the nature of subduction inputs, which are poorly known but are vital to interpretation of the geochemical evolution of the arc crust.

2.2.7.7. International Ocean Discovery Program Opportunities

The International Ocean Discovery Program (IODP) is proposed as a 10-year program beginning in 2013, with a focus on four main research themes, two of which have strong synergy with the goals of GeoPRISMs and SCD science in particular: Earth in Motion and in Earth Connections.

Several SCD research targets in the AASZ, such seismogenic zone segmentation, mass fluxes, and the fate of volatiles can be addressed through scientific drilling. Earth in Motion addresses dynamic processes that occur on human time scales, including those leading to and resulting from earthquakes, landslides, and tsunami. Scientific ocean drilling can resolve the frequency, magnitude, mechanisms, and impacts of these events. Documenting the controls on the timing, size, nature, and effects of megathrust earthquakes is important for characterizing associated hazards and for understanding the underlying mechanisms that may control the nature of slip, and determine why there is such a variability in seismic behavior along the AASZ. Given the high rate of seismicity in the AASZ, scientific ocean drilling is well positioned to elucidate earthquake and faulting processes possibly through continuous, real-time monitoring from subseafloor observatories installed in boreholes. Scientific ocean drilling at key input locations along the AASZ can also explore fluid flow in seafloor sediments and volcanic crust determine how much CO_2 and water are fed into subduction zones, where their return to the surface may dictate the along-strike variability in Aleutian arc magmatism. Proposed drilling expeditions in the AASZ region can be organized through workshops that identify potential scientific objectives and research opportunities in the region. The dissemination of existing site survey data and plans for acquisition of new data would be a key component of these workshops.

2.2.7.8. Rapid Response

The frequent seismic and volcanic activity in the AASZ illustrates the potential for large magnitude events that would require a rapid response to document post-event processes. Examples of recent events that NSF has supported with Rapid Response Research (RAPID) grants are the 2010 earthquakes in Chile and Haiti, the 2011 earthquakes in Japan and New Zealand. Examples in Chile of such a response is the collection of an open community dataset using portable seismograph deployments supported by the IRIS Consortium to record aftershocks for approximately six months post-event and the marine geophysical characterization of structural changes in the seafloor that resulted from movement along faults and submarine landslides (SIOSEARCH). A rapid response program for an event in the AASZ should leverage existing infrastructure and logistical knowledge of the AVO and USGS.

2.2.9. Broader Impacts

2.2.9.1. Geohazards

Fundamental contributions to understanding earthquake and tsunami hazards can be made through GeoPRISMS. Studies of the Alaska Peninsula and the Amlia fracture zone can help us understand the geologic controls on megathrust ruptures, variations in locking behavior along the megathrust, and tsunami generation. In the aftermath of the devastating tsunami that resulted from the 2011 M9.0 Tohoku Japan earthquake, concerns are heightened as to whether a similar tsunami could be generated along the Alaskan-Aleutian subduction zone. A Tohoku-like tsunami triggered by an earthquake along the Alaskan margin would cross the Pacific Ocean and cause extensive damage along the highly populated U.S west coast and Hawaiian shores, with ports being particularly vulnerable. As a case in point, a tsunami caused by a near-trench earthquake in 1946 off Unimak Pass caused significant damage along the U.S. west coast, took 150 lives in Hawaii, and inundated shorelines of south Pacific islands and Antarctica. Currently, assessments of the seismic and tsunami potential of the Alaska margin lag far behind assessments of the

Cascadia margin, despite the fact that 4 of the twelve instrumentally recorded giant earthquakes ($Mw \geq 8.5$) that have occurred worldwide were from the Alaska margin.

The chief hazard presented by volcanoes of the North Pacific region is from airborne clouds of volcanic ash, which can severely damage and disable jet engines of aircraft that inadvertently fly through them. Accurate forecasting of eruptions and close monitoring of ongoing eruptions by AVO and other groups provide the most direct approach to alleviating volcanic hazards to air traffic over the North Pacific. At a basic research level, the GeoPRISMS focus on the storage, transfer and release of volatile components in magmas, provides an opportunity to better understand the interrelationships of volatile contents, magma chemistry and eruption dynamics that underlie the processes by which volcanic ash is formed. Direct measurement of volatile species and related elemental abundances (H_2O, CO_2, F, Cl, S) in melt inclusions in tephra from a large variety of AASZ magma types will create linkages between key volatile components (especially H_2O), and other more widely known geochemical parameters. Linking these geochemical measurements to textural features in volcanic ash, which record the physical characteristics of eruptions, will greatly expand the database of observations in natural samples from which the dynamics of explosive eruptions may be inferred and modeled. For some volcanoes, geophysical data collected by GeoPRISMS will complement these volatile studies, allowing for more complete hazard assessments or improved monitoring. AVO and GeoPRISMS scientists can work closely on this problem; AVO will actively use any seismic and geodetic data supported by GeoPRISMS that are available for enhanced volcano monitoring capability.

2.2.9.2. Student and Teacher Involvement

Established pathways exist through GeoPRISMS and EarthScope to convey important GeoPRISMS research results in Alaska into college classrooms around the country, including through the development of GeoPRISMS mini-lessons and the GeoPRISMS Distinguished Lectureship Program. Both resources can also be adapted to younger or informal science audiences, enhancing broader impacts on local communities in Alaska. Involving nearby schools and communities in instrument deployment and data collection has also proven effective in engaging residents in scientific activities in their area. Efforts to develop a GeoPRISMS REU program would also enable new training opportunities for future scientists interested in Alaskan studies. Cooperation with existing state-wide programs will further these activities as research ramps up in the Alaska Primary Site.

2.2.9.3. Engaging Local Communities

Small, relatively isolated towns are sprinkled across the Aleutian Islands, Alaska Peninsula, and Cook Inlet. Larger communities and Alaska's main city (Anchorage) are located within the Cook Inlet region. Residents in these areas are routinely exposed to the hazards associated with the subduction zone. But because many communities are accessible only by boat or plane, outreach poses particular challenges. GeoPRISMS activities in Alaska offer an excellent opportunity to connect with people who live next to this active plate tectonic boundary. Scientists can take the opportunity to visit schools and give community presentations while visiting remote communities. Deploying instruments near schools is another means to engage young people and educate them on their surroundings. Education and outreach efforts should also involve follow-up with local communities on the results of scientific investigations in the area (not just visits during field campaigns) either in person or remotely (e.g., via video conference).