GeoPRISMS Subduction Cycles and Deformation White Papers

Exhumed Subduction Margins: An important record of deformation and metamorphic processes
Author: Mary Leech

Seismic Hazards, Continental Deformation, and Mantle Recycling Associated with the Himalayan Continental Subduction Zone
Authors: James N, Larry Brown, and INDEPTH Team

Metamorphic Processes Implementation Strategy - GeoPRISMS SCD
Authors: S. Penniston-Dorland, G. Bebout, B. Hacker, H. Marschall, M. Feineman, T. John, P. Agard, P. van Keken, G. Abers, J. Filiberto, T. Zack, J. Gross, J. Ague, E. Baxter, J. A lt, M. Cloos

Subduction Initiation and the Need to Study Forearc Crust
Authors: Mark K. Reagan, Robert J. Stern, David W. Scholl, Osamu Ishizuka, Yasuhiko Ohara, Kenichiro Tani, James Gill, Julian Pearce

Africa-Arabia-Eurasia Plate Interactions and Implications for the Dynamics of Mediterranean Subduction and Red Sea Rifting
Authors: R. Reilinger, B. Hager, L. Royden, C. Burchfiel, R. Van der Hilst

The SW North American Cordillera: an exposed, accessible and underutilized archive of Paleozoic to Cenozoic subduction-initiation processes
Authors: J. Saleeby, J. Shervais, K. Marsaglia, R.J. Stern, M. Gurnis, and Henry Dick

An Implementation Strategy for Understanding Subduction Initiation (SI); Integrated Studies of Naked Forearcs, Ophiolites, and Geodynamic Modeling
Authors: Robert J. Stern, Yildirim Dilek, Taras Gerya, Michael Gurnis, Osamu Ishizuka, Wei Leng, Kathleen Marsaglia, Julian Pearce, Mark K. Reagan, John W. Shervais, Yoshiyuki Tatsumi, Scott A. Whattam

The Southeast Mariana Forearc Rift: A Modern Analogue for Forearc Extension during Subduction Initiation
Authors: Robert J. Stern, Fernando Martinez, Julia Ribeiro, Mark Reagan, Yas Ohara, and Osamu Ishizuka

The Hikurangi Margin, New Zealand: an important natural laboratory to understand subduction thrust behavior
Authors: Laura Wallace, Susan Ellis, Stephen Bannister, Stuart Henrys, Rupert Sutherland, Daniel Barker, Agnes Reyes, Philip Barnes, Joshu Mountjoy, John Townend, Rebecca Bell, Nathan Bangs, Harold Tobin, David Okaya, Susan Schwartz, Eli Silver, Demian Saffer, Kelin Wang, and Ake Fagereng

The Gulf of Alaska Margin: Potential Focus Site for GeoPRISMS SCD
Authors: Lindsay L. Worthington, Sean P.S. Gulick, John M. Jaeger

Illuminating the architecture of crustal magmatic systems in the Cascade region

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White paper proposal for the Cascade region; MARGINS program

Illuminating the architecture of crustal magmatic systems in the Cascade region

Summary:

In order to: (1) resolve major tectonic controls on volcanism along the Cascade arc, and (2) determine the configuration of crustal magma transport and storage, including the extent and characteristics of highly crystalline magma bodies (crystal mushes; potential sources zones for explosive silicic magmas), we propose that a variety of high-resolution seismic and MT methods should be used to image the crust and upper mantle in strategic locations in Cascadia. Our first choice would be to focus data gathering efforts on Mount St. Helens (MSH), with potential of a follow-up survey of Mount Hood as (a) both volcanoes have erupted within the last 250 years, (b) the volcanoes are close to urban centers (Portland, OR; Columbia River shipping channels), (c) there is a wealth of detailed geologic, petrologic, and geophysical information on Holocene MSH, (d) the arc magmatic front shifts abruptly westward from Mount Hood to MSH, associated with forearc basaltic volcanism in the Portland metropolitan area, (e) previous surveys using both seismic tomography and MT data have outlined interesting regional structures in the upper-to-lower crust that require further investigation.

Project:

Intermediate arc magmas (andesites, dacites) have compositions closely similar to estimates of the bulk continental crust, but such intermediate magmas are difficult to interpret unambiguously because of complex processes of differentiation, mixing, and assimilation involved in their formation. At a basic level, it is important to have a clearer understanding of where arc magmas stall in the crust, in what volumes, and why magma storage differs from one volcano to another. Armed with this information, geochemists could develop more tightly constrained and quantitative interpretations of the processes of crystallization, assimilation, melt extraction, and mixing in the middle and lower crust; geophysicists could more accurately interpret the apparent granitoid-dominated mid-crustal seismic velocities in arcs; and volcanologists could infer the magma recharge times, lengthscales, and depths recorded by geodetic, seismic, and other monitoring signals.

Imaging of crustal magmatic architecture will be challenging in the Cascades due to the generally low eruptive fluxes of volcanic centers (which is suggestive of compact magmatic systems), but this concern is countered by the extensive infrastructure (roads, power, telecommunications) available to support an intensive geophysical study; the wealth of previous work on the geology, eruptive history, petrogenesis, and upper crustal geophysical imaging for MSH; and already established close working relations between land managers (US Forest Service) and the volcano monitoring community (USGS, Pacific Northwest Seismographic Network). Moreover, easy access to the greater MSH – Mount Hood region would permit numerous low-cost concurrent and follow-on studies by research groups of diverse affiliation.

Specific questions to address include: 1) Is there a well-defined zone in the deep crust where parental magmas stall and assimilation and differentiation take place? 2) Is this zone localized to the base of the crust, suggestive of a density control on magma storage, or is it more extensive? 3) What lies above this deep zone: dikes feeding to the seismically imaged shallow crustal reservoir, or a more vertically integrated mush column that may approach trans-crustal extent? 4) MSH mainly erupts dacites, and many of these carry Pleistocene zircons (Claiborne et al. 2010) suggestive of the presence of a long-lived evolved crustal intrusive complex or mush body. However, during the period 1950 to 1750 years ago, multiple basalt types erupted through the MSH conduit system (Mullineaux 1996, Clynne unpublished). Local earthquake tomography studies have only been able to penetrate ~7-8 km below MSH and show evidence for only a relatively small magmatic reservoir or widened conduit (Waite and Moran 2009). Is there a sizeable silicic mush body beneath the volcano or not? 5) Some interpretations posit that MSH dacites are mainly melts of the deep crust (e.g., Smith and Leeman 1987; Pallister et al. 1992; Pallister et al. 2008), so can a region of deep crustal melting be recognized and how large is it? 6) MSH sits atop the St Helens seismic zone, and seismic refraction profiling to the north (Parsons et al. 1998) suggests that the seismic zone marks the buried eastern edge of the Paleocene Siletzia basaltic seamount province. How does this terrain boundary influence magma storage and transport? 7) Magneto-telluric (MT) imaging reveals a mid-crustal conductor in the southern Washington Cascades that merges with high conductivity at the shallow MSH conduit system. To the north, the crustal conductor reaches the surface in anticlinal exposures of Eocene sediments, elsewhere concealed by the Oligocene and Miocene volcanic section (Egbert and Booker 1993; Stanley et al. 1996), but in the MSH – Mount Adams region it has been interpreted as a widespread body of magma (Hill et al. 2009). Which is it? 8) MSH marks a pronounced westward step in the Cascades volcanic front, moving northward, associated with enigmatic forearc basaltic volcanism in the Portland area. Regional P- and S-wave tomography are suggestive of a discontinuity in the subducting slab beneath that area (Schmandt and Humphreys 2010) that might account for the shift in volcanism. Can the slab be better imaged in the northwest Oregon – southwest Washington area to investigate the presence of a discontinuity, with implications for generation of MSH magmas by slab-edge melting? 9) When MSH last erupted, the volume of magma released exceeded what would be inferred by its deflation. This difference could signify recharge counterbalancing withdrawal, or it could result from expansion of bubbles in non-erupted mushy magma (Mastin et al. 2008). Can high-resolution geophysical techniques resolve bubbly magma?

We propose deploying a dense network of broadband seismometers and MT receivers radially around MSH, and extending several tens of kilometers in both the E-W and N-S directions, coupled with active source experiments. The seismic data will be used for receiver function analyses; local earthquake (Vp and Vs), teleseismic body-wave, noise-correlation, and active-source tomography inversions; and shear-wave splitting studies. The MT data will be used to construct full 3-D conductivity models. A complementary active seismic tomography and scattered wave imaging experiment will illuminate the crustal structure and Moho details. We also suggest that lines connecting both volcanoes across the Columbia River would be important to better image the fundamental transition that occurs in the area. This depths-to-daylight study of dangerous volcanic systems would provide dividends for both science and for society.

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Deformation measurements across an entire subduction plate boundary: Cascadia Subduction Zone

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Proposed site: Cascadia Subduction Zone

Themes addressed: (From the GeoPRISMS Draft Science Plan)

4.1 What governs the size, location and frequency of great subduction zone earthquakes and how is this related to the spatial and temporal variation of slip behaviors observed along subduction faults?

4.2 How does deformation across the subduction plate boundary evolve in space and time, through the seismic cycle and beyond?

Key existing and forthcoming data/infrastructure: 1) Moored-buoy for continuous GPS-Acoustic measurements of horizontal deformation and continuous seawater pressure measurements at the seafloor with a low-drift sensor and in-situ physical oceanographic measurements for sounds speed and density. 2) Earthscope, Plate Boundary Observatory, Ocean Observatories Initiative-Regional Scale Nodes (seafloor cable) and -Endurance Array (buoys), Cascadia Initiative Ocean Bottom Seismometer array.

Discussion:

We propose an experiment to measure crustal deformation along a profile that crosses the entire region of a subduction zone from the incoming plate, the offshore continental slope and the sub-aerial continent. Subduction thrust faults generate the largest earthquakes and their submerged portions are where tsunami are generated causing the most devastating geo-hazard of recent times (Figure 1). However, little is known about the dynamics or even the kinematics of deformation offshore. Space-based tracking based solely upon electromagnetic energy (GPS, InSAR, etc) can track deformation of the sub-aerial region down to the coast, but cannot follow the deformation offshore where it continues to increase during the interseismic period, and where tsunami are generated with co-seismic release. GPS tracking of surface platforms combined with acoustic ranging to seafloor transponders has proven to be an effective means of measuring offshore deformation within subduction zones with sub-centimeter resolution [*Gagnon et al.*, 2005, *Matsumoto et al.*, 2008]. However, to date, data have been collected infrequently during semi-annual, annual, and bi-annual visits with a ship lasting a few days. Sensors to measure vertical deformation by observing seawater pressure at the seafloor have been left in place to record continuously, but to date they have drift rates of several centimeters per year [*Polster et al.*, 2009]. They also are sensitive to changes in the density of the water column and the sea surface height. To address these issues, we have developed a moored-buoy that provides continuous, sustained measurements of both horizontal and vertical deformation of the seafloor, the sea surface height, and the density of the water column beneath the buoy (Figure 2). Using GPS and acoustics, horizontal positions of the seafloor are measured once per minute. Initial tests in shallow water over a few months show resolution of the horizontal component consistent with previous ship-based systems at the centimeter level [*Chadwell et al.*, 2009]. Vertical deformation is measured with water pressure sensors that periodically switch to a constant pressure standard, allowing sensor drift to be quantified and removed. Oceanographic effects, measured by the buoy and CTD string, are likewise removed from the pressure signal leaving seafloor vertical motion as the residual. Deepwater tests are currently underway and preliminary data suggests cm/yr resolution will be attained.

We propose to deploy this system along a profile cutting across the Cascadia Subduction Zone (CSZ) and supplement it with one or two campaign-style GPS-Acoustic arrays with drift-compensated pressure sensors along the same profile. Sub-aerial deformation is already continuously monitored with GPS at hundreds of sites along the CSZ. Seafloor deformation measurements at just a few sites could meet the Science plan goal 4.2 – "How deformation across the subduction zone evolve?". Additional data sensors from the OOI will contribute to addressing Science plan goal 4.1 –"… what governs large events?... ". Earthquake seismicity and crustal structure derived from the Cascadia Initiative OBS array would also contribute. However, we note that pressure sensors deployed on these OBSs will suffer from several centimeters of drift per year and be unable to resolve interseismic deformation along the plate interface.

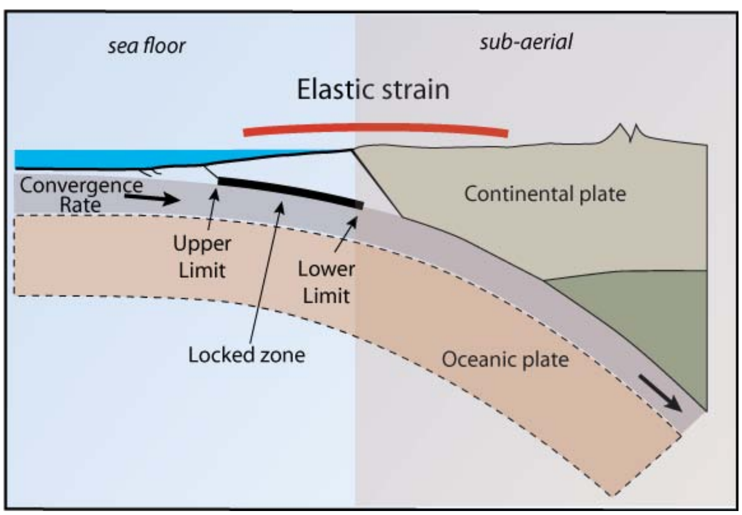

Figure 1: Profile view of subduction process indicating the significance of the offshore region.

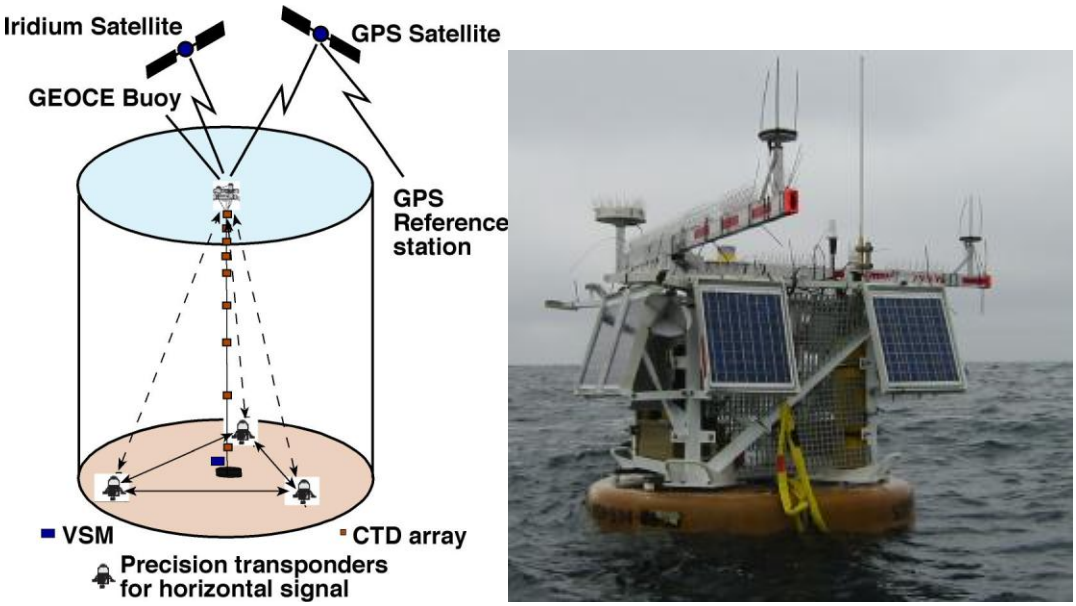

Figure 2: Moored-buoy for continuous horizontal and vertical deformation measurements: concept (left), implementation (right).

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Four-D Investigation of Subduction Initiation (SI) Magmatism as Revealed in Tethyan Forearc Ophiolites

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Introduction and Scope

Oceanic crust preserved in intra-oceanic forearc settings develops during subduction initiation and may preserve a complete igneous and geochemical record of melt evolution during the first 5-8 million years of subduction-induced magmatism (Reagan et al. 2010). Dredging, diving, and drilling provide but limited samples from modern forearc environments, making a systematic, age-constrained 4-D study of SI igneous stratigraphy and structure difficult and expensive. The results of the earlier studies of forearc crustal architecture and its magmatic record, based on DSDP Leg 60 and ODP Legs 125 and 126 expeditions to the Izu-Bonin-Mariana (IBM) system in the 1970's and 1980's, played a fundamental role in understanding oceanic crust formation in the upper plates of intra-oceanic subduction zones, and led to the development of the suprasubduction zone (SSZ) ophiolite concept (Pearce et al. 1984; Dilek 2003). Recent submersible (Shinkai 6500) studies of the IBM forearc indicate seafloor spreading formed forearc oceanic crust during the first 7 million years of SI magmatism (Reagan et al. 2010; Stern et al. 2010). The geological record of the IBM forerac shows a time-progressive evolution from 51-52 Ma forearc basalts (FAB), to 48 Ma boninitic lavas, and 44-45 Ma arc lavas prior to the construction of a mature magmatic arc with discrete volcanic centers. This geochemical trend of the SI-related IBM forearc crust is analogous to that of many well-preserved Tethyan SSZ ophiolites in the eastern Mediterranean region (Dilek & Furnes 2009). We, therefore, propose the designation of a Tethyan ophiolite as a focus site for the GeoPRISMS Subduction Cycles and Deformation (SCD) initiative.

Our study of some of the best-preserved Phanerozoic SSZ ophiolites in different orogenic belts demonstrate that their internal structure-stratigraphy and geochemical signatures indicate a seafloor spreading origin in forearc-incipient arc settings during subduction initiation (Dilek & Furnes 2009, 2010). In general, there is a well-developed magmatic stratigraphy in the extrusive sequences of these ophiolites from older MORB-like lavas at the bottom towards younger island arc tholeiite (IAT) and boninitic lavas in the upper parts (Shervais 2000; Ishikawa et al. 2002; Dilek et al. 2008). A similar progression of the lava chemistry also occurs in crosscutting dike swarms ad sheeted dikes, indicating increased subduction influence in the evolution of ophiolitic magmas through time. Lherzolitic peridotites in structurally lower parts of the upper mantle sequences of these ophiolites represent the residue after MORB melt extraction. Harzburgite and harzburgite-dunite associations higher up in the mantle sequences and below the mafic-ultramafic cumulates (transitional Moho) are crosscut by networks of orthopyroxenite (opxt) veins, which include hydrous minerals (amphibole). These orthopyroxenite veins represent reaction between host harzburgite (depleted, residual peridotite) and infiltrating Si-rich (boninitic) melt (Dilek & Morishita 2009). The lateral and vertical progression of melt evolution in the crustal and upper mantle units of these ophiolites traces different stages of SI-related magmatism, providing an opportunity to investigate the 4-D structure, stratigraphy, and time-progressive evolution of oceanic lithosphere formation in forearc settings of the Mesozoic Tethyan subduction zone systems. The geochemical evolution of these Tethyan ophiolites was governed by slab dehydration and accompanying metasomatism of the mantle, melting of the subducting slab and sediments and repeated episodes of partial melting of metasomatized peridotites.

Primary Site and Proposal

We propose to designate the Jurassic Mirdita ophiolite in Albania in the Mediterranean region as a GeoPRISMS Subduction Cycles and Deformation (SCD) initiative Primary Site for further investigations for SI magmatism. The Mirdita ophiolite occurs in a nearly 40-kmwide belt bounded by the conjugate passive margin sequences of the Apulia (west) and Pelagonia (east) microcontinents (**Fig. 1**). The ophiolite and its gently-dipping sedimentary cover shows very little post-emplacement deformation, indicating that the igneous stratigraphy of the Jurassic oceanic lithosphere has not been affected by the Alpine orogenic events (Dilek & Furnes 2009).

The ~10-km-thick Eastern Mirdita Ophiolite (EMO) includes tectonized harzburgite and dunite with extensive chromite deposits, as well as ultramafic cumulates including olivine clinopyroxenite, wehrlite, olivine websterite, and dunite forming a transitional Moho with the overlying lower crustal section. The plutonic rocks are made of pyroxenite, gabbronorite, gabbro, amphibole gabbro, diorite, quartz diorite, and plagiogranite. A well-developed sheeted dike complex has mutually intrusive relations with the underlying isotropic gabbros and plagiogranites and fed the overlying pillow lavas. Dike compositions change from older basalt to basaltic andesite, andesite, dacite, quartz diorite, to late-stage andesitic and boninitic dikes as constrained by crosscutting relations. The ~1.1-km-thick extrusive sequence comprises basaltic and basaltic andesitic pillow lavas in the lower 700 m, an andesitic, dacitic and rhyodacitic massive sheet flows in the upper 400 m. Boninitic dikes and lavas occur as the youngest igneous products within the EMO (**Fig. 1b**). Cpx porphyroclast-bearing harzburgites occur in the lower parts of the upper mantle units, whereas harzburgites and dunites are more abundant in structurally higher parts of the peridotites. Dunite is commonly associated with chromitite layers (Morishita et al. 2010). Opxenite veins and dikes crosscut the peridotite foliations and the lithological boundaries between dunites (chromitite) and harzburgites, indicating its late-stage formation.

Major and trace element compositions of minerals in the Cpx-harzburgites indicate that they were formed as the residue of less-fluxed partial melting, and are similar to those in abyssal peridotites from mid-ocean ridges. Harzburgites have more depleted major element compositions than the Cpx-harzburgites. Light rare earth element (LREE)-enrichment in clinopyroxene coupled with hydrous silicate mineral inclusions in harzburgit spinels indicate these were produced as a result of enhanced partial melting of depleted peridotites due to infiltration of hydrous LREE-enriched fluids/melts. Refractory harzburgite, high-Cr# spinel-bearing dunite, and orthopyroxenite are genetically related to the late stage boninitic magmas in the crustal section of the EMO. In contrast, the Cpx-harzburgite is a residue related to mid-ocean ridge basalts (MORBs) or the "MORB-like" forearc basalt (FAB), as proposed by Reagan et al. (2010) from the IBM forearc system. Thus, we think that in the Jurassic Mirdita ophiolite we have an exceptionally well-preserved and exposed forearc oceanic lithosphere, which we can investigate through systematic mapping, sampling and drilling to put together a coherent story of the geochemical products of SI magmatism from its mantle geochemical reservoirs to the forearc-embryonic arc crust construction, and the effects of mantle metasomatism via melt and fluid flux and migration through the Tethyan mantle. We can accomplish these goals by systematic sampling of the crustal and upper mantle units of the EMO for whole-rock major oxide and trace-element analyses, electron microprobe and laser ICP-MS mineral analyses, and isotopic analyses (Rb/Sr, Sm/Nd, and Pb/Pb). We will better understand the crustal properties and geochemical features of magmas generated from melting of H_2O-rich mantle beneath a forearc setting in SSZ environments. The results of this investigation should provide new insights about forearc lithosphere evolution during SI (temporal constraints on changes in magmatic outputs), better characterization of boninite P-T-H_2O variations (links models to melts), and along-strike changes in the age, volume, and production rates of SI magmas. It is an excellent and accessible on-land site for 'groundtruthing' for studying forearc magmatic and tectonic evolution. This project also complements and brings synergy to the proposed activities by Stern et al. in their White Paper submitted for the GeoPRISMS Implementation Workshop (Stern et al., 2010).

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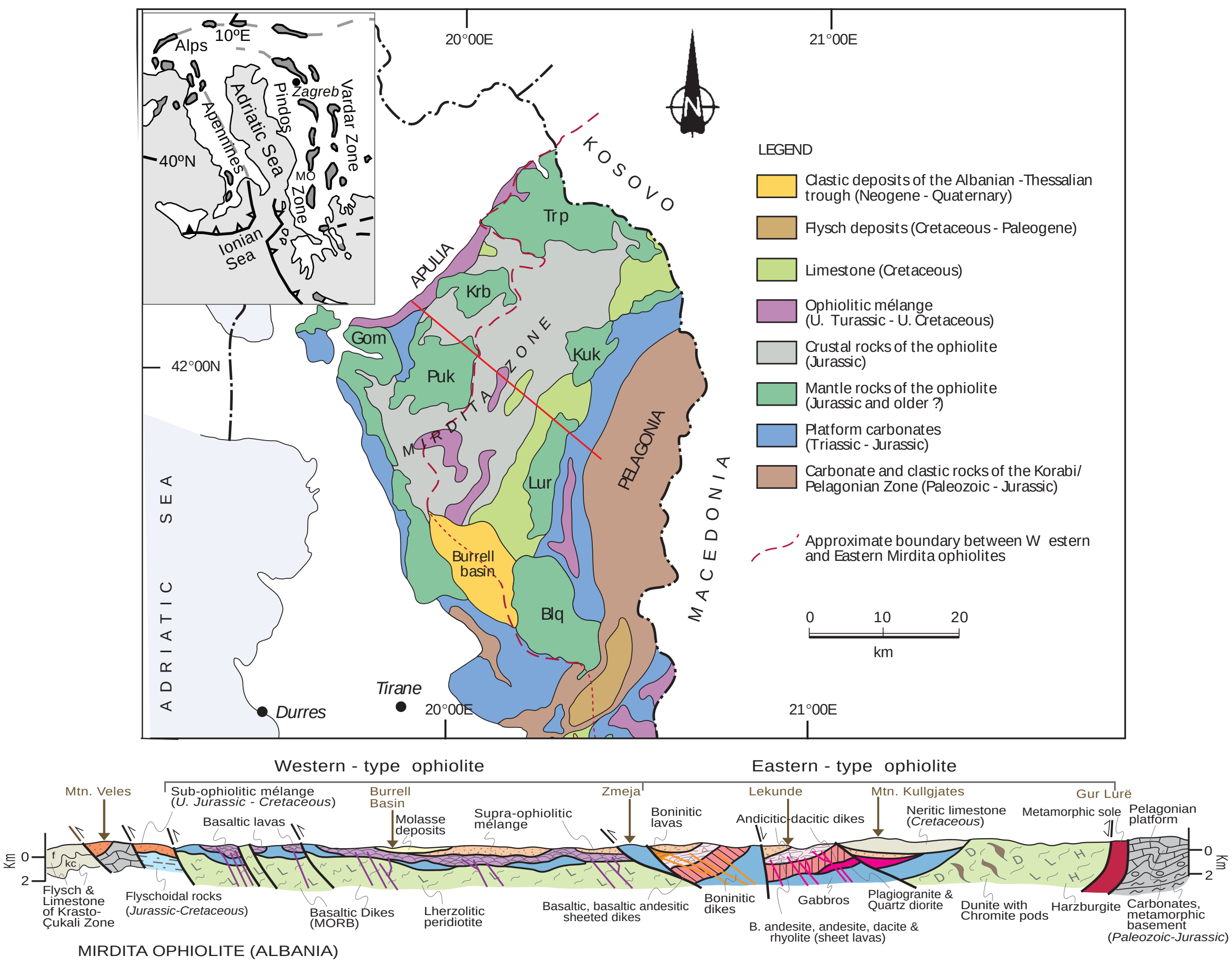

Figure-1: Simplified lithological map and a structural cross-section of the Jurassic Mirdita ophiolite in Albania (modified after Dilek et al. 2008; Dilek & Furnes 2009). The profile location is marked by the red-line on the map. Inset map shows the distribution of the Tethyan ophiolites in the Balkan Peninsula, with the Mirdita ophiolite labeled as MO.

Tracking Volatiles at Mount St. Helens From Magma Chamber Residence to Eruption at the Vent

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Topics/Themes: How are volatiles, fluids, and melts stored, transferred, and released through the subduction system?

Summary: As a means to understand a volcano from top to bottom, we propose a geochemical and microtextural examination of eruptive products in order to track the dynamics of magma mixing, devolatilization, and fragmentation from within the magma chamber, through the volcanic conduit, and out of the vent during eruption. We will focus on Mount St. Helens (MSH) due to the extensive petrological and analytical work already performed at this location and the possible selection of the Cascadia subduction zone as a GeoPRISMS focus site for the SCD initiative. The proposed study will directly address one of the primary topics/themes (see above) and will have broad implications for other active volcanoes. In addition to improving the understanding of an active volcanic system, the research described here will also help to clarify the role of various volatile elements in magmatic systems, their effects on magma rheology, and their use as geochemical tracers for H_2O behavior during magma mixing, decompression, devolatilization, crystallization, and fragmentation. This study will focus specifically on Li, B, and S, and how the behavior of these fluid-mobile elements compares with that of H during volcanic processes.

Project Proposal: In order to gain a more comprehensive understanding of volcanic processes and the role of volcanoes in cycling materials between the atmosphere, hydrosphere, and lithosphere, we propose an integrated study of the path of volatiles and their interaction with host magmatic fluids and solids as they are transferred from magma chambers at depth, through a volcanic conduit and vent finally to be deposited on the land surface. This will shed light on eruption drivers and characteristics of eruptions controlled by volatile exsolution, as well as chemical interactions between volatiles, melt, and minerals within the magmatic system.

Products from both the 1980 and the 2004 eruptive events at MSH will be examined in order to build upon the extensive work that has already been conducted on these eruptive stages [*1-19*]. Examination of the 1980 samples will focus on deposits from the lateral blast, Plinian explosion, and cryptodome. Examination of the 2004 products will focus on ash from the initial phreatic explosions and various stages of lava dome extrusion. Direct comparison between explosive and effusive products will allow better constraint of volatile behavior during different styles of magma ascent. The various analyses conducted will occur simultaneously at the collaborating institutions and will involve a large number of samples (hundreds of individual crystals and ash grains) in order to establish a statistically rigorous dataset that can then be utilized to model volatile behavior in the MSH system. Total time required for the project is estimated at 4-5 years.

Using the OmniPressure Laboratory at Arizona State University, experiments will be performed at various static pressures and temperatures to determine the diffusion and partitioning behavior of the listed fluid-mobile elements (H, Li, B, S) specifically within MSH minerals (focusing on plagioclase and hornblende) and melts, as previous studies have noted enrichment of some of these elements in MSH products [*7,9,11,12*]. Our experiments will allow quantification of trace element diffusivities in the various minerals examined, permitting direct calculation of volatile exsolution rates and future use of eruptive products to determine pressure/temperature conditions in the magma based upon trace element concentrations.

Polished sections of hornblende phenocrysts will be chemically mapped using secondary ion mass spectrometry (SIMS) to determine the zoning patterns of volatile elements within these hydrous minerals. In particular, we will examine possible evidence that reveals influx of volatile-rich magmas at depth in the plumbing system, prior to magma ascent into the volcanic conduit. Previous geochemical analyses have shown evidence of Li enrichment in products from both the 1980 and 2004 eruption, and these studies have attributed this enrichment to vapor transport from a deeper magma source [*7,9,11,12*]. Various hornblende textures will provide information on magma chamber processes and the transition from chamber residence to conduit ascent [*1,3*]. Hornblendes lacking breakdown textures will permit characterization of magma chamber conditions, but hornblendes that also display a breakdown rim (either as a result of decompression or heating) will signify a transition in the dynamic conditions of the magma, and the behavior of volatile elements in these hornblendes will be particularly useful in deciphering stages of devolatilization during ascent through the conduit or magma mingling at depth in the chamber. We predict that reaction textures will be associated with gradients in rapidly diffusing chemical or isotopic species that can be used, in addition to the experimental studies of breakdown kinetics [*1,3*], to set timing limits on texture development. Diffusive re-equilibration of Li in minerals due to new magmatic conditions results in large isotopic gradients in δ^7Li. Changes in B concentration and δ^{11}B are expected to be extremely slow, based on rates of B isotope equilibration in tourmaline [*20*].

Plagioclase phenocrysts and microphenocrysts will be depth profiled using SIMS to examine chemical variations during the final stage of decompression-induced crystal growth within the volcanic conduit [*21-23*]. In lava samples, this will track magma ascent from the chamber to effusion at the vent. For explosively erupted samples, this will allow quantification of pressure/temperature and devolatilization/crystallization conditions immediately prior to eruption [*22,23*]. High-resolution (~10 nm per datum) examination of plagioclase compositions during the final stage (<50 μm) of crystal growth will provide information on the physical dynamics during conduit ascent (Fig. 1). A wide range of P-T-t space is accessible using different minerals, chemical or isotopic systems, and by combining high spatial-resolution depth profiling and conventional microbeam lateral traverses.

Using stereo-scanning electron microscopy (SSEM), ash grains will be imaged and a digital elevation model (DEM) will be constructed from the stereo-pair image using specialized software (MeX). Utilizing another software tool (BubbleMaker), bubble volumes are determined from the constructed DEM [*24-26*]. Work is currently in progress to determine the bubble number densities, bubble size distributions, and role of microlites as sites for heterogeneous bubble nucleation [e.g., *27*] in distal ash samples derived from the 1980 eruption at MSH (Fig. 2). Additional samples will be examined from other 1980 tephra deposits in various locations in order to determine the physical parameters that cause volatile exsolution in the shallow conduit to transition to magma fragmentation at the vent, constraining one of the final roles of volatiles in the subduction system. Samples from the initial phreatic phase of the 2004 eruption will allow comparison between different styles of fragmentation mechanisms at the same volcano. In addition to SSEM, selected ash grains will also be imaged with X-Ray Ultra-Microscopy (XuM), which utilizes the X-rays generated by the SEM to pass through objects and project an image onto a target, allowing visualization of components *within an ash grain* [*28*], including microlites acting as vesicle nucleation sites [e.g., *29*].

If the Cascadia subduction system is selected as a GeoPRISMS focus site, the project outlined above can also be applied to other volcanoes within that system in order to determine the role of fluid-mobile trace elements on an *arc-wide scale*. We suggest that Cascadia would represent one of the best candidates for a focus site due to the foundation of work already performed and the use of this previous research (and the work stemming from it) in addressing some of the fundamental goals of the SCD initiative and the GeoPRISMS program.

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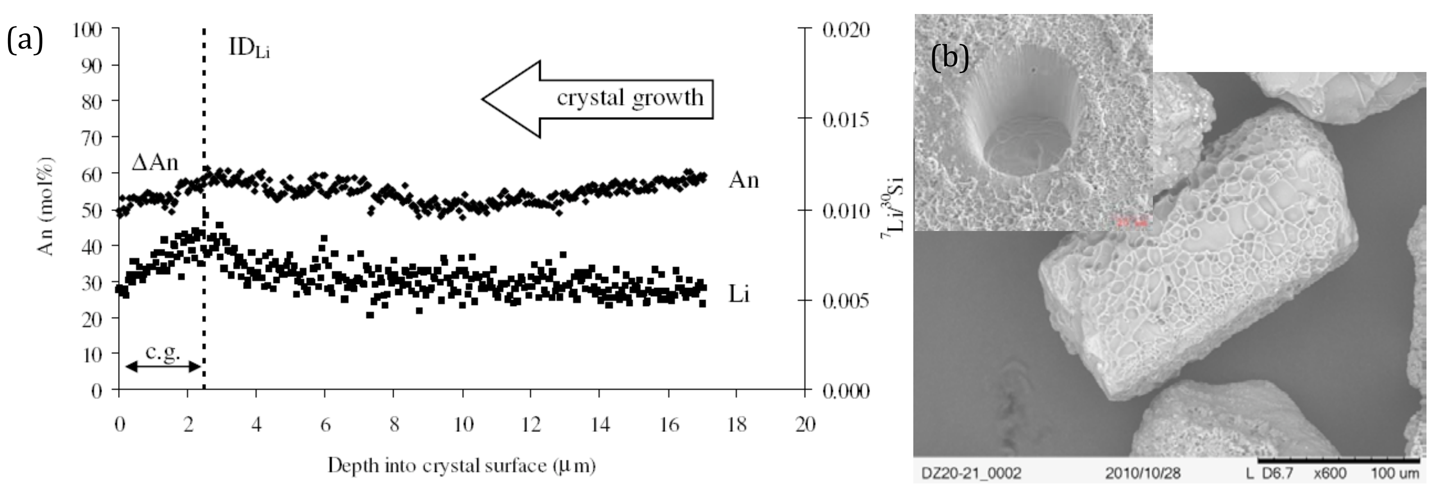

Fig. 1 (a) SIMS depth profile into plagioclase phenocryst derived from an explosive eruption of Soufrière Hills Volcano, Montserrat, which was used as the field area for development of this particular SIMS technique [*21*]. The final few micrometers of crystal growth (c.g.) shows decreasing anorthite content (ΔAn) and decreasing Li, which is marked by an inflection (ID$_{Li}$), both of which result from decompression and volatile exsolution in the volcanic conduit during ascent [*22,23*]; (b)

secondary electron image of microphenocryst derived from distal ash samples of the Mount St. Helens 1980 eruption, similar to samples that will be selected for SIMS depth profiling with the inset image providing an example of a depth profiled crater in a crystal surface.

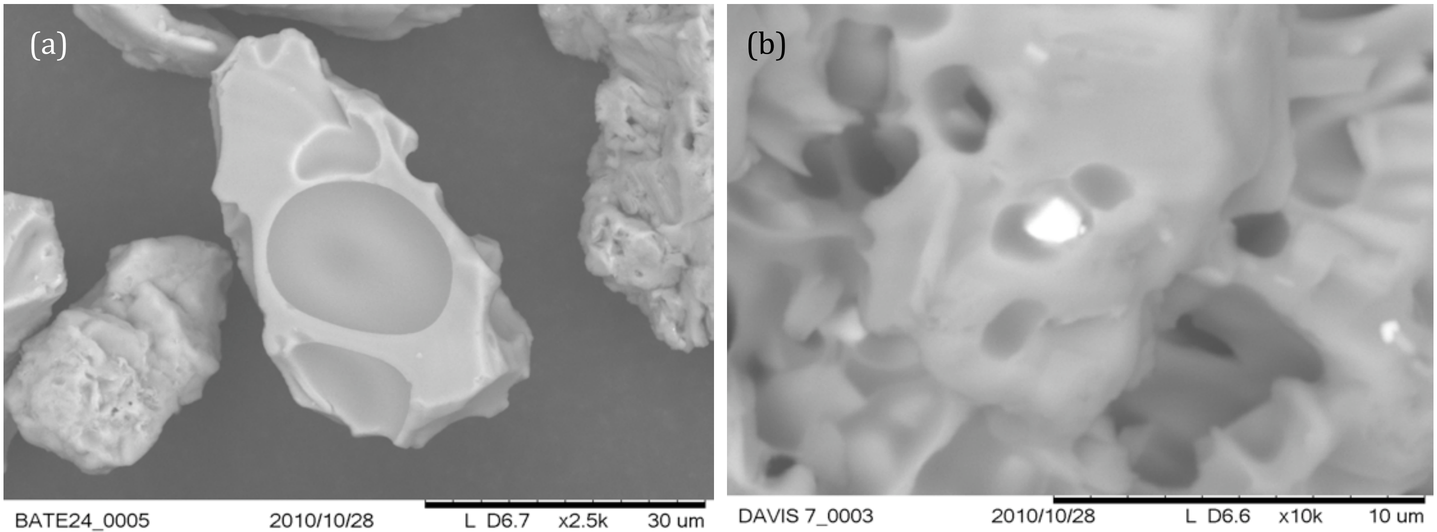

Fig. 2 Secondary electron images of ash particles derived from distal deposits of the 1980 Mount St. Helens lateral blast: (a) A single ash grain ~50 μm in length displaying vesicle walls. Grains like these will be used to create a digital elevation model from stereo-pair images in order to reconstruct the original vesicle volume at the moment of fragmentation; and (b) a ~1 μm-sized vesicle nucleating on a magnetite microlite. Nucleation sites within individual ash grains can be imaged using X-Ray Ultra-Microscopy (XuM).

Computational geodynamics as a core component of a broad-based Subduction Initiation research program

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GeoPRISMS Theme: 4.6. What are the physical and chemical conditions that control subduction zone initiation and the development of mature arc systems?

Emerging tools in computational geodynamics provide unprecedented opportunities to quantitatively link earth dynamics to the geological record/geophysical signature of subduction initiation in time and space. By making these links, we can catapult our understanding of the dynamics of plate tectonics forward. This will help overcome a major failure of geodynamics, our inability to reproduce the evolution of the plate tectonic system over the last ~100 Million years [1].

The other White Papers for Subduction Initiation (SI) paint a picture of an emerging kinematic framework of where subduction zones form, of the evolving magmatic and structural products that unfold locally as subduction zones nucleate and evolve, and how plate motions change both regionally and globally. What emerges is that although SI is a transient phenomenon, it is a vital phase of the plate tectonics cycle. Unfortunately, there seem to be substantial differences between model predictions both between studies as well conclusions drawn from models compared to the observational record. Some models suggest that self-nucleation at fracture zones should be difficult [2], while the preferred interpretation of the IBM system is one of self-nucleation [3]. Models of SI at passive margins suggest that only the margins with the thickest continental lithospheres and the smallest density differences should be stable on time scales of several million years [4], but all passive margins seem to be stable since the Mesozoic [5].

Based on advances in geodynamics and emerging trends in computational science, we expect the following classes of approaches will be possible components of a well-rounded SI research program:

<u>Fully-time dependent models of global plate motions</u>. In the past, global flow models suffered through low resolution and the inability to account for slabs acting as stress guides. This meant that the traditional conceptualization of how plates are driven by slab pull was never fully realized. By using advances in Adaptive Mesh Refinement (AMR) that allows the mesh to focus on those areas of the domain with large gradients in material properties [6,7], global models of plate motions and mantle flow with resolutions even less than 1 km can now be reached [8,9] (Fig. 1-2). These models allow the subducting plate to slide by the overriding plate with only a narrow fault between them and for the subducting plate to plastically fail as it bends. Perhaps most important for regional tectonic studies, is that the motion of micro-plates emerge from models of global plate motions (Fig. 2). Indeed, Stadler *et al*. [8] found that the rapid roll-back of the Tonga-Kermadec and New Hebrides subduction zones was emergent in global models. This means that that our understanding of the dynamics will improve dramatically if we can link regional and global scales self-consistently. An extrapolation of current compatibilities and the rapid development of solution methods with advances in parallel computer hardware suggests that in several years time we will see models like those shown in Fig. 1-2 being integrated over the last 100

Million years. This suggests the possibility of linking details of SI to the time evolution of the major plates

Regional, multi-physics models of Subduction Initiation. The basic mechanics of subduction initiation at passive margins, fracture zones, and ridges, must be resolved in high-resolution models in two and three dimensions. The evolving force balance and coupled structural and magmatic evolution during subduction initiation is complex [2]. Unfortunately, an agreed upon paradigm for the dynamics of SI has not been reached and models will require (Fig. 3) a careful consideration of all of the resisting forces (basaltic oceanic crust, viscosity of lithosphere and mantle, elasticity of the bending plate, thermal diffusion) as well as factors favoring SI (preexisting thermal and composition buoyancy differences at margins, serpentinization of existing margins, transition of crust to eclogite, water release from the slab, melting of the growing mantle wedge, plate compression).

Earlier models of subduction initiation at old fracture zones showed a fundamental change from compression (and uplift) and extension (and subsidence) as a new subduction zone formed [2] (Fig. 4). Such models with visco-elastic plates with plastic failure showed that rapid back arc extension follows SI. Although, only two dimensional, the models demonstrated how computational models allowed the reinterpretation of existing observations while also motivating new field campaigns. Recently, 3-D models with realistic non-linear rheologies showed how ridges interact with a trench [10]. Although not SI models, they demonstrated how evolving plate kinematics emerged from a model that also predicted the tectonics of the over-riding plate in terms of the space-time distribution of volcanism [10]. Based on software and hardware improvements, we expect the regional generic models will be 3-D incorporating the complex plate geometries that are likely critical to SI.

Inverse Models. Models of plate tectonics and regional tectonics have traditionally been cast in a forward sense. However, at large scales, models of mantle convection have been cast as inverse problems using an adjoint of the energy equation [11]. These models have proven to be extremely effective in linking seismic images, plate motions, and stratigraphy on regional scales [12]. Again, extrapolation of current capability in conjunction with high-resolution seismic images suggests that inverse models of subduction initiation could emerge during the course of the GeoPRISMS program.

The capabilities of regional and global geodynamics is now accelerating and will afford not only the ability to link the details of fault structures and vertical motion to incipient slab dynamics, but also the history of magmatism and petrology associated with the initial descent of the slab. The link between geodynamics and observational programs will benefit from the new open source paleogeographic system, GPlates (http://gplates.org), which is explicating linked to computational models. Extrapolating the pace of developments in software and hardware, we expect that fine scale tectonic details will be part of the large-scale motion of tectonic plates, including changes in plate motion.

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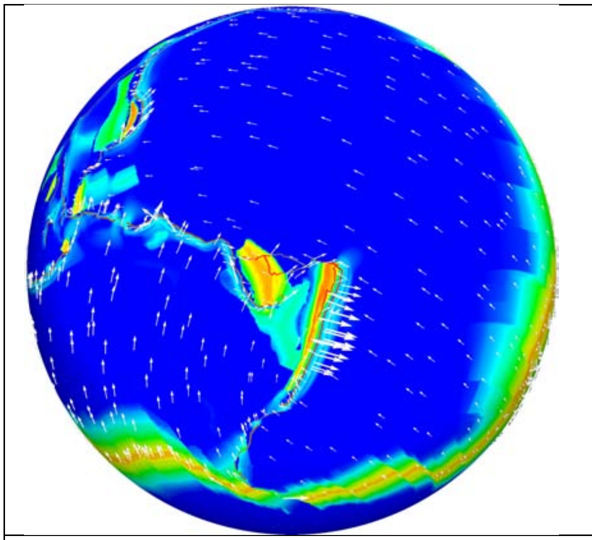

Fig. 1. A new generation of global models of plate motions and mantle flow that capitalize on the latest advances in computational science [6,7] from Stadler *et al*. [8] and Alisic *et al*. [9]. This model of the whole solid earth is used to predict a variety of quantities, including plate motions shown as white arrows.

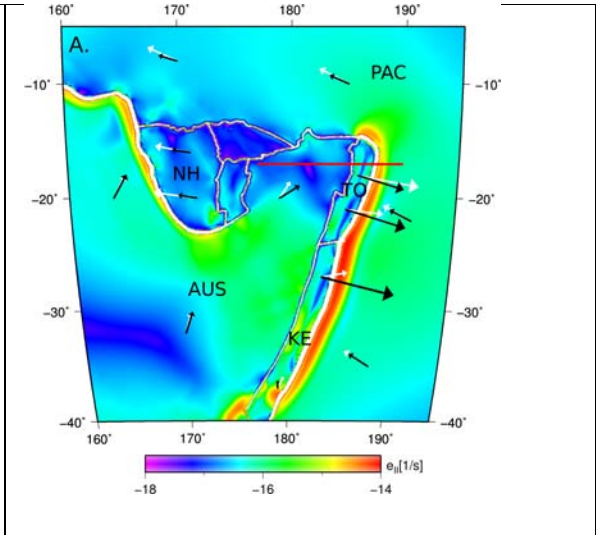

Fig. 2. The new global motion models, for the first time predict not just the motion of the major plates but also micro-plates. Indeed, Statdler *et al*. [8] recently demonstrated that rapid back arc motion, like that seen for the Tonga-Kermadec and New Hebrides subduction zones was an emergent consequence of slabs falling through the upper mantle. From [8,9].

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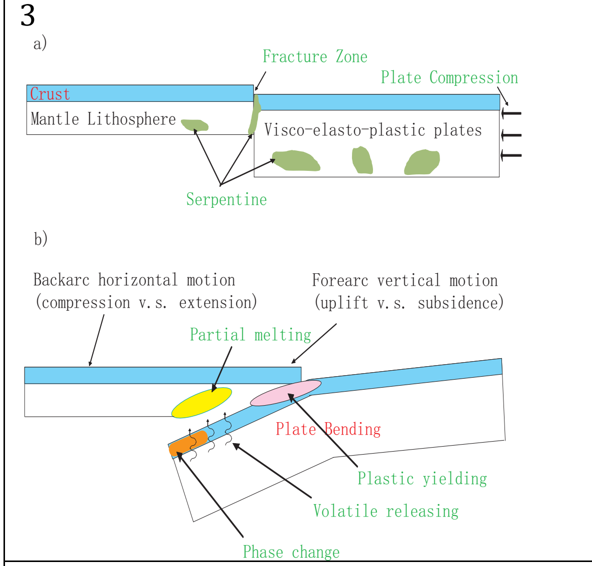

Fig, 3. The different physical properties that enhance (in green letters) and retard (in red letters) the growth of Subduction Initiation that will be incorporated into a new generation of 3-D regional, multi-physics models.

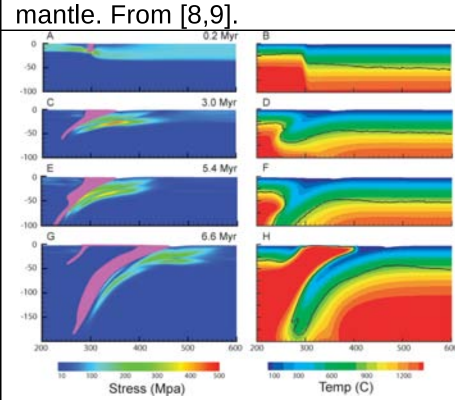

Fig. 4. An earlier, time-dependent model of SI at a fracture zones in medium with visco-elasto plastic plates. The models showed a phase of rapid back arc extension following SI -- consistent with the evolution of SI and back arc extension in the Western Pacific. From Gurnis *et al*. [2].

The New Zealand region: A key natural laboratory for studying subduction initiation

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Themes addressed: 4.6. What are the physical and chemical conditions that control subduction zone initiation and the development of mature arc systems?

Key types of data/infrastructure: Active and passive source seismic experiments, deep sea drilling, onshore outcrop data, seismic stratigraphy, geochemical analysis and geodynamic modeling.

Subduction initiation is a vital, but poorly understood phase of the plate tectonic cycle. Computational studies and interpretation of the Mesozoic and later plate tectonic history suggest that subduction initiation profoundly alters the force balance on plates [1,2]. If that is the case, then our picture of the dynamics of plate tectonics is incomplete. If we hope to make fundamental advances in understanding the forces driving and resisting plate motions, then a detailed picture of subduction initiation is needed. The geodynamic force balance and the tectonic conditions likely evolve quickly during subduction initiation (over several millions of years) and magmatic and structural processes can overprint earlier geological events. Nearly half of all presently active subduction zones initiated during the Cenozoic [2], and thus provide multiple opportunities to better understand the process through geophysical and geological studies. The New Zealand region contains examples in different phases of evolution, from juvenile (in the case of Puysegur) to fully developed (Tonga-Kermadec, Hikurangi/Taupo).

Puysegur. To find key evidence to constrain geodynamic processes, we must study a subduction zone that has *partially proceeded* through the nucleation stage. Existing geological and geophysical evidence suggest that the Puysegur Trench and Ridge (Figure 1) just south of New Zealand is slowly transitioning from a forced to a self-sustaining subduction system. The Puysegur region could be a natural laboratory to study the kinematics of this vital phase of plate tectonics, potentially uniquely so in the world, especially in terms of its well-constrained convergence history [3]. Many of the constraints on dynamics can be determined by further field work and analysis.

Puysegur is a region ideally suited to constrain geodynamic processes of subduction initiation because of (1) a clear association between submarine and subaerial geomorphological indicators and geophysical structure; (2) a well constrained plate convergence history; (3) onshore and offshore targets for detailed hypothesis testing; and a (4) juvenile island arc.

Existing marine geophysical surveys of Puysegur are sparse but suggest that the vertical motions are partially caused by the newly subducting lithosphere and thickening crust [4]. All models of subduction initiation (either conceptual or mechanical) have the thrust interface nucleating and growing. State-of-the-art surveys (Figure 2) could help distinguish between competing scenarios for subduction initiation (including if the new subduction interface is on a new fault or an old fracture zone). Modern MSC surveys with a 6 km streamer could image the nascent dipping plate boundary in this region. Detailed marine geophysical surveys of the Puysegur Trench and Ridge could be mounted to test the hypothesis that this incipient subduction zone is slowly making a transition from a forced to a self-sustaining state. The *R/V Marcus Langseth* is an ideal platform to carry out seismic refraction, with OBSs, and multi-channel seismic surveys to collect structural and geological tests on geodynamic models. For example, refraction lines would be used to constrain the crustal thickness and velocities of the lower crust and upper mantle, whereas MCS lines would reveal the velocity and structure of the upper crust (Figure 2). Appropriately designed MCS surveys could be linked to the detailed sequence stratigraphy already completed closer to New Zealand. Moreover, substantially thermochronology has already been completed onshore that shows the detailed space-time pattern of rock uplift associated with SI in the onshore Fiordland segment of Puysegur [5].

Tonga-Kermadec. Tonga-Kermadec subduction may have initiated in the Eocene, associated with a change in Pacific Plate motion. Recently, seismic-reflection and rock-sample data have been used to propose that the first-order physiography of the New Caledonia Trough and Norfolk Ridge formed in Eocene and Oligocene time, and was associated with the onset of subduction and back-arc spreading at the Australia-Pacific plate boundary [6]. The analysis suggests permanent subsidence of the New Caledonia Trough and transient uplift of Lord Howe Rise during Eocene and Oligocene initiation of Tonga-Kermadec subduction [6].

North Island (Hikurangi/Taupo) Further south of Tonga-Kermadec, subsidence curves from oil wells in central North Island, New Zealand show a rapid (~0.2 mm/y for 7 my) and regional subsidence in the Late Oligocene [7]. This event has been interpreted to represent subduction initiation in the New Zealand region, but the link, if any, to subsidence in the New Caledonia trough 1000 km to the north is not clear. Furthermore, the Northland region of North Island has extensive ophiolite outcrops also tied to the subduction initiation process [8]. The east-west Miocene subduction zone is expressed by a distinct magmatic arc, and this subduction system evolved into the current north-south Taupo-Hikurangi subduction zone (e.g., Nicol et al., 2007).

In conclusion, New Zealand should be a GeoPRISMS focus site: it not only has the best modern example of subduction initiation (Puysegur), but also a rich Cenozoic stratigraphic and volcanic history of the processes involved. Furthermore, all these modern and Cenozoic examples are relatively understudied but easily accessible.

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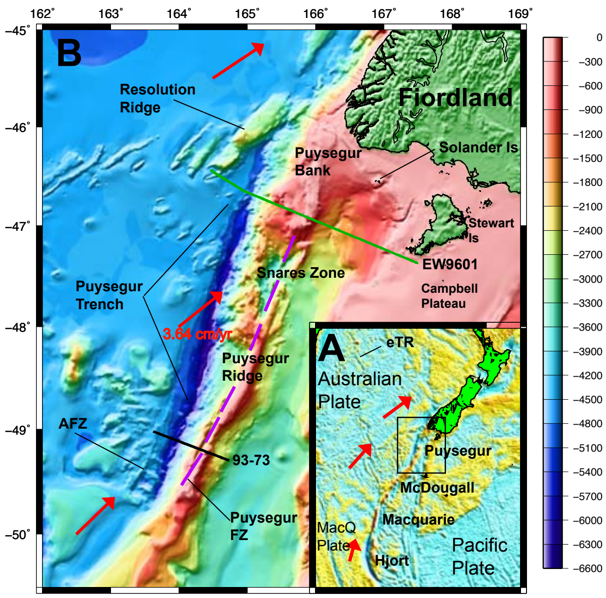

Figure 1. A. Location of the Puysegur region (black rectangle). B. Bathymetry (scale bar is depth in meters) of the Puysegur Ridge and Trench region just to the south of the South Island of New Zealand. The sector denoted Puysegur Trench has experienced active subduction. Bathymetry assembled by NIWA from a variety of surveys. In both A and B, the red arrows are the relative motion of AUS or MACQ with respect to fixed PAC from the MORVEL present day plate model. The ideal location to test models of subduction initiation is within the Snare Zone. The feasibility of collecting seismic data to test geodynamic models, including imaging the top of the down going slab as it first penetrates into the mantle is shown in the Next Figure. In all probability this is the only region on the planet where we can capture a subduction zone evolving from a forced to a self-sustaining state.

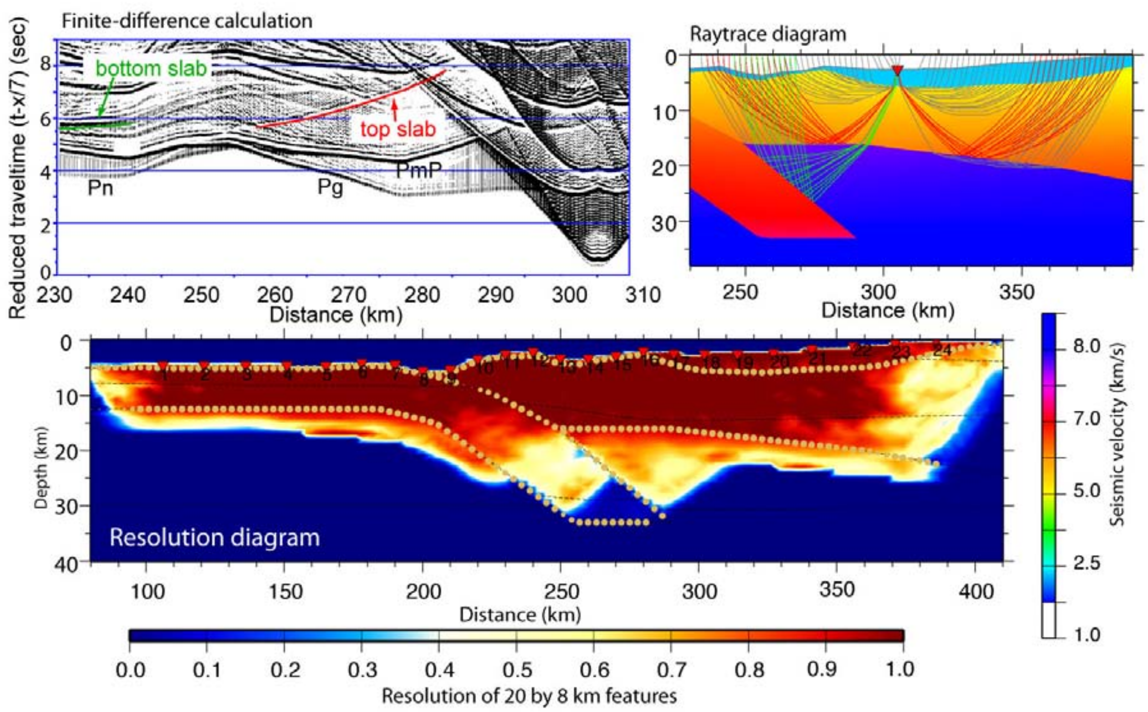

Figure 2. Feasibility tests showing how an active source seismic experiment with an OBS array across the Puysegur Trench (see Fig 1) could measure the top of the slab in the nucleating trench as well measure the thickness of the crust. Such parameters could constrain the dynamics of SI. This is the only location on the planet where a slab has partially nucleated with a clear plate tectonic and geological history -- making it a critical target for the GeoPRISMS program.

The Aleutian island arc near Adak as a GeoPRISMS focus site: Finally, a Subduction Factory that actually makes continental crust?

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Volcanic arc systems are one of only two environments on Earth that produce unsubductable and therefore (by one definition) "continental" crust. However, a fundamental discrepancy — the so-called "andesite paradox" — appears to exist between the bulk composition of continental crust (~andesite) and the bulk composition of island arcs studied to date (~basalt), as inferred from both seismic surveys and geochemical studies. Recent studies in the Izu-Bonin-Marianas arc have only deepened the mystery: despite the presence of thin mid-crustal layers that might be relatively silicic (e.g., [*Kodaira et al.*, 2007; *Suyehiro et al.*, 1996]), the seismic velocities of the island arc crust are significantly higher than that of continental crust and indicate a bulk composition, and primary magma, that is essentially basaltic [*Tatsumi et al.*, 2008]. This raises important questions: Have island arcs ever been a significant contributor to continental growth? If so, does this imply that island arc compositions in Earth's past were different than today? Are there any modern island arcs that produce crust that looks "geophysically" like continental crust?

The best place in the world to address these questions is the central Aleutians near Adak Island. Lavas and (especially) plutons near, and west of, Adak are more similar to the composition of

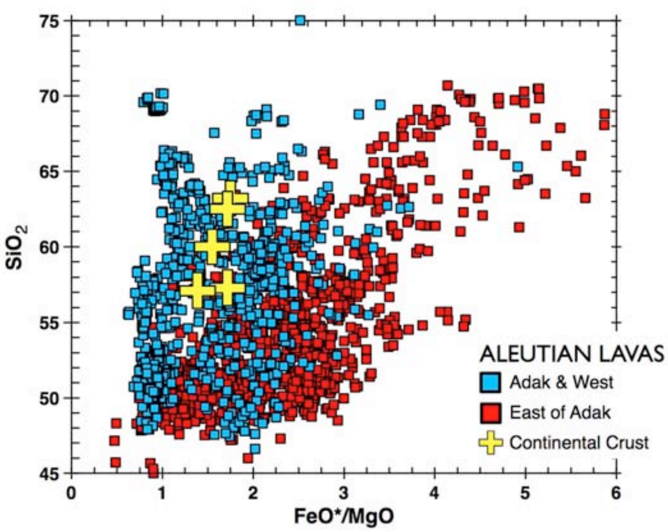

Figure 1. Silica vs. FeO/MgO plot of Aleutian lavas, including both dredge hauls and lavas sampled from volcanoes. Note the similarity between lavas at and west of Adak and the values for continental crust. Lavas east of Adak are dominantly basaltic in composition and predict faster bulk crustal velocity, as found in the 1994 Aleutians seismic survey.

continental crust than are magmatic rocks from any other oceanic arc (e.g., Fig. 1). This is true of both major and trace element chemistry (e.g., [*Yogodzinski and Kelemen*, 2007]). Aleutian lavas show a fundamental, first-order along-arc change in major-element composition on a regional scale, from dominantly tholeiitic east of Adak to dominantly enriched, calc-alkaline west of Adak. A similar trend is seen in trace elements, but the systematic along-arc change in *major elements* presents a rare opportunity to link arc geochemistry with seismic velocity structure. Given existing geophysical surveys in the Aleutians east of Adak [*Fliedner and Klemperer*, 1999; *Holbrook et al.*, 1999; *Lizarralde et al.*, 2002; *Shillington et al.*, 2004; *Van Avendonk et al.*, 2004], similar surveys further west would enable such comparisons.

We suggest that a crustal-scale seismic survey (Fig. 2), combined with geochemical sampling and modeling, of the Aleutian arc near and west of Adak will provide a fundamental test of the hypothesis that island arc magmatic processes can (and therefore may have in the past) produce crust that, both chemically and geophysically, resembles continental crust. The data compiled in Figure 1 suggest that if there is *anyplace* on Earth where actively forming island arc crust should have the geophysical characteristics of average continental crust, it is in the central and western Aleutians. Failure to find such crust here would effectively close the case on modern island arcs as analogs for continental crust. This area thus enables a *definitive* hypothesis test of the "andesite paradox."

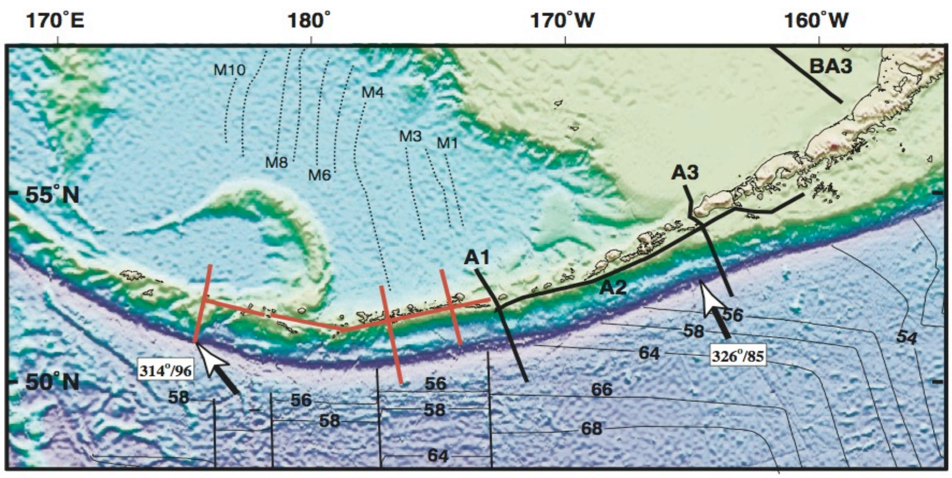

Figure 2. Notional seismic survey across the central/western Aleutians. Red lines show one possible layout of deep-crustal seismic surveys; bold lines labeled A1, A2, A3, and BA3 are MCS/wide-angle seismic lines of the 1994 Aleutian seismic experiment. Lighter labeled lines on the Pacific plate are oceanic lithosphere isochrons in m.y., and dashed lines in the Bering Sea are Cretaceous magnetic lineations of the relict Kula plate. Large arrows indicate Pacific plate motion vectors, labeled with azimuths and speeds in km/my.

Other compelling reasons exist for selecting the Aleutians as a GeoPRISMS focus site. First, the central Aleutians are the intact product of ~50 m.y. of island arc magmatism and offer a relatively pristine, simple setting to study subduction processes. The lack of intra-arc rifting is crucial because it enables the time-integrated magma flux and the bulk composition of the arc to be directly measured by seismic methods; only a relatively simple correction is necessary for pre-existing oceanic crust, whose structure is readily obtainable. Second, the Aleutians encompass systematic along-arc changes in "input" (forcing functions) and "output" (lava chemistry). Well-documented, systematic along-strike variations in subduction parameters make the Aleutians the best place in which to evaluate the effect of input forcing functions on magma flux, lower and mid-crustal composition, and mantle wedge structure in a pristine island arc (Figure 3). Third, existing reconnaissance reflection/refraction studies, especially the 1994 Aleutians experiment, provide an important framework for designing modern, higher-level studies. The 1994 experiment established that active-source airgun arrays can provide clear vertical-incidence and wide-angle returns from the arc Moho and the slab, at depths up to 50 km [*Holbrook et al.*, 1999]. Finally, the Adak region has very well-characterized seismicity for a purely oceanic arc segment. Monitoring began in 1965 [*Engdahl*, 1971] and continued through the early 1990's [*Taber et al.*, 1991]. This wealth of data, coupled with numerous earthquake studies means that the geometry and structure of the slab are known to first-order.

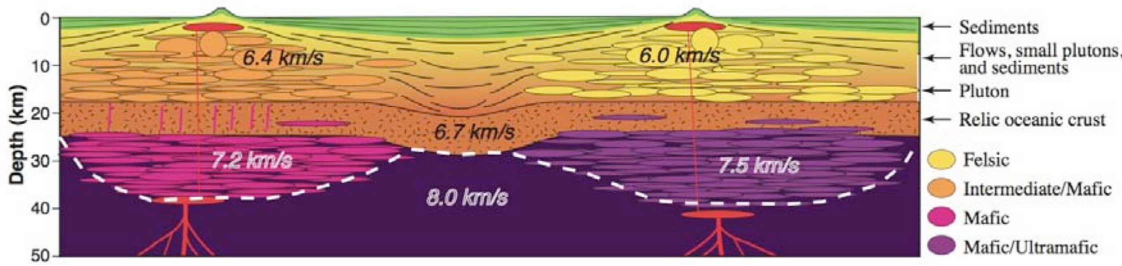

Fig. 3. Cartoon to illustrate one possible scenario of along-arc variations in crustal structure and to highlight our generally poor understanding of magmatic emplacement processes in volcanic arcs. Melt extraction that becomes focused in the mantle results in focused magmatic accretion, producing along-arc crustal thickness variations. Estimates of flux and composition based on cross-arc measurements alone could be misleading for this situation. Also indicated are two end-member scenarios for fractionation of a uniformly basaltic primary magma. On the left, little fractionation takes place and basaltic lavas are erupted, as at Atka.

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The leading edge of the mantle wedge:
Structural and metamorphic studies of peridotite thrust over metasediments & basalts

Peter Kelemen, Jamie Connolly, Brad Hacker, Greg Hirth and Craig Manning

We propose to study mantle peridotite thrust over metasediments and metabasalts, in order to provide direct observations of the leading edge of the mantle wedge in subduction zones. Taken together, exposures where the basal thrust of the Oman ophiolite brought peridotite over Cretaceous metasediments at (a) ~ 160°C and 3 kb (Kelemen & colleagues, unpublished data), (b) the basal thrust of the Trinity peridotite in California juxtaposed hanging wall peridotite with metasediments and metabasalts at ~ 500 to 650°C and 5 kb (Peacock & Norris, J. Met. Geol. 1989), and (c) peridotites within felsic gneisses in the ultra-high pressure metamorphic belt of western Norway at ~ 700°C and 30 kb (e.g., papers by Brad Hacker, Hannes Brueckner and their colleagues), provide a series of points along plausible subduction zone geotherms which will allow us to make specific observations that are potentially applicable to subduction zones worldwide. We will study localized deformation along thrust faults and lithological contacts, and constrain the relative importance of localized versus distributed deformation. We will determine the extent and nature of geochemical mass transfer from underlying metasediments and basalts into overlying mantle peridotites. And, we will delineate the combined physical and chemical processes arising from disequilibrium fluid transport combined with retrograde metamorphism in mantle peridotite.

A variety of recent studies have emphasized the importance of the “cold nose” overlying shallow subduction zones – the leading edge of the mantle wedge, where peridotite thrust over subducting sediments and oceanic crust. Properties of the “cold nose” are invoked to explain rheology, geodynamics, geochemical fluxes and fluid transport in the shallower parts of subduction zones. The nose is thought to act as a kind of geochemical filter for return flow of pore waters, and then for ascending fluids derived by prograde metamorphism of subducting sediments and metabasalts. Reaction with these fluids drives hydration and carbonation – retrograde metamorphism – of mantle peridotite, forming hydrous minerals such as serpentine and talc, and carbonates such as magnesite. Fore arc cold springs and serpentine mud volcanoes demonstrate the extent of alteration, and yield clues about coupled chemical and physical processes during reactive transport of subduction zone fluids. Low seismic velocities and high attenuation in the nose are attributed to retrograde metamorphism. Serpentine and talc in the nose, particularly in the hanging wall of the master thrust, are thought to be weak materials that rheologically decouple the forearc from the subducting plate. Cooling of the nose by conduction into the underlying, subducting crust and by advective flow of cold fluids through the wedge is considered to be the cause of exceptionally low heat flow in fore arcs worldwide. Despite its low temperature, the nose is thought to be dynamically stable due to the relative buoyancy of the retrograde mineral assemblage.

While most of the views summarized in the previous paragraph are based on inferences from geophysical data, they are so widely invoked as to be considered axiomatic. Indeed, we believe that they are generally true. However, we really don’t understand chemical and physical processes in the cold nose very well. For example, alteration of peridotite is commonplace, and fundamentally important for the reasons outlined above but we don’t understand the feedbacks between fluid flow and metamorphic reactions that – under some circumstances – allow the retrograde process to proceed. Retrograde processes are thought to be uncommon because they are self-limited, via a variety of negative feedbacks described below. And yet, in the preceding paragraph we invoked nearly complete hydration to explain the properties “cold nose”, worldwide.

In igneous and metamorphic rocks, fluid porosity and permeability may be negligibly small, so retrograde processes are supply limited. Furthermore, fluids enhance diffusion and so act as catalysts for recystallization. Prograde reactions produce fluids, in a positive feedback, while retrograde reactions may consume all available fluid long before recrystallization is complete. Finally, in an initially open system, retrograde reactions may increase the solid volume. This may fill porosity, destroy permeable flow networks, and armor reactive surfaces, limiting fluid supply and slowing reaction rates. Thus, rocks overcome by these limitations often contain a hodge-podge of disequilibrium mineral assemblages formed by incipient, but arrested, retrograde metamorphism. Often, peridotites in outcrop are 10 to 60% hydrated, with abundant relicts of the original, mantle minerals.

However, 100% hydrated peridotites, known as serpentinites, are common. Less familiar, but of increasing scientific interest, are "listwanites", 100% carbonated peridotites composed of, magnesite + quartz, such as those we have recently been studying at and just above the thrust bringing mantle peridotite over metasediments in Oman. How do serpentinites and listwanites form, when retrogression is self-limiting? Two end-member explanations have been offered. Many metamorphic petrologists consider that such reactions occur at constant volume, in which expansion due to decreasing solid density is balanced by dissolution and export of chemical components in a fluid. However, with notable exceptions, most studies of serpentinites, and our work on listwanites in Oman, suggest that alteration was nearly isochemical except for addition of H2O and/or CO2.

Alternatively, MacDonald & Fyfe (T'phys 1985) proposed that increasing stress due to volume expansion in an elastically confined volume causes fractures, which in turn increase or at least maintain permeability and reactive surface area, in a positive feedback mechanism that allows retrograde reactions like serpentinization to proceed to completion. This, and other similar processes involving regulation of permeability via (bio) chemical feedbacks, forms the primary hypothesis motivating our proposed project. It has been the topic of recent theoretical work, for example by Jamtveit and colleagues, and Kelemen and co-workers. So far, theory is only qualitatively linked to observations.

Our proposed studies will establish the relative timing of fracturing and metamorphism, via documentation of statistically significant numbers of cross-cutting crack and vein relationships, to quantify the observation that alteration and fracture were coeval and hierarchical. And, we will quantitatively compare fracture and vein density to the overall extent of matrix alteration.

To pick another problem, the nature and extent of mass transfer between subducting material and overlying peridotite are variable, and difficult to understand. We observe 1 to 100 m scale, tabular bodies of 100% carbonated peridotite that formed at low temperature and pressure in Oman, under conditions in which modeling studies (Connolly and co-workers, Manning and co-workers) predict little or no decarbonation in the downgoing slab, and yet we observe very limited evidence for chemical interaction of peridotite bodies with surrounding felsic gneisses in western Norway, where these disparate lithologies – e.g., quartz and olivine – are thought to have been juxtaposed at UHP and then granulite facies conditions for many millions of years. Our studies will constrain the processes that control these very different, somewhat counter-intuitive outcomes.

Finally, the localization of deformation along the interface between altered peridotite and subducting crust is almost always assumed, and commonly observed, and yet it is not that obvious why it occurs. For materials with a temperature dependent rheology, why doesn't deformation migrate away from the cold subduction interface, into warmer material within the mantle wedge? Does this ever occur? To what extent is deformation in the cold nose controlled by fractures versus ductile flow of serpentine or talc? Our studies will provide direct observations to constrain the nature and extent of these processes, and field data that can be used to test and refine extrapolations based on laboratory investigations of rheology.

Comparing coeval plutonic and volcanic rocks in the Aleutian arc: Are primitive, mafic lavas representative of arc fluxes?

Peter Kelemen, Sam Bowring, George Gehrels, Steve Goldstein, Mike Gurnis, Brian Jicha, Bob Kay, Suzanne Mahlburg Kay, Mike Perfit, Matt Rioux, Dave Scholl, Tracy Vallier and Gene Yogodzinski

Studies of geochemical cycling in subduction systems commonly assume that primitive basaltic magmas are representative of the compositional flux through the arc Moho, and/or of the bulk composition of arc crust. These assumptions are rarely tested. The Aleutian arc is unique among intra-oceanic arcs in its widespread exposure of Paleogene and Neogene, mid-crustal, felsic plutonic rocks, as well as their host lavas. Preliminary data suggest that many Aleutian plutonic rocks are derived from parental magmas that are geochemically distinct from typical basaltic lavas in the arc (Figure 1), perhaps because relatively hydrous magmas degas and stall in the mid-crust. If so, mafic lavas might not be representative of arc crustal bulk composition, or of net magmatic flux through the Moho into arcs. In order to evaluate this hypothesis, and a host of other fundamental questions, it is necessary to make a systematic comparison of the composition of coeval Aleutian plutonic and volcanic rocks.

Continental crust has been generated via geochemical processes similar to arc magmatism, perhaps followed by later reworking of arc crust. However, arc lavas worldwide are dominantly “mafic”, or basaltic, while continental crust is “felsic”, with an andesitic or dacitic bulk composition. Also, it is often inferred that bulk arc crust is mafic, on the basis of dominantly basaltic lavas, and high lower crustal seismic P-wave velocities in some arcs. As a consequence, petrogenetic processes have been proposed to produce felsic crust from a mafic protolith, including (1) formation of a felsic mid-crust via magmatic differentiation of basalt, followed by (1a) “delamination” of dense, mafic or ultramafic lower crust, or (1b) subduction and then “relamination” of buoyant, felsic mid-crustal rocks during subduction erosion and arc-arc collisions. Alternatively, (2) mid-crustal plutons, or entire arc sections, may be derived from mantle-derived andesitic magmas, rather than from the basaltic magmas common among lavas.

Notably, recent seismic data on the Izu-Bonin-Mariana (IBM) arc, together with reconstructed arc seismic sections for the Jurassic Talkeetna arc and the Jurassic-Cretaceous Kohistan arc, all suggest that these intra-oceanic arcs have a relatively felsic bulk composition, at least above the seismic Moho. Perhaps (as in hypothesis 1), all three arcs underwent substantial modification by delamination, or (as in 2) voluminous, early arc magmatism included a large proportion of primitive andesite. And, in the case of IBM, perhaps mafic to ultramafic cumulates are still present below the Moho. Seismic velocities for Aleutian lower crust appear to be higher than for IBM, but interpretation of these data is complicated by the unusual nature of the two arc crossings, and the oblique fore-arc to arc geometry of the one strike line. In any case, our focus here is on the plutonic middle crust.

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

Furthermore, understanding the genesis of felsic plutons that are coeval with dominantly basaltic lavas can provide fundamental insight into the processes of arc crustal accretion, regardless of whether felsic plutons are differentiated from typical arc basalts or not. In one view, high temperature, low-H_2O mafic melts with low viscosity erupt readily, whereas lower temperature, higher-H_2O felsic magmas undergo degassing in the mid-crust, and become too viscous to ascend further. In order to understand arc magmatism, it is essential to test this hypothesis, and quantify the nature of any systematic bias arising from such physical processes. For example, studies of H_2O-contents in melt inclusions in lavas might not yield an unbiased estimate of H_2O contents in the magmas that form plutons.

Throughout most intra-oceanic arcs, felsic mid-crustal rocks are not exposed at all. The Miocene, tonalitic Tanzawa plutonic complex in Japan is inferred to be tectonically exposed, felsic mid-crust from the IBM arc. However, it is geochemically distinct from continental crust (e.g., Tanzawa is depleted in K and light REE, whereas CC is enriched), and lacks spatial and temporal context with the rest of the arc.

In contrast, the Aleutian chain has characteristics that make it ideal for a study of plutonic rocks in an intra-oceanic arc. (A) The Aleutians have never been rifted, and still contain strata recording ~ 40 Ma of arc history. (B) Some primitive lavas have Nd, Sr, Pb and Hf isotope ratios indicating a depleted upper mantle source, similar to the MORB source. These are the isotopically depleted end-member among arc lavas worldwide. They are dominated by juvenile igneous material, rather than recycled components from continental crust and terrigenous sediments. (C) Despite their lack of recycled, older continental material, these same primitive Aleutian lavas have compositions almost identical to bulk continental crust, more so than in any other intra-oceanic arc. Formation of juvenile igneous rocks with the composition of continental crust is occurring in the Aleutians today. (D) Intrusive rocks – predominantly quartz diorite to granodiorite – are exposed on many of the larger islands together with their host volcanic rocks. The widespread presence of exposed intrusions in the Aleutians provides an unmatched opportunity for direct study of mid-crustal plutonic rocks, and their relationship to coeval volcanics.

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

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

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

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

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

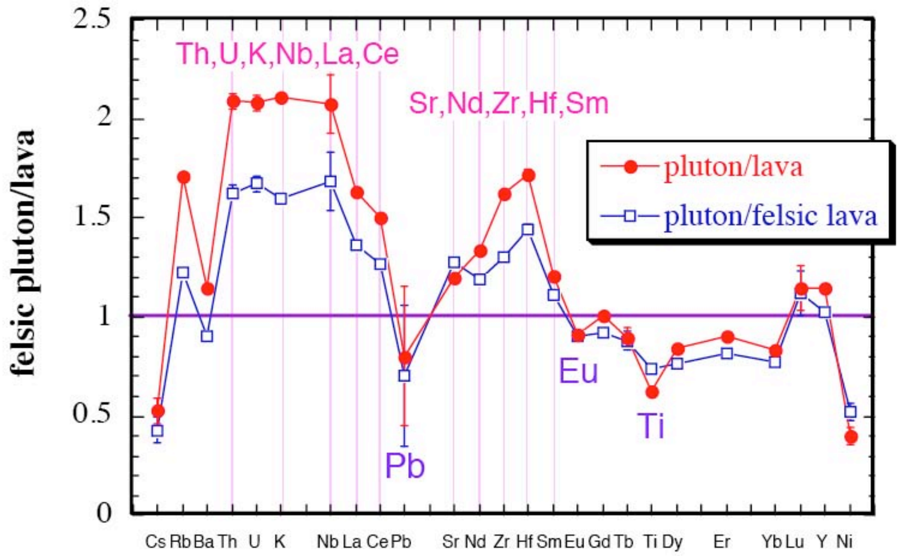

Figure 1: Average Aleutian felsic plutons (> 55 wt% SiO_2) compared to average lavas and average felsic lavas (> 55 wt% SiO_2). See Kelemen et al., AGU Monograph, 2003 and Treatise on Geochemistry, 2003 for data sources. Felsic plutons are enriched in some incompatible elements, compared to lavas, indicating that the plutons probably represent liquid compositions. The large difference at the same SiO_2 (and at the same molar Mg/(Mg+Fe) or Mg#, not shown) suggests that the plutons were not derived by crystal fractionation from the same parental magma composition as the lavas. Either (1) mixing of evolved and primitive compositions was systematically more important in forming the plutons, or (2) the plutons had a parental melt that was systematically different from the parent for the lavas. The data summarized here are mainly for Holocene lavas and Miocene plutons, so it is not yet clear whether the differences reflect spatial or temporal variation in magmatic processes.

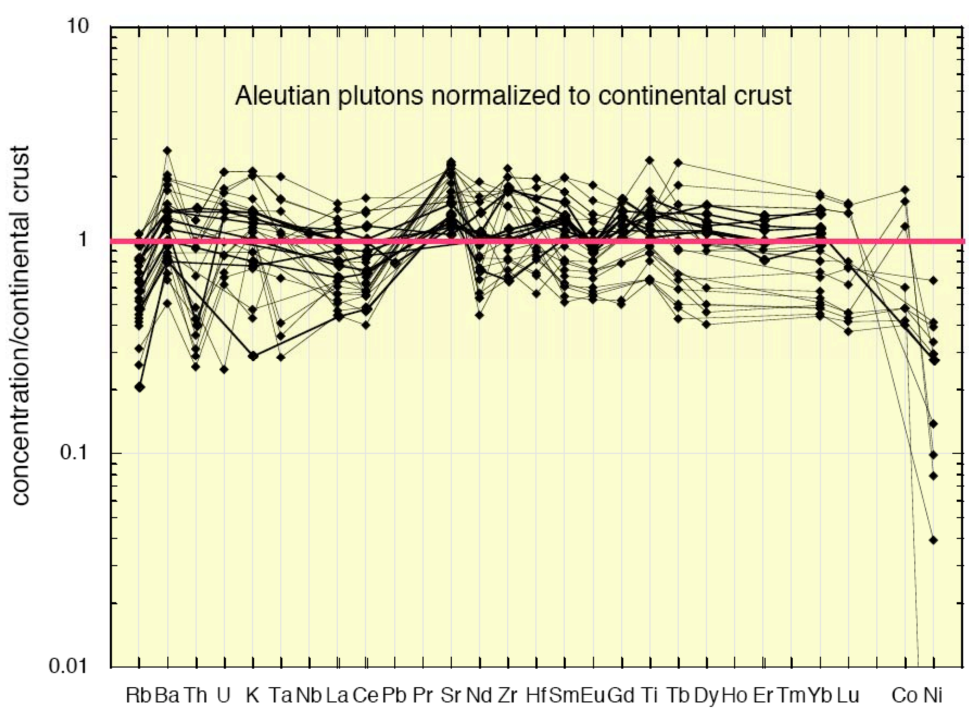

Figure 2: Comparison of average composition for Aleutian felsic plutons (> 55 wt% SiO_2; compilation in Kelemen et al., 2003) with bulk continental crust (Rudnick & Gao, Treatise on Geochemistry, 2003).

Exhumed subduction margins: an important record of deformation and metamorphic processes

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Active subduction zones will be a fundamental part of the new Subduction Cycles and Deformation initiative in GeoPRISMS, nonetheless, some key aspects of their geology cannot be studied from the surface: seismic images are limited by km-scale wavelengths in the deep crust and upper mantle; monitoring active seismicity is limited to moderate to large earthquakes; deformation and rheology is inferred from geodetic observations that are filtered by the overlying lithosphere; and metamorphic processes must be inferred by the geochemical products returned to the surface, potentially transformed, through the overlying crust. All of these processes can and must be addressed by focused geological study of exhumed subduction margins; though examples abound worldwide, we should not restrict ourselves to any single fossil site, but certain locations offer unusual opportunities.

Exposures of pseudotachylite in lower crustal rocks in two locations in western Norway result from frictional melting during intermediate-depth paleo-earthquakes in the overriding plate during Caledonian subduction. Local pseudotachylite veins occur within or adjacent to eclogite-facies shear zones in otherwise metastable granulite-facies gabbroic rocks in both the Bergen Arcs and on Flakstadøy in the Lofoten Islands (e.g., Austrheim and Boundy, 1994; Steltenpohl et al., 2006). Field relations at both localities suggest a close interplay of multiple subduction-related processes in the deep crust near the plate interface between brittle and ductile deformation, metamorphic reactions, and fluid infiltration (Bachmann et al., 2009).

Estimates of P=1.5-2.1 GPa and T~700ºC suggests depths ≥50-60 km, nominally below the brittle-ductile transition, for eclogite-facies metamorphism and coexisting shear zone formation in both locations (Jamtveit et al., 1990; Markl and Bucher, 1997), and pseudotachylite formed at eclogite-facies conditions based on the presence of high-pressure garnet and omphacite crystals in these quenched frictional melts (Austrheim and Boundy, 1994; Steltenpohl et al., 2006). While the pseudotachylite has not been directly dated, eclogite-facies metamorphism and the coeval shear zone deformation occurred at c. 430 Ma (e.g., Steltenpohl et al., 2003; Glodny et al., 2008); these ages suggest a genetic link between pseudotachylite formation and subduction deformation in the overriding plate during the Scandian phase of the Caledonian orogeny.

Pseudotachylites are interpreted as quenched frictional melts resulting from localized deformation at seismic strain rates (0.1-1 m/s; Cowan, 1999). The melt volumes represented by these Norwegian pseudotachylite veins implies seismic energies corresponding to small magnitude earthquakes: micro-earthquakes up to a magnitude of ~1 for melt volumes approximating those in the Lofotens based on calculations in Wenk et al. (2000), while Bjornerud et al. (2002) estimate a minimum magnitude of ~3.3 for pseudotachylite veins in the Bergen Arcs. The correlation of pseudotachylite with eclogite-facies shear zones suggests deformation styles change between high-velocity brittle faulting and slow, ductile shear in the lower crust.

Whereas eclogite-facies metamorphism and the associated density increase and accompanying rapid(?) volume decrease probably did not trigger the earthquakes because pseudotachylite also occurs in uneclogitized gabbro (in the Bergen Arcs, Bjornerud et al., 2002), these brittle deformation events likely opened pathways for fluid infiltration that led to localized metamorphic reactions. It is clear that the rheology of the lower crust changed during Caledonian deformation:

a strong, dry granulitic lower crust deformed brittlely during the pseudotachylite-forming events; the resulting in fluid infiltration and eclogitization was accompanied by ductile shearing demonstrating significant strength reduction (Bjornerud et al., 2002).

Geological study of exhumed subduction margins such as this in western Norway should be part of the new Subduction Cycles and Deformation initiative in GeoPRISMS. Exhumed subduction margins are particularly well-suited for addressing key questions put forth in the Draft Science Plan as they relate to the interplay between brittle and ductile deformation, metamorphic reactions, and fluid infiltration: 1) What controls the size, location and frequency of great subduction zone earthquakes and how is this related to the spatial and temporal variation of slip behaviors observed along subduction faults?; 2) How does deformation across the subduction plate boundary evolve in space and time, through the seismic cycle and beyond?; and 3) How do subduction zone processes affect the rheology and dynamics of the plate interface?

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Seismic hazard, continental deformation and mantle recycling associated with the Himalayan continental subduction zone

By James Ni, Larry Brown and the INDEPTH Team

The continued northward motion of India since the closure of the Tethys Ocean has uplifted the Himalaya Mountains and the Tibetan plateau. In the past two decades, numerous geophysical experiments conducted in the Himalayas and Tibet have discovered that Indian continental lithosphere is being subducted beneath the Himalayas and southern Tibet in a relatively coherent and simple geometry [e.g. Ni and Barazangi, 1984; Zhao et al., 1993], and that this geometry is not much different from that observed along oceanic subduction zones. We recognize that many medium-sized thrust-type events and great Himalayan earthquakes (magnitude greater than 8) have occurred along the Main Himalayan Thrust [e.g. Ni and Barazangi, 1984]. However, a large cluster of mantle earthquakes (70-90 km in depth) was found beneath the High Himalayas [Figure 7, Sheehan et al., 2008]. Both large and great earthquakes post immense seismic hazard for hundreds of millions of people who live in the Himalayas and its foreland (India, Nepal, Bhutan and Bangladesh).

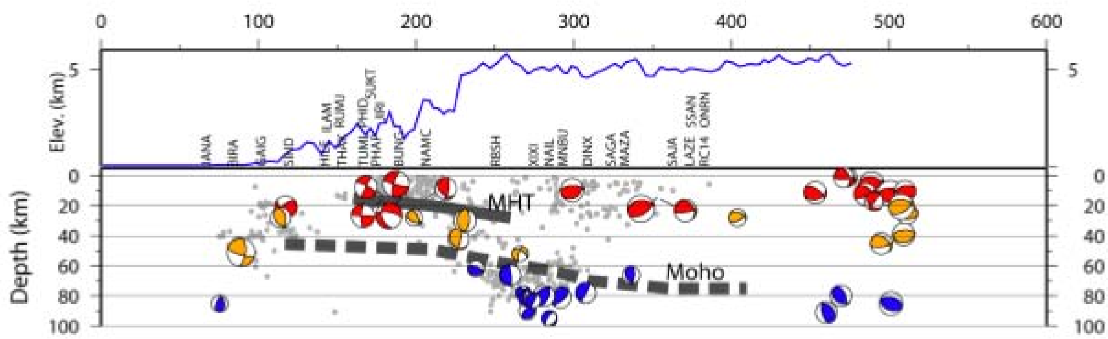
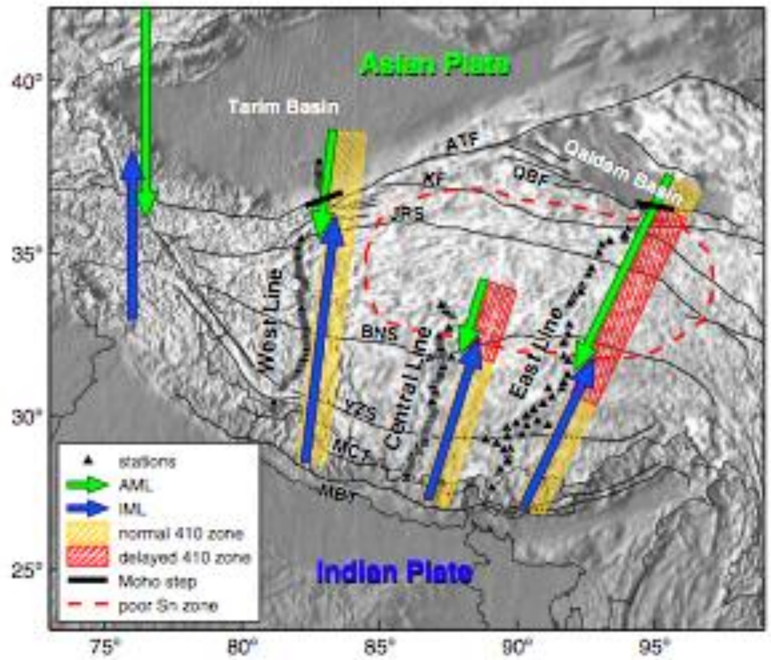


Figure 7. Cross section showing seismicity and focal mechanisms. Grey lines denote Main Himalayan Thrust (MHT) and the Moho from Schulte-Pelkum et al. (2005). Regional topography is plotted above the seismicity with approximate locations of the HIMNT stations.

At present, what we have learned is that there are seismic gaps along two-thirds of the Himalayas, which, when combined with a geodetic convergence rate of ~1.8 cm/yr, suggest that one or more M=8 earthquakes may be overdue [Roger Bilham, Earthquake in India, http://cires.colorado.edu/~bilham/Erice.htmnce]. A region of abnormally high seismicity occurring in western India appears to be related to plate fragmentation. Apparent fragmented suducting Indian plate beneath southern Tibet is recently imaged from finite-frequency tomography [Liang et al., 2010]. Searching the connection between the fragmented Indian plate beneath the Himalayas and southern Tibet is crucial in understanding the earthquake gaps and seismic characteristic of the greater Himalayas.

The subducted Indian continental lithosphere reaches to central Tibet, but there are E-W variations. In the east, near 92°E, the subducted Indian continental lithosphere reaches about 200 km north of the Zangbo Suture [Li et. al., 2008; Zhao et al., 2010], in central Tibet it reaches Bangong Nujiang Suture (BNS) and in western Tibet it reaches Jiansha-River

Suture (JIS) (See Figure below).



The leading edge of the subducted Indian lithosphere has different dipping geometry [Tilmann et al., 2003; Li et al., 2008] and it has a back-arc that is reminiscent to oceanic back-arc. Convection and associated partial melting has produced significant post-collisional potassic and ultra-potassic volcanism in the Tibetan plateau. The subducted continental lithosphere may be delaminated and mixed with the asthenosphere. Hence, Tibet is the best place to study how much continental material is being recycled back into the asthenosphere.

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Metamorphic Processes Implementation Strategy - GeoPRISMS SCD

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We propose an implementation strategy with a **Metamorphic Processes** theme for inclusion in the GeoPRISMS SCD initiative. This theme will include studies of metamorphic processes that address SCD key questions involving the role of volatiles, fluids and melts, geochemical cycling, and the end-products of metamorphic processes within subduction zones. Investigation of exposed high-pressure terrains will allow us to disentangle processes of mixing and material transport occurring within the subducting slab. Interpretation of isotopic and chemical signals in arc volcanic rocks and of geophysical data relies ultimately on understanding **processes** of release and transport occuring within and above the subducting slab. This theme will directly address the program's intent to expand the dimensions of the original program by including "consideration of ancient and exhumed margins." Field-based studies of fossil subduction-zone metamorphic rocks, allied experimental work, and modeling of thermal evolution and related dehydration histories will all be included within this theme. We propose to emphasize coordinated, interdisciplinary approaches, in which a variety of scientists, including metamorphic petrologists, geochemists, and geophysicists will use field, analytical, modeling and experimental approaches, and work together to understand transport and redistribution processes occurring at high *P* and *T* within the dynamic subduction zone environment.

Why choose a thematic approach? A thematic approach has a number of benefits. First, it will allow room for global comparisons among fossil subduction zones and comparison of fossil subduction zones with modern convergent margins. Second, it will allow for optimal combinations of field sites to maximize the diversity in P-T history, lithology, exhumation-related overprinting, and subduction environment. Finally, it will maximize the input from experimental and theoretical studies.

SCD Questions to be addressed by contributions from the Metamorphic Processes theme:

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

Research that currently addresses this question includes modeling subduction-zone thermal evolution [e.g., 1, 2] and related dehydration histories [3-6] with the goal of quantifying fluid fluxes. These models can be tested by constraints from subduction-related metamorphic rocks [7-10]. The models can be refined by better constraints on model inputs. Theoretical models mostly consider slab dehydration; greater focus on CO_2 and on halogens, S, and N, will place important constraints on full volatile budgets in subduction zones. Element mobility and processes of mass transfer are other topics addressed by studies of metamorphic rocks. Investigation of features such as veins and metasomatized rocks, including hybridized rocks in mélanges, provides insight into mechanisms of fluid transport, fluid-flow paths, mobility of elements, and mixing processes within subduction zones [8, 11-15]. Examination of serpentinites from mélange complexes and the eruptive deposits of serpentine mud volcanoes constrains the mobility of elements at low P-T conditions during subduction [16-18]. Mineral solubility experiments have demonstrated large solubility increases with increasing pressure whereas phase equilibria and *in situ* experiments are beginning to demonstrate the importance of silica and alumina polymerization in fluids under sub-arc conditions [19]. The role of polymers in controlling the composition of subduction-zone fluids and the effects of chlorine and other ligands need to be investigated. Geochronology has the potential to constrain devolatilization timescales and fluxes [20] and provide an upper bound on timescales of fluid flow events of thousands to hundreds of thousands of years [21-22]. Speedometry based on diffusion modeling of fast-diffusing elements is another tool that can allow determination of timescales of such brief events [23-27]. From this temporal information we can start to understand metamorphic porosities and permeabilities in order to integrate fluid release and element transport into our models.

- What are the geochemical products of subduction zones, from mantle geochemical reservoirs to the architecture of arc lithosphere, and how do these influence the formation of new continental crust?

Subduction zone metamorphic processes are a primary means of mass fractionation between crust and mantle. The residua of metamorphic processes in the slab may contribute to regions of anomalous isotopic composition in the deep mantle [28-30] and may play a role as a source for ocean island basalts [31-32]. Metamorphic processes such as dehydration, fluid flow, and metasomatism are involved in the concentration and transport of elements creating ore deposits associated with arc magmatism.

Overarching scientific topics in the GeoPRISMS Draft Science Plan addressed by the Metamorphic Processes theme (question numbers are linked to the following figure)**:**

1) **Fluids, Magmas and Their Interactions**: Metamorphic processes generate fluids and magmas involved in subduction-zone processes, and fossil subduction zones preserve records of these processes.

1a) What volatile and non-volatile elements are released by the metamorphic reactions occuring in the downgoing slab and mantle wedge?

1b) What are rates, timescales and lengthscales of devolatilization and hydration reactions, and how do these rates affect rock rheology? What is the role of reaction kinetics during fluid flow?

1c) What are the compositions and physical characteristics of fluids within subduction zones and how do they evolve? How do fluid compositions affect element mobility in fluids? What are the fluid fluxes during metamorphic processes? What are the fluid-flow paths (fractures, channels, grain scale porous flow) and dominant mechanisms (advection, diffusion) within the subducting slab and overlying mantle wedge? What physical and chemical properties of rocks affect their transport properties? What are the durations of fluid flow events?

1d) What special metamorphic processes occur along interfaces between different rock types (e.g., along the slab sediment–mantle wedge interface) and what signature do they impart to fluids and magmas?

1e) Does the formation of hybrid rocks (such as in mélange zones) result in transient sinks for volatiles and trace elements, with unique physical properties and *P-T* stabilities?

2) **Geochemical cycles**: Metamorphic processes play a key role in the cycling of various elements through subduction zones.

2a) What is the effect of fluid composition on trace element partitioning and isotope fractionation in subduction zones? How do elements partition among minerals and fluids and where do they reside in minerals? How do isotopes fractionate and how do fractionation factors evolve with changing *P* and *T*?

2b) How do processes in the forearc affect the overall budget of elements in the subduction zone?

2c) What is the role of slab-sourced diapirs in mass transport in subduction zones?

2d) Where in the subduction system does the material removed by subduction erosion go? What role does subduction erosion play in fluid and magma generation and in the evolution of continental crust?

2e) What happens to subducted continental margins? How long do they remain in the mantle and what role do they play in fluid and magma generation and in the evolution of the continental crust?

2f) What is the alteration state of a slab as it enters a subduction zone? How much pore water goes down within the subducting sediment and what happens to the associated chlorine?

2g) What is the ultimate fate of subducted slab components as they are recycled into the deep mantle?

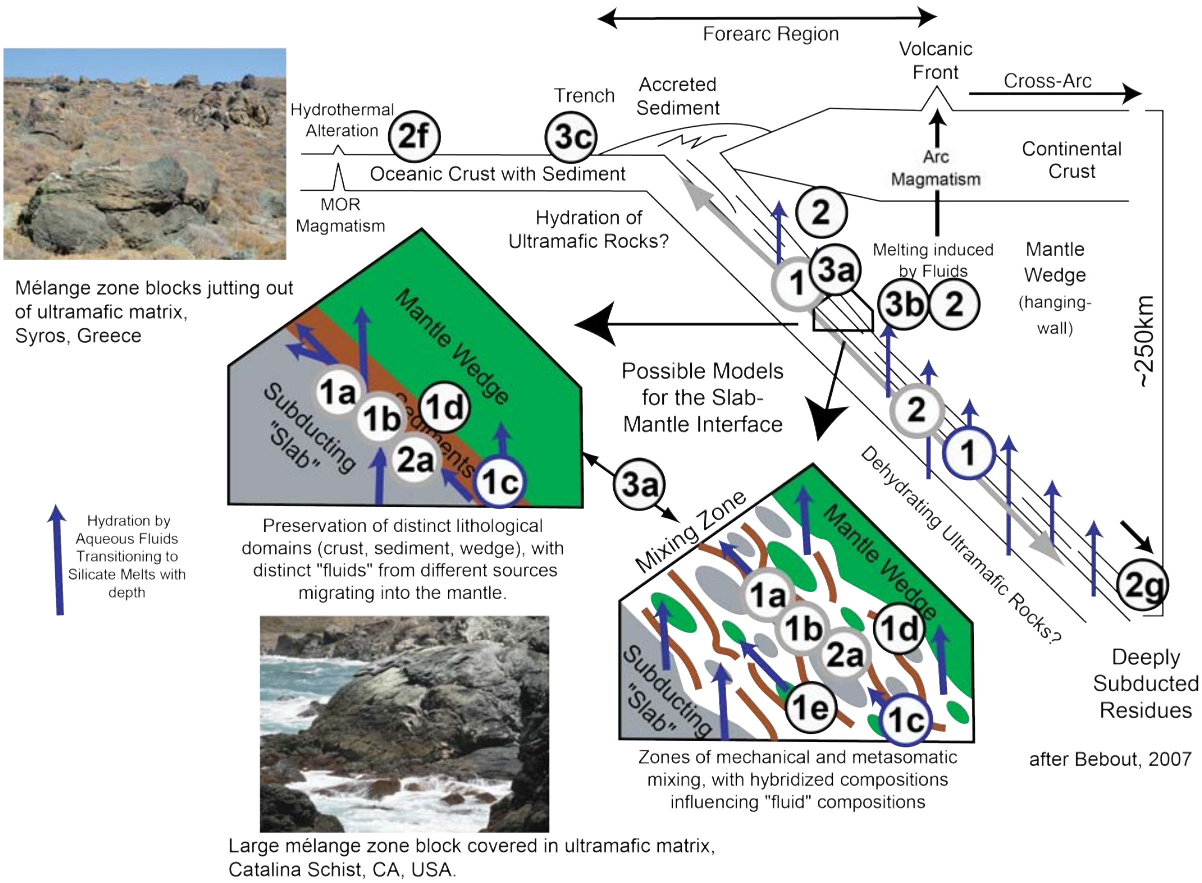
2h) Can global-scale mass balances be verified by exhumed subduction-related metamorphic rocks?

3) **Plate Boundary Deformation and Geodynamics**: Fossil subduction zones record deformation histories and provide information about physical properties of rocks found within active systems

3a) What is the nature of the slab–mantle wedge interface and how does it change with depth and over time? How much fluid is channelized upward along the décollement? What can we learn from exposed metamorphic rocks about the processes that occur at the interface (i.e., in the "subduction channel") and its physical, chemical, and seismic properties [e.g., 33]?

3b) How do metamorphic processes affect the seismic velocity structure of the slab and wedge? What does seismology tell us about metamorphic processes in the slab and wedge?

3c) What are the implications of serpentinization of the subducting slab in the outer rise [e.g., 34] and deeper? What are the implications of serpentinization in the forearc mantle wedge?



Sketch of a subduction zone showing numbers corresponding to key questions identified above.

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SUBDUCTION INITIATION AND THE NEED TO STUDY FOREARC CRUST

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This page added by the GeoPRISMS office.

The draft science plan for the Subduction Cycles and Deformation (SCD) initiative of GeoPRISMS poses as one of its key questions: *What are the physical and chemical conditions that control subduction zone initiation (SI) and the development of mature arc systems?* Understanding how subduction begins and evolves is important for this effort because: (1) a significant proportion of oceanic arc crust is generated during SI, thus understanding its composition is crucial for understanding the overall mass balance of this potential source of continental crust; (2) SI appears to occur nearly simultaneously over length-scales of many thousands of kilometers, and thus affects global plate motions, volatile fluxes, and rates of volcanism; and (3) asthenospheric flow and geological structures including those generating seismicity in modern subduction zones, depend in part on how subduction starts and evolves through time.

SI and the transition to mature, central-vent arc volcanism is best preserved in the rock record of oceanic forearcs. For example, the Izu-Bonin-Mariana (IBM) forearc has long been known to have sequences of unusual volcanic rocks related to arc infancy (e.g. Meijer, 1980; Stern and Bloomer, 1992). Recent Shinkai 6500 diving has further shown that this forearc preserves the entire magmatic history from SI through arc maturity. Similar SI lithologies with similar ages have been encountered in the Tonga-Kermadec and Aleutian forearcs. Siletzia (the Cascadia forearc) may be another SI-related forearc, but this is not yet clear. Thus, we propose that to address the question posed above, some SCD research should be focused on *in-situ* Pacific forearcs.

The IBM forearc provides a rich example of what such focused studies can reveal. The results from on-land studies of forearc islands as well as drilling, dredging and Shinkai 6500 diving since the 1970's (e.g. Hussong et al., 1981; Fryer et al., 1992; Taylor et al., 1992; Reagan et al., 2008; Ohara et al., 2010) has allowed construction of a rough geological map of the IBM forearc (Fig. 1), as well as delineation of its magmatic stratigraphy related to SI. The deepest parts of the inner trench slope consist of depleted peridotites overlain by a thin layer of gabbroic rocks. Above and to the west of the gabbros, the most abundant igneous rocks are MORB-like basalts and associated diabases termed "forearc basalts" (FAB; Reagan et al., 2010). These rocks are the first volcanic manifestations of SI. Several $^{40}Ar/^{39}Ar$ and U-Pb ages from the Bonin-islands region and near Guam place the age of FAB eruption at ~52 Ma (Tani et al., 2009; Ishizuka et al., 2009; Ishizuka unpublished data, 2010). Lavas with compositions transitional to boninite have ages of about 49 Ma (Cosca et al., 1998). Low- to high- Ca boninites are upslope and west of the FAB, and have ages of 48 to 44 Ma (Ishizuka et al., 2006). Eruption of tholeiitic and calcalkaline arc lavas have ages stretching back to 45 Ma (Reagan et al., 2008), thus the transition from SI to "normal" arc volcanism required 6-7 million years of subduction-zone development.

The SI-related stratigraphy preserved in the Tonga-Kermadec forearc appears to be nearly identical to that of the IBM forearc. Peridotites are at the deepest levels, with sequences of gabbroic rocks and basaltic through rhyolitic lavas cropping out up-section and to the west (Bloomer and Fisher, 1987; Bloomer et al., 1994). The oldest radiometrically dated igneous rocks are gabbros with ages of ~52 Ma (K. Tani, unpublished data 2010), and a 46.6 Ma basalt from Eua island (Ewart et al., 1977). Early-arc volcanics also are preserved on Fiji, with basaltic through boninitic and tonalitic rocks having ages stretching back to more than 45 Ma (Todd et al., 2007).

Little is presently known about the oceanic portion of the Aleutian forearc. Nevertheless, Eocene-aged lavas and sediments crop out on or near islands in the central and western Aleutians islands. The oldest two radiometrically dated samples of the Aleutian arc massif have $^{40}Ar/^{39}Ar$ ages of ~46 Ma. One was dredged from just offshore of Kiska Island (Jicha et al. 2006); the other was collected from Medny Island (Layer et al., 2007). Compositionally, both samples are basalt, but closely associated rocks on Medny Island are more evolved. These islands cap the thickest part of the arc crust and both have fossiliferous sediment derived from a middle Eocene ridge. Arc plutonic bodies increase in age southward toward the Aleutian Trench, and it is thus presumed that SI-related lavas that could be as old as ~50 Ma exist within the deeply submerged and thinner crust of the forearc (Scholl, 2007).

It is remarkable that SI occurred nearly simultaneously during the Eocene over this broad an area, and by studying Pacific oceanic forearcs, we should gain a much better understanding of SI and its dynamic consequences. One of the most fundamental remaining questions about SI is whether it occurs spontaneously or requires an initial stage of active compression (Stern, 2004; Hall et al., 2003). Gaining a better understanding of lava geochemistry through time and space for all three forearcs should resolve this question. Studying SI over this broad scale also would lead to a clearer understanding of crustal production rates, the compositions of bulk arc crust, and the effects of subduction on asthenospheric flow.

We therefore propose that one focus of SCD should be to advance studies of SI by focused investigations of circum-Pacific forearcs. We need to assess the diversity of forearc structure, composition, and evolution in order to decide if the IBM model is globally applicable or not. Doing so in concert with geodynamic modeling and studies of on-land ophiolites would promote a much better understanding of the geochronology, petrology, and geodynamics of SI overall. Our studies of these forearcs are necessarily at different stages of maturity, and further studies should take advantage of the different glimpses of forearcs that these provide. We know enough about the IBM forearc to target additional geophysical surveys and forearc diving and drilling towards robustly defining the structure, age, and composition of crust associated with SI and arc infancy. Thus, proposals should be invited for further study the IBM forearc. More foundational studies of the Tonga-Kermadec and Aleutian forearcs also should be invited, and an investigation of the record of Cascadia SI preserved in the Oregon-Washington forearc should begin.

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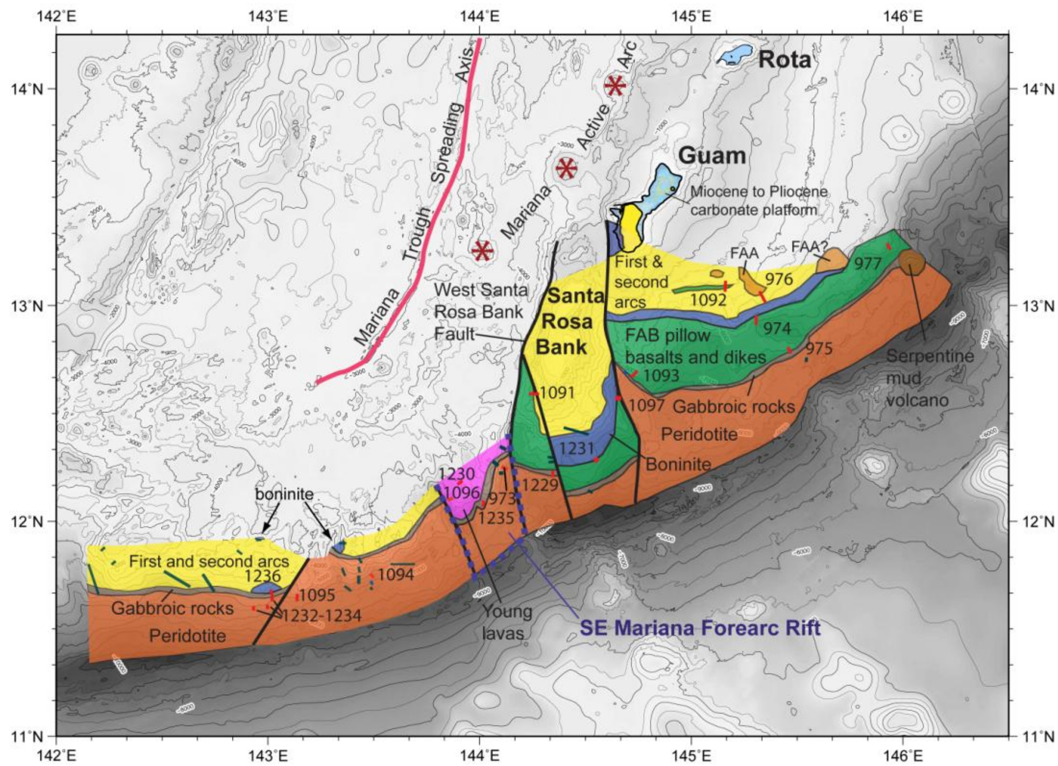

Figure 1 – Geological map of the Mariana forearc near Guam. The red lines with numbers represent locations of Shinkai 6500 dives. Dredges are shown with green lines. The SI and early-arc sequence is west of the West Santa Bank Fault. Most lithological units are descriped in the text. "First and second arcs" refers to the Eocene to Oligocene and Miocene arcs respectively. FAA are "forearc andesities", which are Oligocene-aged high-Mg andesites.

Africa-Arabia-Eurasia plate interactions and implications for the dynamics of Mediterranean subduction and Red Sea rifting

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Our proposed GeoPRISMS Initiative is based on the premise that understanding the mechanics of plate motions (i.e., the force balance on the plates) is necessary to develop realistic models for plate interactions, including processes at subduction and extensional (rifting) plate boundaries. Important advances are being made with new geologic and geophysical techniques and observations that are providing fundamental insights into the dynamics of these plate tectonic processes. Our proposed research addresses directly the following questions identified in the GeoPRISMS SCD Draft Science Plan: 4.2 (How does deformation across the subduction plate boundary evolve in space and time, through the seismic cycle and beyond?), 4.6 (What are the physical and chemical conditions that control subduction zone initiation and the development of mature arc systems?), and 4.7 (What are the critical feedbacks between surface processes and subduction zone mechanics and dynamics?).

It has long been recognized that the Greater Mediterranean region provides a natural laboratory to study a wide range of geodynamic processes (Figure 1) including ocean subduction and continent-continent collision (Hellenic arc, Arabia-Eurasia collision), lithospheric delamination (E Turkey High Plateau, Alboran Sea/High Atlas), back-arc extension (Mediterranean basins, including Alboran, Central Mediterranean, Aegean), "escape" tectonics and associated continental transform faulting (Anatolia, North and East Anatolian faults), and active continental and ocean rifting (East African and northern Red Sea rifting, central Red Sea and Gulf of Aden young ocean rifting). The juxtaposition of this wide range of inter-related geodynamic processes in an accessible area of focused geological and geophysical investigations (NSF CD and EU initiatives), and within a plate system for which relative plate motions are simple and well constrained by geodetic and plate tectonic observations, offers an important opportunity to investigate the relationships between relative plate motions and the structural evolution of inter-plate subduction and rifting systems, and to use these relationships to constrain quantitative, dynamic models. Recent geologic and geophysical constraints on the temporal evolution of Mediterranean subduction systems (Royden and Husson, 2009) offer further opportunities to investigate the role of continental subduction and other factors in modifying subduction processes. Additional opportunities to constrain dynamic processes are likely from comparisons of the large-scale dynamics of the Arabia-Eurasia and India-Eurasia continental collisions (Figure 2; Almendinger, Reilinger, and Loveless, 2007; Royden, Burchfiel, and Van der Hilst, 2008).

We propose a broadly based, integrated study of post-Late Oligocene Mediterranean and Middle East/East African tectonics to test the hypothesis that Mediterranean extension and the structural evolution of the Arabia-Africa rift systems (Red Sea and Gulf of Aden) result from slowing of Africa-Eurasia convergence and the associated increase in Africa-Arabia relative plate motion, and that slowing of Africa-Eurasia convergence results from a reduction in the northward pull of the subducting Neotethys oceanic lithosphere. This hypothesis is based on initial observations of the style and timing of tectonic events around the periphery of the African (Nubian) Plate, including, 1) Initiation of Red Sea, Gulf of Aden, and the East African rift system (Afar Triple Junction) at 24±4 Ma (Bosworth et al., 2005; ArRajehi et al., 2010) roughly simultaneously with the onset of Mediterranean back-arc extension (Alboran, Belleric, Aegean basins; Jolivet and Faccenna, 2000), 2) Simultaneous changes at 11 ± 2 Ma in the rate and orientation of extension for both the northern (Sinai) and southern (Afar/Danakil) Red Sea (McClusky et al., 2010), as well as for the character of extension in Mediterranean basins (e.g., Krijgsman and Garces, 2004, McClusky and Reilinger, 2010), and 3) Recent (<5 Ma) changes in the orientation of Africa-Eurasia convergence (Calais et al., 2003), that may be related to the initiation of ocean rifting in the Red Sea.

Geodetic observations (Reilinger et al., 2006) and plate tectonic reconstructions (McQuarrie et al., 2003) of Africa-Arabia-Eurasia plate motions reveal a remarkably simple scenario (Figure 3) involving a roughly constant convergence rate for the Africa/Arabia Plate with Eurasia (i.e., prior to Africa separating from Arabia at ~ 25 Ma). The initiation of continental rifting in the Red Sea and Gulf of Aden at ~ 25 Ma coincides with the slowing of Africa-Eurasia convergence while Arabia continued at about the same rate that is not significantly different from the present-day GPS rate (Figure 3). Africa-Eurasia convergence underwent a second episode of slowing and a change to more N-S relative motion at ~ 11 Ma, corresponding to an increase in the rate of extension across the Red Sea and Gulf of Aden. Also at ~ 11 Ma extension in the Mediterranean changed character (e.g., Krijgsman and Garces, 2004). These observations suggest that changes in the character of the plate boundary are directly related to changes in the rate and orientation of plate convergence/divergence.

Why Africa rifted from Arabia remains enigmatic. It seems unlikely that collision of the Apulia Promonitory with Eurasia caused slowing of Africa because it collided in the early Eocene, well before the initiation of rifting. Furthermore, >10 Myr of continental collision of Arabia with Eurasia has had little, if any, effect on Arabia-Eurasia motion (Figure 3). Perhaps rifting initiated as a result of weakening of the Africa-Arabia continental lithosphere above the African Hot Spot (Buck et al., 1999, Ebinger and Casey, 2001), gravitational driving forces due to uplift above the Hot Spot, and plate tectonic driving stresses related to "pulling" of the African plate by the dense subducted Neotethys lithosphere (Bellahsen et al., 2003). Further slowing of Africa-Eurasia convergence at 11 ± 2 Ma corresponds temporally with the initiation of full oceanic rifting in the Gulf of Aden; slowing that was perhaps due to a further reduction in the pull on Africa from the subducting ocean lithosphere. The most recent changes in Africa-Eurasia convergence involve an increase in the westward motion of Africa with respect to Eurasia (Calais et al., 2003). This change corresponds temporally with the initiation of ocean rifting in the Red Sea and may correlate with a reduction in the eastward pull on Africa across the Red Sea from subduction along the Zagros-Makran subduction zone.

In order to advance understanding of the relationships between plate motions, the active tectonic and structural evolution of plate boundaries (i.e., subduction and rifting), and their underlying dynamics, we recommend the following integrated studies of the Africa-Arabia-Eurasia plate system:
—Integrate geodetic, plate tectonic, and geologic observations to reconstruct in space and time the detailed evolution of the Red Sea (from the Suez-Dead Sea fault system to the southern Red Sea-Afar).
—Focused seismic investigations of mantle structure and anisotropy in the Caucasus, the Hellenic arc-Cyprus arc junction in SW Turkey, and the Cyprus arc-Dead Sea Fault, East Anatolian fault junction in SE Turkey and Syria to constrain mantle structure (subducted slab) and anisotropy (mantle flow) at these critical junctions.
—Quantitative geodynamic modeling of broad scale plate motions to constrain contributions from the range of forces acting on the plates.
—Geologic studies of the timing of onset and changes in the style of tectonic extension in the Mediterranean.

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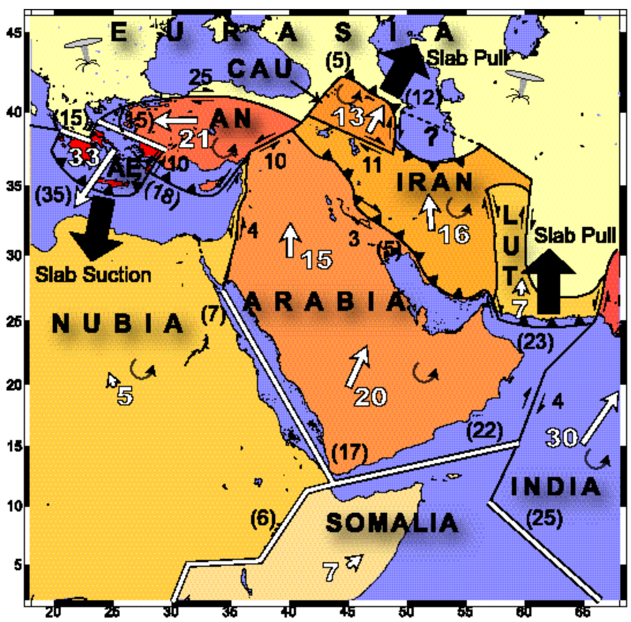

Figure 1. Schematic tectonic map of the Arabia-Africa-Eurasia zone of plate interaction. Names refer to plates and blocks. Double lines are extensional plate boundaries, plain lines are strike-slip boundaries (paired arrows show direction of strike-slip motion), and lines with triangles are thrust faults. Dark numbers are GPS-derived slip rates (mm/yr) on block-bounding faults (numbers in parentheses are dip-slip and those without are strike slip). White arrows and corresponding numbers show GPS-derived plate velocities (mm/yr) relative to Eurasia. Curved arrows show sense of block rotation relative to Eurasia. Dark, heavy arrows show hypothesized forces associated with active subduction acting on the plate/block system and causing counterclockwise rotation of Arabia, Central Iran, and Anatolia relative to Eurasia.

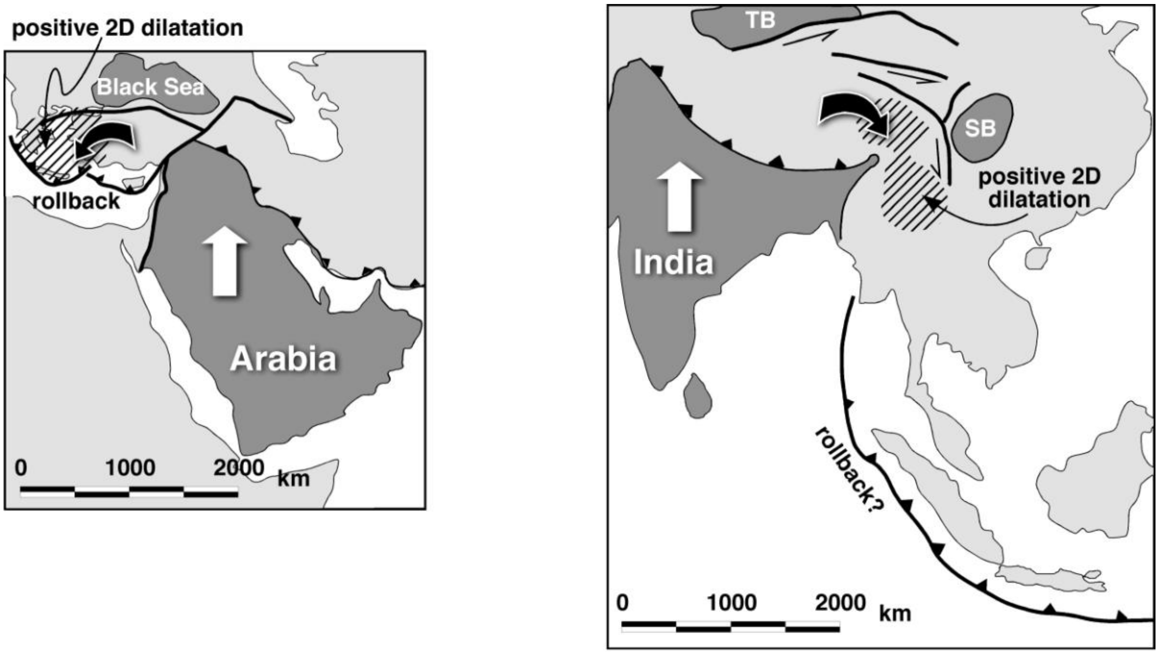

Figure 2. Anatolia and Tibet as mirror images of one another, highlighting the relationship between trench rollback and positive 2-D dilatation (from Allmendinger, Reilinger, and Loveless, 2007).

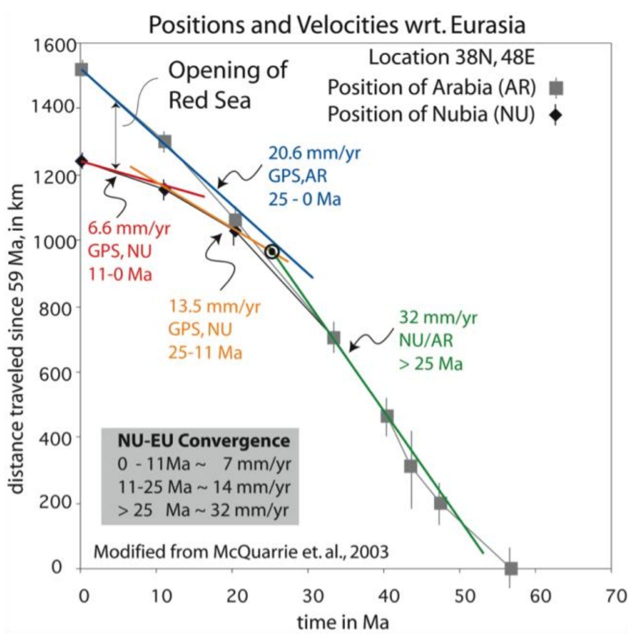

Figure 3. Plate Tectonic reconstruction of the motion of a point on the AF-AR plate since 57 Ma compared to present-day GPS rates (red for AF, blue for AR). Note that the rate of AR-EU convergence has been constant (within uncertainties) since 25 Ma (time of initiation of the Red Sea rift) and AF since 11 Ma, and that AF slowed wrt EU in 2 steps (25 Ma, 11 Ma). Modified from McQuarrie et al. (2003).

GeoPRISMS White Paper - Theme 4.6 (Subduction Inception)
The SW North American Cordillera: an exposed, accessible and underutilized archive of Paleozoic to Cenozoic subduction-initiation processes

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A major question asked by the GeoPRISMS Science Plan concerns the conditions that control subduction zone initiation and subsequent arc maturation. One approach is to study modern examples of this process (e.g., Mussau, Puysegur), which, given their largely submarine setting, would rely largely on geophysical data, and core, submersible, and dredge samples. Some older intraoceanic examples (e.g., Izu-Bonin-Mariana) are also limited to these sorts of data sets. Alternatively, the Pacific margin of North America offers the opportunity for broader field-based studies of the *in situ* products of subduction inception along a continental margin, as well as potential intraoceanic examples in accreted terranes.

The SW North America Cordillera contains a rich history of subduction initiation events as recorded in its ophiolite belts, and patterns of arc magmatism, regional deformation and basin subsidence. At least five distinct events are readily recognized spanning early Paleozoic to mid-Cenozoic time (Fig.1), and additional less obvious events can be argued for. There is much to be learned about this fundamental plate tectonic process from integrative studies of structure-stratigraphy, petrology-geochemistry and geodynamic modeling applied to each of the five principal events. These events are diverse in nature, some having close analogues in active plate tectonic settings potentially offering an approach of comparative and iterative studies between exhumed crustal sections and active patterns of deformation, magmatism and plate kinematics. The essential features of these five events are summarized below primarily from the perspective of ophiolite petrogenesis and tectonic history. Even though there is an abundance of geological data in the literature for each event, little research has been conducted that specifically targets key features and relations focused on the process of subduction initiation. We bring the key features of each case into focus here with aims of stimulating and drawing together multi-disciplinary researchers in the fields of structure-stratigraphy, petrology-geochemistry and geodynamics in order to move our understanding of subduction initiation (SI) to a substantially deeper level.

1. Early Silurian SI is well recorded in the polygenetic Trinity ophiolite consisting of Early Ordovician MORB mantle lithosphere and nonconformably overlying supra-subduction ophiolitic crustal rocks (cf. Metcalf et al., 2000). SI in this case was within an intra-oceanic environment located off the distal flank of the Cordilleran passive margin continental rise with subsequent arc activity in later Silurian through Devonian time constructing a regional fringing arc system (McCloud-Stikine system) that runs most of the length of the central to northern Cordillera. The scale and internal complexity of this accreted arc terrane are comparable to the Philippine arc. The Trinity ophiolite segment of the McCloud-Stikine arc is perhaps the only area where this event can be studied in detail because of the subsequent accretion of a second outboard arc system (Insular arc), which has severely overprinted most of the McCloud-Stikine arc.

2. Late Permian SI is well recorded along the Sierra Nevada western Foothills ophiolite belt and its oblique truncation locus across the southwestern terminus of the Cordilleran passive margin and its fringing McCloud-Stikine arc (cf. Saleeby, 2011). The ophiolite belt records large offset transform tectonics, and related oceanic core complex development in Ordovician through Pennsylvanian MORB lithosphere. The oceanic transform circuited directly into a complex boundary transform system that truncated the passive margin and its fringing arc. The MORB ophiolite belt was accreted to the hanging wall of a Late Permian neo-subduction zone. Regional extensional tectonism and strike-slip slivering along the truncated passive margin, its marginal basin and the fringing arc are in accord with the timing and kinematics of oceanic and boundary transform displacements, and the superposing of thrust belt deformation across the same region is in accord with the kinematics and timing of SI. Regionally extensive upper plate thrusting indicates a substantial forced phase of SI, which in early Mesozoic time rapidly changed to self sustaining with the widespread eruption of typical proto-forearc volcanic associations. The early stages of the Foothills ophiolite belt SI event has a number of similarities to the Macquarie-Puysegur trench/Alpine fault system, which to our knowledge has yet to render proto-forearc volcanic associations that would signal transition to self sustaining subduction.

3. Middle Jurassic SI is well recorded in the Coast Range ophiolite (CRO) of California and related terranes in Oregon and Washington. The CRO preserves a complete SSZ ophiolite assemblage, with early fore-arc basalts and related gabbros, boninites, arc tholeiites, and calc-alkaline arc assemblages, overlain or intruded in places by younger MORB-like volcanics and hypabyssal dikes (e.g., Shervais et al 2004). It is intimately associated with both an overlying forearc basin assemblage (the Great Valley Group) and an underlying subduction accretion complex (the Franciscan complex) (Hopson et al 2008). Choi et al (2008b) document evidence for formation of the CRO by subduction initiation along an oceanic fracture zone, a model that is supported by detailed studies of mantle tectonite petrology (Choi et al 2008a; Jean et al 2010). Nonetheless, remnants of the CRO vary greatly in stratigraphy and lithology depending on location, which implies a complex origin and evolution that likely varies along strike.

4. Late Jurassic SI is recorded for the Josephine ophiolite, which formed by Middle Jurassic inter-arc basin rifting over a period of ~5 m.y. at the end of the Middle Jurassic (cf. Harper et al., 1994). The Josephine ophiolite consists of an intact supra-subduction mafic crustal section that was rendered from the underlying Josephine peridotite. The ophiolite formed at a spreading center that split apart an Early to Middle Jurassic island arc complex, much like the Mariana Trough has rifted the West Mariana Ridge. In parallel to the Mariana system the inner ribbon of the rifted Jurassic arc became volcanically inactive as rifting progressed, and subsided to become a remnant arc while the outer ribbon became the basement for a neo-volcanic arc that fringed the Josephine inter-arc basin. Basement correlations and sediment provenance data clearly relate the remnant arc to the neo-arc basement ribbon. After ~5 m.y. of inter-arc basin spreading, subduction initiated beneath the remnant arc with a minimum of ~100 km of rapid underthrusting of the Josephine interarc basin floor. Such structural overlap is clearly seen in seismic reflection data and in superposed structural windows through the upper plate remnant arc. Following ~5 m.y. of rapid subduction the inter-arc basin ophiolite was obducted over the rear edge of the neo-arc as the neo-arc impinged on the remnant arc bounding subduction zone. The reason for the collapse of this system and the forcing of this SI event is poorly understood, but is thought in some way to be related to both the oblique impingement of the Insular arc terrane, and rapid changes in plate motions at the end of Jurassic time that are well recorded in the North America APW path. The style of subduction initiation and interarc basin closure that is so clearly recorded in this system is commonly depicted in conceptual plate tectonic cartoons, even though an active modern analogue is apparently missing on Earth at this point in geologic time.

5. Late Eocene SI is recorded for an ~600 km long segment of the Cordilleran active margin along what was to become the Washington-Oregon Coast Ranges known as Siletzia (cf. Wells et al., 1984). This event is marked by the impingement of an oceanic large igneous province into the pre-existing subduction zone that had extended along coastal California through coastal British Columbia from at least as far back in time as the mid-Cretaceous. A large fragment of the LIP was accreted to the subduction zone, and then subduction stepped westwards leaving a lithosphere-scale nappe wedged between the paleo- and neo-subduction zones. The postulated origins for the accreted LIP include a plume head centered on the, then, newly established Kula-Farallon ridge, a leaky fracture zone in the Farallon plate, or the proto-Yellowstone hotspot. There are no active environments exhibiting this form of SI on Earth today.

In sum, we suggest that the SW North American Cordillera should be considered as an auxiliary site because, as per the GeoPRISMS implementation structure, 1) it represents end members of critical parameters (continental and intraoceanic SI); 2) it supplies critical components for global comparison; 3) it exhibits phenomena likely to be obscured at primary sites (provides broader access to products through large outcrop areas that also exhume different stratigraphic/crustal levels); and 4) it documents different stages of margin evolution as well as periodicity of processes.

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FIGURE 1. Tectonic map of North America with trends of subduction events discussed in the text. Modified from Muehlberger (1992).

AN IMPLEMENTATION STRATEGY FOR UNDERSTANDING SUBDUCTION INITIATION (SI); INTEGRATED STUDIES OF NAKED FOREARCS, OPHIOLITES, AND GEODYNAMIC MODELING

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Subduction initiation (SI) is a fundamental yet unresolved solid Earth problem. Why subduction starts remains contentious because it is a transient event and neither the geological record nor the geodynamics of SI are understood. How a subduction zone forms and evolves exerts important controls on the operation of the mature subduction zone, including the depletion and fabric of forearc lithosphere, asthenospheric flow, and how slab-derived fluids traverse downwelling mantle. The crust generated during SI makes up the vast majority of juvenile arc crust and this interacts with and influences the composition of mature arc melts. SI must be easy because it happens often: nearly half of all presently active subduction zones began during the Cenozoic (Gurnis et al., 2004). We are now beginning to decipher the geologic record of SI. Recent manned submersible diving on the IBM inner trench wall indicates that IBM SI occurred ~ 51 Ma (the time of the change in Pacific plate motion indicated by the Emperor-Hawaii seamount chain bend; Sharp and Clague 2006) and was accompanied by seafloor spreading and MORB-like basaltic volcanism (Reagan et al., 2010). Similar efforts to understand SI of potential focus sites such as the Cascades, Aleutians, or New Zealand vicinity are required if we are to understand how these convergent margins formed and function.

Our understanding of SI has advanced such that a focused interdisciplinary effort is now warranted. Such an effort should produce quantitative and realistic geodynamic models of SI that incorporates force balance, lithosphere-asthenosphere interactions, fluid migration, and melt generation. These models should address why and how the ~200 km wide forearc, the site of extensive melting and seafloor spreading during SI, is transformed into the coldest tectonic environment on Earth. This change in the behavior of the overriding plate must reflect a change in the behavior of the sinking lithosphere, from flexed sinking to down-dip motion and true subduction (Fig. 1). This effort would also address whether SI requires compression (Hall et al., 2003) or can happen spontaneously, due to the excess density of old oceanic lithosphere alone (Stern, 2004). These and other SI-related questions are ripe to be answered by focused, coordinated investigations and dialogue involving geodynamicists, field geologists, marine geoscientists, and geochemists. A three-pronged approach involving (1) marine studies of forearcs, (2) on-land studies of ophiolites, and (3) realistic geodynamic modeling should be the centerpiece of this effort, and is outlined below.

Marine studies of naked forearcs: Intra-oceanic forearcs preserve a high-fidelity magmatic and stratigraphic record of SI and lack thick blankets of obscuring sediment. Thus, a detailed investigation of 'naked' forearcs would illuminate SI and early arc evolution (see Reagan et al. White Paper). Naked forearcs are distant from continents and are flanked by deep trenches, making study and sampling expensive and difficult. Shinkai 6500 diving in the Mariana forearc near Guam discovered a magmatic stratigraphy of lower basalt (termed fore-arc basalt or FAB) overlain by boninite that formed by seafloor spreading prior to retreat of the magmatic axis away from the trench (Reagan et al., 2010; Fig. 1). Eruption of MORB-like basalts and calcalkaline arc lavas required 6-7 million years of subduction-zone development. A similar pattern of volcanism is encountered to the north, in the Bonin forearc (Ishizuka, pers. comm., 2010). Key advances in understanding forearc crustal structure were made as a result of DSDP Leg 60 and ODP Legs 125 and 126 expeditions to the IBM forearc in the 1970's and 1980's. Enough knowledge now has been gained to target forearc drilling and other marine geoscientific studies with a goal of robustly defining the structure and composition of crust associated with SI and early subduction.

On-land study of ophiolites: Because ophiolites are exposed on land, they are easier and cheaper to study than forearcs, but not all ophiolites form during SI. We can use our understanding of SI magmatic stratigraphy identified for the IBM forearc, which is seen in many of the best preserved ophiolites (Shervais, 2001; Pearce 2003, Dilek and Furnes, 2009), to identify well-preserved SI ophiolites for detailed field and laboratory studies. Such ophiolites should also be selected with the intention of drilling and coring, to better compare its extrusive and mantle rocks with those recovered by forearc drilling. In particular, we can use for this purpose the recently articulated "Ophiolite Rule" (Whattam and Stern, submitted), which states that SI ophiolites preserve a magmatic stratigraphy of MORB-like basalt at the base overlain by arc lavas (±boninite), which provides an independent way to identify SI ophiolites. This understanding opens the door for on-land ophiolitologists to contribute fundamentally to understanding SI (See White Papers by Dilek et al., Saleeby et al., and Shervais et al.).

Geodynamic modeling: Numerical modeling methodology of SI is mature and accounts for high resolution in both regional and global two- and three-dimensional models, realistic visco-elasto-brittle/plastic rheology of rocks, topography evolution, fluid and melt transport above slabs and magmatic crust growth (e.g., Hall et al., 2003, Gerya et al., 2008; Nikolaeva et al., 2008, 2010; Zhu et al., 2009; Stadler et al., 2010). Nevertheless, such modeling often lacks crucial data that can be compared with an existing variety of SI models. Geodynamic modeling of SI processes should be fully integrated with studies of forearcs and ophiolites from earliest stages of the project (See White Paper by Gurnis et al.). Analyzing existing and newly constructed numerical models of SI should help for (i) delineating of sites in forearcs where crucial information on SI is likely to be present, (ii) analyzing existing passive/transform plate boundaries worldwide (e.g. Stadler et al., 2010) to determine their stability and suitability for observing early stages of SI and (iii) constructing refined 2D and 3D numerical models of SI (e.g. Hall et al., 2003, Gerya et al., 2008; Nikolaeva et al., 2008, 2010; Zhu et al., 2009) applicable to observational sites. Modeling is also needed to provide broader context for these observations, including how the asthenosphere flows and melts, how fluids penetrate into the overriding asthenosphere, how hinged slab subsidence evolves into downdip subduction, how hot forearc mantle cools and becomes lithosphere, and how subduction initiation is a cause or a consequence of global plate motions. Fundamental factors controlling the sinking of slabs during SI are still not understood. In order to better understand the melting process and the sequence of magmatotectonic products observed in naked forearcs, new petrological models need to be incorporated into SI geodynamic modeling, e.g. pHMELTS (Hebert et al., 2009). Furthermore, with the advent of much powerful computational resources, 3-D SI models with visco-elastic-plastic rheology are demanded. Geodynamic modeling is especially important to understand what allows the slab to sink and how and where this process is facilitated through interaction of globally confined plates (e.g. Stadler et al., 2010).

Momentum for the research activities outlined above is provided by recently planned IODP drilling in the Amami Sankaku Basin in the Philippine Sea, with an expedition tentatively scheduled for 2012. A major objective of this expedition will be to penetrate over 1300 m of sediment and oceanic crust, some of which existed when IBM subduction began. The cored volcanic and sedimentary section should record the inception of IBM subduction, shedding light on the mode of initiation (induced vs. spontaneous), as well as arc evolution. Detailed data from this site will be used to test models based on integrated studies promoted herein.

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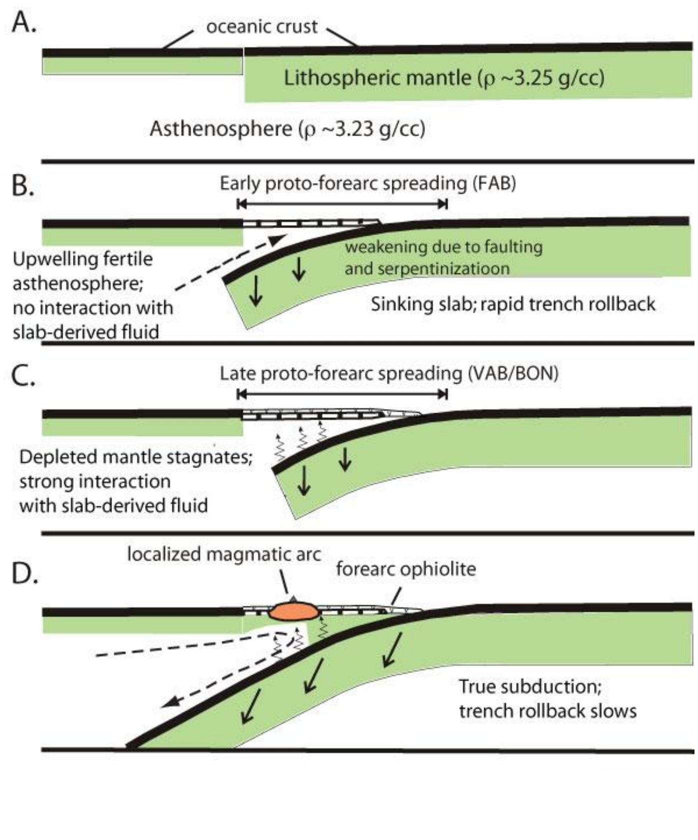

Fig. 1: Subduction initiation, formation of the forearc, and evolution of magmatic systems. A) Older, thicker, colder, and denser lithosphere (right) is juxtaposed with young, thinner, hotter, and more buoyant lithosphere across a zone of weakness (e.g. fracture zone). B) subsidence of old lithosphere allows asthenosphere to flood over it. Upwelling asthenosphere melts due to decompression, generating MORB-like basalt (forearc basalts of Reagan et al., 2010) accompanied by seafloor spreading. C) continued lithospheric subsidence or beginning of downdip motion of slab is accompanied by penetration of slab-derived fluids into upwelled mantle, causing melting of depleted harzburgite. (D) Downdip motion of lithosphere signals start of true subduction, which terminates rapid trench rollback and proto-forearc spreading. Forearc mantle cools and igneous activity retreats ~200 km to what becomes the magmatic arc. IBM SI encompassed ~7 m.y. for the complete transition from initial seafloor spreading to normal arc volcanism. BON =Boninite; FAB = forearc basalt; VAB = volcanic arc basalts.

The Southeast Mariana Forearc Rift: A Modern Analague for Forearc Extension during Subduction Initiation

Robert J, Stern, Fernando Martinez, Julia Ribeiro, Mark Reagan, Yas Ohara, and Osama Ishizuka

Subduction initiation (SI) is associated with broad zones of extension and volcanism in what becomes the forearc. These “infant-arc” tectono-magmatic regimes erupt voluminous MORB-like tholeiites (FAB of Reagan et al., 2010) to form forearc crust, Yet, the nature of protoforearc extension during SI remains speculative because such short-lived spreading regimes have no counterpart among presently active arc systems. We assume SI seafloor spreading is like modern mid-ocean ridges but the different tectonic regimes and especially different water fluxes suggest there may be significant differences. The SE Mariana Forearc Rift (SEMFR; Fig. 1A, B) provides an actualistic example of forearc extension that illuminates SI protoforearc extension. This unusual region of forearc extension results from the opening of the Mariana Trough back-arc basin ~4.5 cm/year at the latitude of Guam (Kato et al. 2003), causing the southern Mariana convergent margin to reform as it rapidly lengthens. The SE margin is rapidly evolving and has yet to stabilize as a convergent plate margin, as evidenced by the fact that it has no well-defined magmatic arc, in spite of a subducted slab at the appropriate depth, and widely melted mantle. Forearc rifts like SEMFR are uncommon, because forearcs are generally relatively cold, strong, and stable. Rifts near convergent plate boundaries occur at other locations where trenches bend sharply and rollback induces extension in the overlying plate, such as at the northern end of the Tonga Trench and at the southern end of the New Hebrides Trench. The lesson from SEMFR is that SI infant arcs are likely to have had broad, poorly localized zones of extension and volcanism

SEMFR is bathymetrically defined by a complex, diverging set of NE-SW trending ridges SW of Guam (Fig. 1A, B). So defined, it encompasses a region ~150 km NW-SE and ~70 km NE-SW. Sidescan sonar imagery reveals high acoustic backscatter over the region from the backarc spreading ridge to the trench, indicating broadly distributed basement exposure and volcanism (Martinez et al., 2000). Seafloor imaging reveals abundant normal faulting, volcanic ridges composed of pillowed basalts, abundant talus of fresh basalt, and little sediment cover. 6 samplings of SEMFR seafloor during 2008 and 2010 recovered only fresh basalt. SEMFR is flanked to the E by a N-S ridge of gabbro and peridotite (Michibayashi et al., 2009). Detailed petrologic studies at Shinkai dive 1096 indicate these basalts are essentially siilar to back arc basin basalt (BABBl Ribeiro et al., 2010). Earthquake locations confirm that deformation is broadly distributed, with both extensional and strike-slip focal mechanisms. These datasets reveal pervasive, diffuse, and complex extension, with an axis that is oriented at high angles to the trench and backarc spreading ridge and parallel to the plate convergence vector. Trench-parallel rifting of the southern Mariana margin ruptured the pre-existing forearc lithosphere and caused mantle wedge asthenosphere to flow from the backarc region over the subducting slab to near the trench. This flow of asthenosphere towards the trench over a very shallow subducting slab is similar to what is thought to occur during SI.

The diffuse nature of SEMFR extension and volcanism may be caused by high water flux from the slab to the overlying mantle. Water reduces olivine and thus mantle strength by orders of magnitude relative to anhydrous mantle (Peslier et al., 2010). At mid-ocean spreading centers mantle dehydration accompanies melt extraction yielding a strong compositional lithosphere and a narrow plate boundary zone (Fig. 1C; Phipps-Morgan 1997). Beneath the southern Mariana convergent margin (and during SI), however, continuous water flux from the subducting slab may effectively counter mantle dehydration as a result of melting. Water flux from any subducting plate is at a maximum beneath the forearc, decreasing rapidly with increasing depth (Hacker, 2007). High water content of mantle beneath SEMFR may result in weak mantle which stimulates melting at the same time that is precludes formation of strong compositional lithosphere and thus localization of extension. SI magmatism and extension may be similarly diffuse, for similar reasons.

One complication is that early SI magmatism (FAB) shows little evidence that water was important during melting (only one FAB glass has been analyzed, with 0.1% H_20). If this is representative of FAB, what happened to the water that must have been released from the slab during this time? Was it absorbed by the overlying mantle before it reached the region of melt generation? Certainly water has effectively permeated and presumably weakened the mantle above the slab by the time that upper boninites are generated, but what happened to the water at the beginning, when FAB formed? There were clearly heterogeneous influences of subducted materials in FAB; the nature of the heterogeneity in time and space, the causes, and the dynamic implications need further work to evaluate.

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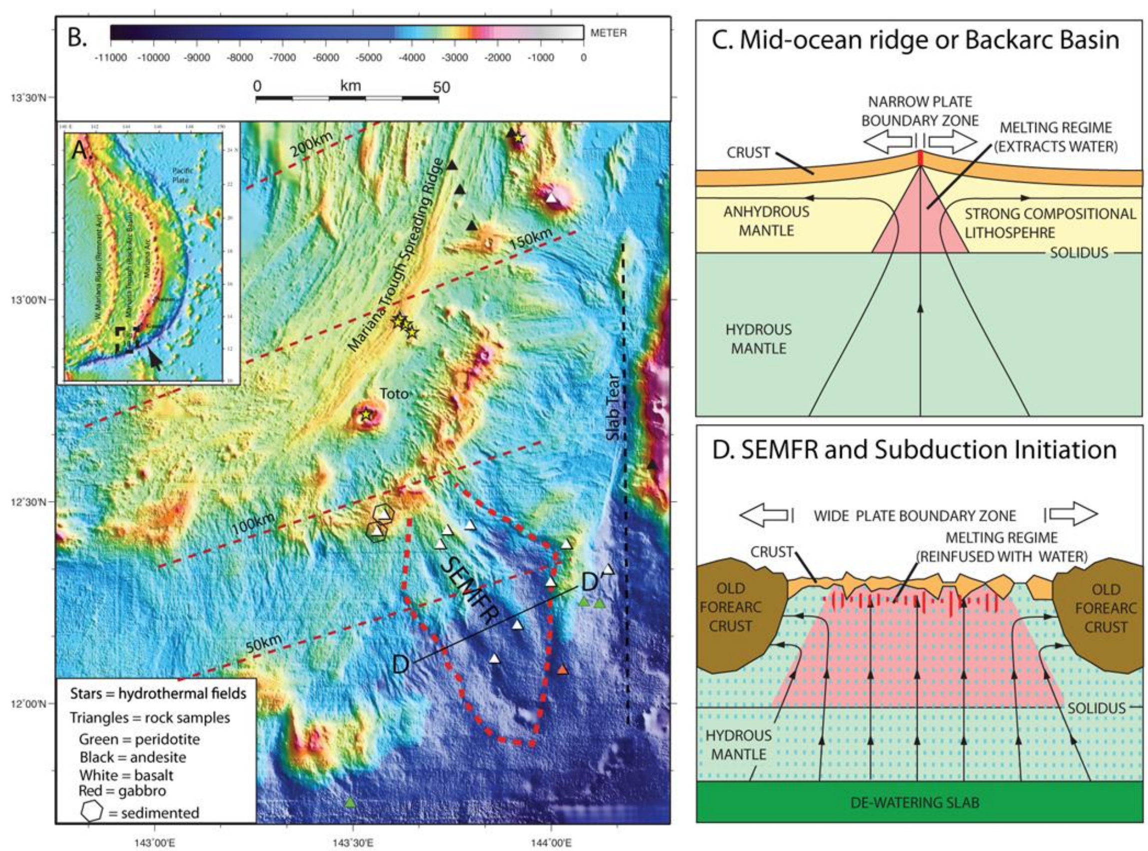

Figure 1. A) Location of SE Mariana Forearc Rift (SEMFR) in Mariana arc (dashed box). Arrow shows plate convergence vector. B) S. Mariana Trough and SEMFR showing location and lithologies of seafloor samples. Dashed red lines show approximate depth of subducted Pacific plate; note inferred position of slab tear beneath major N-S fault (West Santa Rosa Bank Fault). The andesitic volcano ~13°15'N, 144°E is as far SW as the Mariana volcanic arc can be traced; BAB spreading axis may have captured arc magma supply SW of this point. Magma chamber beneath BAB spreading axis imaged by Becker et al. (2010) is at 13°05'. C, D: Model for narrow vs. wide plate boundary zones. Diagrams depict cross-sections perpendicular to a mid-ocean spreading center (C) and parallel to but behind the trench at a convergent margin (D, profile location is shown on B as D-D'). C) Beneath mid-ocean ridges asthenosphere with modest water content (green) flows upward (black arrowed lines indicate mantle flowlines) due to plate separation leading to pressure release melting (pink region) and extraction of water from the mantle with the melt. Residual mantle (yellow) is anhydrous and much more viscous than the underlying modestly hydrous mantle. The generation of strong compositional (dry) lithosphere thus helps focus deformation and crustal magmatism (red vertical line) to a narrow plate boundary zone. D) Beneath convergent margins the underlying subducted slab (dark green) continually releases water to the overlying mantle, leading to low mantle wedge viscosities. Extension, breakup and separation of the pre-existing forearc (dark brown) leads to upward advection of mantle and pressure release melting augmented by hydrous melting (note deeper solidus than in C) and formation of a broad melting regime (pink). Flowlines show only components in plane of cross-section. Actual flow is three-dimensional with significant flow perpendicular to plane of section. Although melt extraction removes water, continual water flux from subducting slab

(blue dashes) prevents mantle dehydration and formation of strong lithosphere. Extension (indicated by region bounded by white divergent arrows) and magmatic crustal emplacement (red vertical lines) are broadly distributed and variable with possible mantle exposure at the seafloor.

The Hikurangi margin, New Zealand: an important natural laboratory to understand subduction thrust behavior

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Why is the Hikurangi margin ideally suited to investigation of subduction thrust processes? In the past decade, a number of geophysical and geological studies at the Hikurangi subduction margin reveal that pronounced along-strike changes in subduction interface behavior also correspond to observed changes in other fundamental subduction margin characteristics (see reviews by Wallace et al., 2009, and Barnes et al., 2010; Fig. 1). These observations have been made possible by New Zealand's large investment (more than 60 Million NZD over the last decade) in land-based monitoring (cGPS and seismometer network; www.geonet.org.nz), >7000 km of offshore and onshore active source seismic surveys, and other studies at the Hikurangi margin. GPS measurements reveal that deep interseismic coupling and slow slip events (SSEs; 30-60 km depth) occur at the southern portion of the Hikurangi interface, while the northern Hikurangi subduction thrust is dominated by steady aseismic slip and shallow SSEs (<10-15 km depth). These changes in the depth to SSEs and the downdip limit of the likely seismogenic zone are accompanied by along-strike changes in convergence rate, sediment thickness on the incoming plate, degree of accretion vs. subduction erosion, upper plate stress regime (i.e., a shift from back-arc extension to transpression in the upper plate), geochemical signature of fluids emerging within the forearc, among other characteristics (Fig. 1). Southern Hikurangi is a useful analogue for margins such as Nankai and Cascadia, while the northern Hikurangi margin bears many similarities to Costa Rica. Moreover, this margin offers an opportunity to study a locked subduction thrust capable of producing great megathrust events (southern Hikurangi) and one dominated by aseismic creep (northern Hikurangi), all at a single plate boundary.

Shallow slow slip events at northern Hikurangi enable detailed characterization of the physical properties of the SSE source area. Well-documented SSEs at subduction zones worldwide typically occur at 25-60 kilometers depth, so highly accurate imaging and characterization of the SSE source area is difficult with current technological capabilities. Unlike other SSE locations, the shallow depth of the northern Hikurangi SSEs (<5-15 kilometers depth) makes it amenable to highly detailed investigations, and is an ideal location for testing and developing ideas regarding the genesis of slow slip and the nature of the down-dip transition from stick-slip to aseismic creep behavior. Recently acquired 2-D multichannel seismic (MCS) data from the offshore northern Hikurangi margin reveal a zone of high-amplitude reflectivity near the subduction interface, 5–15 kilometers below the seafloor, that coincides with geodetically determined SSE source areas (Bell et al., 2010) (Fig. 2). These high-amplitude reflective zones are interpreted to correspond to fluid-rich sediments, suggesting that fluids may play an important role in the occurrence of SSEs at the northern Hikurangi margin.

A sampling of the fundamental questions that can be addressed at this margin:

What determines the location of the seismogenic zone and the occurrence of subduction thrust earthquakes**?** The major along-strike changes that we observe in the spatial extent of the likely seismogenic zone at the Hikurangi margin (Fig. 1) cannot be easily explained by one or two simple parameters. For example, thermal models suggest temperatures at the down-dip limit of interseismic coupling and SSEs range from 100-400°C (McCaffrey et al., 2008). Instead, an interplay between upper and lower plate structure, subducting sediment, temperature, regional tectonic stress regime, and fluid pressures probably controls the extent of the subduction thrust's seismogenic zone (e.g., Wallace et al., 2009). However, the extent to which each of these processes plays a role in the seismogenic zone geometry is currently unknown.

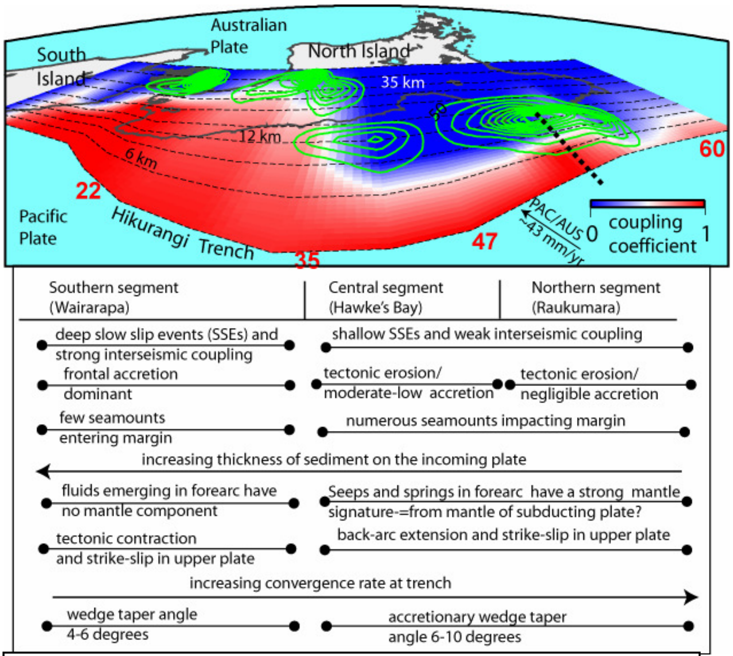

Fig. 1. Perspective view of the Hikurangi margin illustrating the portions of the subduction interface that undergo stick-slip (red to white) versus aseismic creep (dark blue) in terms of interseismic coupling coefficient. Green contours show areas of slip in slow slip events since 2002 (from Wallace and Beavan, 2010). Convergence rates at the trench are labelled as red numbers (mm/yr) near the trench. Motion of the Pacific Plate relative to the Australian Plate (PAC/AUS) is shown with the black arrow. The black dotted line marks the approximate location of the seismic profile in Fig. 2. Along-strike changes in various subduction margin properties are summarized beneath the perspective plot.

Mounting efforts for detailed geophysical transects (active source seismic, MT, heat flow, to name a few) of the stick-slip southern Hikurangi margin and the aseismically creeping northern Hikurangi margin combined with along-strike transects (Fig. 1) have potential to reveal changes in physical properties of the interface and upper plate that may help to solve the long-standing mystery of why some margins produce Great subduction thrust events and others do not. Marked along-strike variations in the geochemistry of fluids emerging in the subaerial forearc suggest variations in the source of the fluids (Reyes et al. 2010), and has implications for the permeability of the upper plate; this setting also offers an opportunity to assess the role that the release of fluids plays in the behavior of the megathrust.

What physical mechanisms control the occurrence of slow slip events? Since 2002, the installation of a continuous GPS network in New Zealand has enabled the discovery of ~15 slow slip events at the Hikurangi subduction margin (Wallace and Beavan, 2010). These SSEs follow the down-dip transition from interseismic coupling to aseismic creep, similar to subduction margins elsewhere (Fig. 1). The deep (35-50 km depth) southern Hikurangi margin events have long durations (1-1.5 years) and larger equivalent moment release (> Mw 7.0; depth, duration and magnitude similar to Alaska SSEs), while the shallow (<15 km depth) northern Hikurangi margin SSEs occur more frequently (every two years), have shorter durations (1 week up to 2 months; depths and duration somewhat similar to Costa Rica SSEs) and smaller equivalent moment release (~6.5-6.8). The systematic along-strike variations in SSE recurrence, duration and magnitude characteristics that we observe at Hikurangi provide an ideal setting to assess the physical controls on the SSE characteristics. Borehole seismometers in the SSE regions at the Hikurangi margin could help to resolve whether or not tremor and/or low frequency earthquakes occur in concert with Hikurangi SSE, while high-quality tiltmeters and densification of cGPS sites would enable detection of smaller SSEs and reveal the full spectrum of SSE behavior.

A broad, international group of researchers recently submitted a pre-proposal to IODP to drill into the northern Hikurangi SSE source area and associated high-amplitude reflectivity zone on the subduction interface at about 5 kilometers below the seafloor in 700-1000 m water depth (Fig. 2). This target is unique, as it is the only well-documented subduction SSE source area on Earth within range of modern offshore drilling methods. The potential for active-source seismic imaging, drilling, down-hole measurements, sampling, and monitoring of the northern Hikurangi margin SSE source area provides a world-class opportunity to definitively test hypotheses regarding the properties and conditions leading to SSE occurrence, and ultimately, to unlock the secrets of slow slip and the nature of the down-dip transition from stick-slip to aseismic creep on megthrusts.

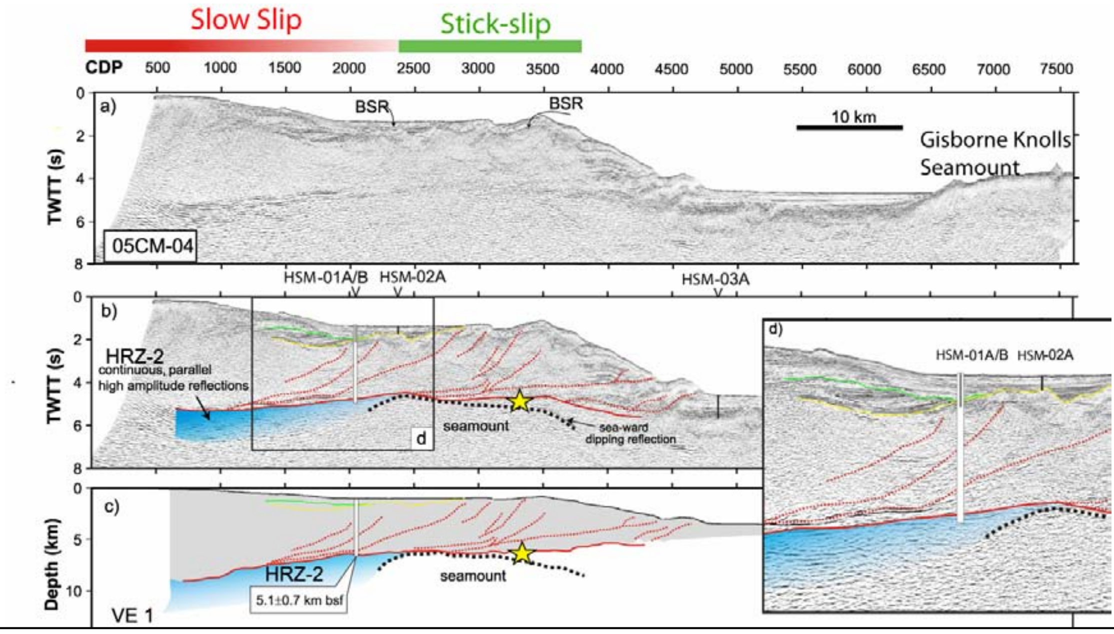

Fig. 2. (a) Uninterpreted and (b) interpreted seismic profile from the northern Hikurangi margin (see location on Fig. 1). Solid red line is the subduction interface, dotted red lines are splay faults within the upper plate. Yellow star denotes position of the March 1947 tsunamigenic earthquake (Doser and Webb, 2003). (c) Depth-converted interpretation. Areas of high-amplitude reflectivity (HRZ; Bell et al., 2010) shaded in blue. Vertical white line shows a potential position for offshore drilling to access the slow slip source area and HRZ intersection the interface at 5.1 km below the seafloor (bsf). Color bar at top of figure schematically denotes the region of the interface that is inferred to undergo stick-slip (green) vs. slow slip (red). BSR = Bottom Simulating Reflector

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The Gulf of Alaska Margin: Potential Focus Site for GeoPRISMS SCD

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

Overview - Convergent glaciated continental margins are premier locations on earth where the interaction of tectonics, orogenic and surficial processes, and continental margin sedimentation can be studied in unison. Field studies strongly suggest that subduction zone and orogenic dynamics are influenced by surficial processes and the sediment delivery rates to subduction zones [*Lamb and Davis*, 2003]. Climate, in turn, directly affects precipitation rates and types, thus controlling the rate and timing of sediment production, which has globally increased during the Neogene [*Zhang et al.*, 2001], potential altering subduction zone dynamics. Southeastern Alaska is one such setting where the deformational and depositional products of this interplay between tectonics and climate are recorded at exceptionally high temporal resolution.

The Gulf of Alaska margin is notable for the transition from 'normal' Pacific plate (PP) subduction beneath North America along the Aleutian Trench to flat-slab subduction and oblique collision of the Yakutat (YAK) microplate with North America (NA) beneath southeastern Alaska. The YAK-NA plate interface extends beneath Prince William Sound and the 1964 Mw 9.2 earthquake epicenter was sourced on this plate boundary, jumping to the adjacent Aleutian megathrust coseismically [e.g., *Shennan et al.*, 2009]; this event illuminates the potential for this transitional tectonic system to enhance geohazards. YAK-NA convergence has also resulted in the uplift of the coastal St. Elias Mountains, which are the most extensively glaciated coastal mountain belt on Earth and are home to North America's second and third tallest peaks, Mt. Logan and Mt. St. Elias. Focusing interdisciplinary GeoPRISMS efforts on the complex tectonic relationships, major earthquake potential and strong glacial-climate signal in the Gulf of Alaska margin will improve understanding of plate boundary deformation, feedback between surface and tectonic processes and the role of large earthquakes in the subduction process.

a) Subduction zone earthquakes: Seismic hazard/deformation - Based on modern GPS velocities [*Elliott et al.*, 2010] and plate/microplate reconstructions [*Pavlis et al.*, 2004], the fold-thrust belt of the St. Elias orogen has absorbed between 240 and 300 km of convergence during the last 6 Myr. However, attempts to restore the shortening from surface geology and offshore seismic data yield shortening estimates for the last 6 Myr of as little as 36 km [*Wallace*, 2008] to as much as 82 km [*Meigs et al.*, 2008], with <17% of shortening accommodated in the offshore frontal thrusts [*Worthington et al.*, in press]. As such, significant shortening remains unaccounted for. Movement on the décollement at depth during large earthquakes likely accommodates a significant percentage of YAK-NA convergence that is not expressed in surface faults. Eberhart-Phillips [2006] indicate that the 1964 (M9.2) earthquake in Prince William Sound was caused in part by movement on the YAK-NA plate interface. Paleoseismic studies by Shennan [2009] and Shennan et al. [2009] provide evidence for recurring seismic events (~1500 yrs BP and ~900 yrs BP) with asperities covering the St. Elias margin from Yakutat Bay to Prince William Sound.

These events may have been greater in magnitude than the 1964 event and indicate potential for more great events in the future.

b) Plate boundary deformation and evolution - Geophysical studies focusing on the Yakutat microplate show that it ranges from 15-35 km thick and is underthrusting the North American plate from the St. Elias Mountains to the Alaska Range (~500 km), tapering in the direction of convergence. The thickest YAK crust, ~35 km, enters the St. Elias orogen north of Malaspina Glacier, where the orogen displays its highest relief and highest long-term exhumation rates [*Spotila and Berger*, 2010]. Given proposed limits on subductibility of thickened oceanic lithosphere, it is likely that Yakutat microplate subduction in southern Alaska will eventually cease, causing plate boundary reorganization [*Gulick et al.*, 2007]. This reorganization will likely include accretion of unsubducted Yakutat material and a massive underplating event of the flat-slab segment beneath southern Alaska, similar to the underplating event associated with the Laramide uplift in western North America. As such, flat-slab subduction and collision of the Yakutat (YAK) microplate in southern Alaska may characterize the most recent iteration in the process of terrane accretion that has built the tectonic assemblage of the Canada-Alaska Cordillera since the Mesozoic as well as provide a modern analog of Laramide-style orogeny.

c) Climate/surface/tectonic feedbacks - Glacial advance-retreat cycles provide the primary climate forcing that may affect structural evolution of the Gulf of Alaska margin. Recent thermochronologic studies in the area provide evidence for intensified exhumation and uplift onshore in response to focused erosion by glaciers [*Berger et al.*, 2008; *Enkelmann et al.*, 2009]; offshore drilling shows that terrigenous flux throughout the Gulf doubles (or more) at ~1 Ma [*Lagoe et al.*, 1993; *Rea and Snoeckx*, 1995]. Combined with the offshore sedimentary record, these data make a strong case for climatic influence on the evolving deformation of the orogen [e.g., *Berger et al.*, 2008; *Worthington et al.*, in press]. A five-fold increase in sediment delivery to the Aleutian Trench during the Pleistocene [*Piper et al.*, 1973] may have altered subduction zone dynamics through significant along strike and temporal variations in the incoming sedimentary section as well as sediment loading within forearc basins [e.g., *Simpson*, 2010].

d) Synergistic activities- Geo PRISMS focus in the Gulf of Alaska margin can address questions illuminated by recent results from the NSF-Continental Dynamics St. Elias Erosion and Tectonics Project (STEEP) and the upcoming Shumagin Gap seismic study and build upon these datasets. Using the Gulf of Alaska as a GeoPRISMS focus site can also take advantage of the existing seismic (UAF-AEIC) and geodetic networks (UAF; EarthScope-PBO) and current active monitoring of volcanic hazards by the USGS-AVO. Future potential synergistic efforts include the move of the USArray seismic network to Alaska in 2012. Additionally, GeoPRISM studies in the Gulf of Alaska will be uniquely situated to take advantage of IODP drilling results constraining sedimentary inputs and changes in timing of sediment delivery to the Aleutian subduction zone, as both shallow and deep marine targets in the Gulf are tentatively scheduled for drilling in 2012.

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