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White paper proposal for the Cascade region; MARGINS program

Illuminating the structure of the mid to lower crust in the Cascade region

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Summary:
In order to: (1) resolve major tectonic controls on volcanism along the Cascade arc, and (2) determine the extent and characteristics of highly crystalline magma bodies (crystal mushes; potential source zones for explosive silicic magmas), we propose to use a variety of high-resolution seismic and Magneto-Telluric (MT) methods to image the crust and upper mantle in strategic locations in Cascadia. Our first choice would be to focus data gathering efforts in the area from Mount Hood to Mount St. Helens as (a) both volcanoes have activity as recent as the 19th to 21st centuries, (b) the area is close to urban centers (Portland, Vancouver, Columbia River shipping), (c) the arc magmatic front shifts abruptly westward going N from Mt Hood to Mt St. Helens, (d) previous surveys using both seismic tomography and MT data have outlined interesting crustal structures that merit further investigation. We also suggest that detailed imaging of the Crater Lake system would be highly informative in constraining the geometry of magma bodies beneath large silicic centers in a tectonically simple region.

Project:
The origin of petrologic diversity in the Earth’s crust and generation of viscous, highly explosive magma types (silicic magmas such as dacites and rhyolites) remains a fundamental challenge in the Earth Sciences. Over recent years, the synthesis of decades of geochemical data with the mechanics of magmatic differentiation has led to a model where (1) magmas are mostly stored within the crust as crystal mushes (mixture of crystal and silicate liquid whose mobility is inhibited by a high fraction of solid particles; [1-3]), (2) evolved magma compositions (i.e., dacite-rhyolite) are most efficiently produced by the extraction of interstitial melt from these large, long-lived mush zones ([4]).

According to this model, mush zones are expected beneath active volcanic areas producing silicic magmas. Seismic tomography and MT imaging have outlined areas of low density and high conductivity in the upper crust beneath large rhyolitic magmatic provinces, such as the Central Andes ([5, 6]), Yellowstone ([7]) and Taupo, New Zealand.

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These observations imply the presence of extensive, highly crystalline bodies in the mid to upper crust. In the Cascade region, large eruptions of silicic magmas are rare ([10]), and evidence for extensive crustal-level mush bodies is conflicting. Evidence against large mush bodies comes from the abrupt changes in magma composition between successive eruptions, typically small eruptive volumes, and the eruption of distinctly more mafic magmas at radial distances of only ~7-10 km from the main andesite-dacite edifices. Evidence for mush bodies includes abundant Pleistocene zircons carried to the surface in substantially younger eruptions at Mt St. Helens [11], intermittent large volume silicic eruptions from Mt Mazama, Mt St. Helens, Glacier Peak, and the Pleistocene Kulshan caldera associated with Mt Baker, and MT surveys that reveal a highly conductive region in the crust of southern Washington that has been interpreted either as conductive sediments or as magma [11, 12]. Comparing the “magmatic structure” of the Cascade Arc, a subduction zone characterized by a young, hot slab and refractory crust with that of large silicic centers such as the Taupo Volcanic Zone (New Zealand) and Yellowstone is a major goal of this proposal.

In addition to shedding new light on the extent and characteristics of crystal mushes in the crust, several outstanding problems related to the tectonic controls of some major features of the Cascade Arc remain unsolved. For example,

1. Why is the northern part of the arc (from Mt Garibaldi to the Washington – Oregon border) dominated by large, isolated stratovolcanoes while the south-central part (Oregon Cascades) has a nearly continuous close-set vent system (e.g., [10])? A switch from compressional to transtensional tectonics is possible.

2. Why does the arc magmatic front step to the west moving north across the Columbia River, including unusual forearc basaltic magmatism in the urban Portland area?

3. What controls the episodicity in magmatic activity and the longevity of magmatic centers?

Better definition of the structure and state of the crust and upper mantle in the Cascade region using geophysical imaging techniques is the most promising tool to link the tectonics, volcanology and large-scale structures of the complex active margin. We propose to use MT and active and passive seismic tomography and scattered wave imaging from dense grids around and along strategic areas to precisely outline the contours of geophysical anomalies, resolve their sources as due to magma versus buried low-density conductive sedimentary rocks (Vp/Vs contrasts), and thereby obtain accurate estimates of the amount of silicate melt present from the mid crust to the upper mantle. The most promising area for such a deployment of geophysical instruments appears to be around the volcanic centers of Mt St. Helens and Mt Hood. This region is close to densely populated areas, making it an ideal target to study both because of good accessibility to install instruments and because of urban hazards. This area is also one of the most tectonically and volcanically active zone of the Cascade region. Preliminary geophysical information has already been gathered in N-S and E-W transects in the surroundings of these two volcanoes, providing background to guide further investigations.
We are proposing a combined active-passive seismic experiment to image the volcano system from the upper crust to the subducting slab. We propose deploying a large number of broadband seismometers and MT receivers in dense linear and areal arrays across both volcanoes, extending well beyond the volcanoes in both the E-W and N-S directions. The seismic data will be used for receiver function, noise-correlation tomography, shear wave splitting, and local earthquake and teleseismic body wave tomography analyses. 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.

Focusing on a second, tectonically more simple location would be beneficial in terms of isolating the geometries of magma bodies in the crust, particularly in an area producing large explosive eruptions. The Crater Lake region seems an obvious candidate for such an investigation, as it is one of the most active silicic centers in the Cascade Arc; it shows a long-lived history of erupting dacites to rhyodacites, requiring efficient intra-crustal differentiation (and therefore the presence of “magma chambers”). It also was the site of a large, caldera-forming eruption (~50 km$^3$ of erupted material) $\sim 7700$ BP ([12]).
Reference:


Deep Tremor in Subduction Zones: The transition from stick-slip to stable sliding

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Topics/Themes: Subduction Zones

Deep, non-volcanic tremor is a long-duration, low amplitude signal resembling volcanic tremor. The first report of the signal was in SW Japan (Obara, 2002) from high sensitivity (Hi-Net) velocity recordings. The Hi-Net array in Japan is composed of high sensitivity seismic stations and was installed across the Japanese archipelago after the 1995 Hyogoken-nanbu Earthquake by the National Research Institute for Earth Science and Disaster Prevention (NIED). The average spacing of Hi-Net stations is 20-30 km, and includes three-component seismometers buried at a depth of at least 100 m. The high quality of these instruments in tandem with comprehensive coverage across Japan enabled the NIED to discover tremor and explore the systematics of its behavior. Since its discovery in SW Japan, deep tremor has also been observed in other subduction zones such as Cascadia, Alaska and Costa Rica (Schwartz and Rokosky, 2007). Although ideally suited for detecting tremor, high sensitivity, borehole seismic instruments are not absolutely required.

More recently it was shown that deep tremor in SW Japan consists of a swarm of low frequency earthquakes (LFEs). LFEs are small, slow earthquakes (Katsumata and Kamaya, 2003; Ide et al., 2007) that occur primarily during periods of deep tremor and occur as slow shear slip on the down-dip extension of the primary seismogenic zone of the plate interface (Shelly et al., 2007). Deep tremor in Cascadia and Costa Rica is also composed of LFEs on the down-dip extension of the plate interface (see attached Fig., Brown et al., 2009). In each case, the LFE locations suggest tremor occurs as a transient swarm of LFEs in a transitional zone between stick-slip seismicity and aseismic stable sliding of the plate interface.

Although deep tremor has turned into one of the fastest moving fields in modern seismology, the signal and faults that produce it remain mysterious. For example, deep tremor comes from a diverse range of subduction zones. Some are hot (SW Japan), while some are cold (Costa Rica). Moreover, incoming plate age does not seem to be a controlling factor (e.g. Cascadia vs. Alaska) in whether tremor occurs. Another mystery is the differing recurrence intervals of deep tremor. We are very much in the early days of understanding tremor, however, as recording capabilities and methods improve our understanding will improve, and new questions will emerge.

Finally, one of the biggest remaining questions about tremor is the spatial and possible temporal relationship to large earthquakes on the adjacent locked portion of the plate interface. Tremor may outline the down-dip extent of large earthquake rupture (Chapman and Melbourne, 2009), which is a critically important factor in seismic hazard estimation. Slip in the deep continuation of the plate interface should increase the stress
in the up-dip portion of the fault, potentially increasing the probability of a large earthquake during or soon after a transient slip episode (Rogers and Dragert, 2003). This motivates earthquake seismologists to monitor deep tremor because it may contain useful information for studying time-dependent seismic hazard.

References


Cyclical Behavior in Cordilleran Orogenic Systems
White Paper for MARGINS Successor Workshop, San Antonio, 14-17 February, 2010
P.G. DeCelles, P. Kapp, S.L. Beck (University of Arizona)

Cordilleran orogenic systems form along the edges of continental plates above subducting oceanic plates; they are best developed where the rate of convergence between the plates is relatively rapid and the lateral edges of the subducting plate are thousands of kilometers away (Schellart, 2008). Modern Cordilleras occupy the 15,000 km long composite western margin of the American plates, where Pacific-domain plates subduct eastward beneath generally westward moving continental plates. Ancient counterparts abound in the geological record (e.g., Anderson, 1990; Pitcher, 1997; Kapp et al., 2007).

- Outboard arc-trench complexes and inboard retroarc thrust belts constitute the main features of Cordilleran orogenic belts.
- A variety of sedimentary basins, including trench, forearc, intra-arc, hinterland and foreland basins, lie athwart and alongside the orogenic belt.
- Magmatism of calc-alkaline composition is expressed in high elevation stratovolcanoes, ignimbrite platforms, and mid-crustal granitoid batholith belts (Pitcher, 1997). This magmatism exhibits pronounced cyclical behaviour in composition and volume flux (Ghosh, 1995; Haschke et al., 2002; Ducea & Barton, 2007; Gehrels et al., 2009).
- Extensional and strike-slip fault systems cut orogenic hinterland regions, and are commonly associated with mafic magmatism (Marrett et al., 1994; Wells & Hoisch, 2008).
- In the modern South American Cordillera, where crustal shortening is greatest—on the order of several hundred km (McQuarrie, 2002; Oncken et al., 2006)—the crust is approximately double normal thickness (Yuan et al., 2002; Beck & Zandt, 2002), rivaling that of the Tibetan Plateau. Reconstructions of the mainly late Mesozoic North American Cordillera depict an analogous thickening in the central part of the system.
- Peak surface elevations of nearly 7 km and regional average elevation of ~4 km are present in the central Andean Cordillera, and paleoaltimetry studies are beginning to suggest that comparable elevations existed in parts of the central North American Cordillera (Chase et al., 1998; Mulch et al., 2004; Cecil et al., 2006; Cassel et al., 2009).
- Regions of anomalously low elevation also exist in the modern central Andes, and may be linked to dynamic processes in the upper mantle and coupling between upper and lower plates (Beck & Zandt, 2002; Yuan et al., 2002).
- Seismological studies of mantle composition and dynamics in the North and South American Cordilleras demonstrate that large pieces of the mantle lithosphere are presently foundering into the mantle in some regions, and petrological studies of volcanic rocks, xenoliths, and arc batholiths support the idea that delamination or dripping of mantle lithosphere has occurred during the geological past (Kay et al., 1994; Beck & Zandt, 2002; Schurr et al., 2006; Lee et al., 2006).
- Climate in the central Andes is intimately linked to orography, and potential feedback linkages between climate and kinematics are being actively debated (e.g., Vandervoort et al., 1997; Horton, 1999; Montgomery et al., 2001; Lamb & Davis, 2003; Strecker et al., 2009).
- Paleooaltimetry studies of the Neogene central Andes produce seemingly conflicting results, with some datasets indicating abrupt increases to very high elevations, and other datasets suggesting more gradual changes and greater contributions to the isotopic paleoelevation signal by climate (Garzione et al., 2008; Ehlers et al., 2009).

How is one to make sense of all these and many other complexities in Cordilleran systems? Which of these signals are in true conflict, and which are reconcilable within a broader, systems-based synthesis? Which of these signals have unsuspected tele-connections with each other? Clearly an integrated multidisciplinary approach is required to document linkages among these signals.
Significant scientific questions surrounding Cordilleran margins include:

(1) What are the feed-forward and feed-backward relationships among retroarc shortening, hinterland geodynamics, forearc tectonic erosion, arc magmatism, upper mantle dynamics, and climate dynamics in Cordilleran orogenic systems?

(2) Are there temporally predictable, even cyclic, relationships among processes in Cordilleran orogenic belts? For example, cycles in arc magmatism characterize several of the American Cordilleran orogenic belts (Haschke et al., 2002; Ducea and Barton, 2007); are these magmatic cycles expressed in other parts of the Cordilleran system, from the upper mantle to the surface, from the trench to the distal foreland?

(3) How do sedimentary basins that form in Cordilleran systems respond to this array of geodynamic processes? These basins span the entire orogenic system and provide a valuable archive of the tectonic and climatic conditions under which the orogenic belt evolves.

(4) Cordilleran orogenic systems may be considered as the dynamic results of tectonic growth by convergence between oceanic and continental plates, and erosion by processes operating at the lithosphere-asthenosphere boundary and the topographic surface. Thus, the geochemical evolution and dynamics of the upper mantle, oceans, and atmosphere are strongly dependent on the machinery of Cordilleran orogenesis. What are these relationships, and how might they have changed through geological time?

Project focus areas could include virtually anywhere along the western Cordilleras of the Americas (on land and at sea), as well as older Cordilleran systems that expose deeper levels of various parts of the system. Time-space trade-offs would be an obvious way to exploit Cordilleran systems at different stages of evolution, or different stages of exhumation. For example, the North American Laramide province is a natural laboratory for studying highly evolved upper plate response to flat-slab subduction (Saleeby, 2003), whereas modern flat-slab regions in South America provide geodynamic and geophysical views that are no longer available in North America (Wagner et al., 2005). Similarly, the North American and South American Cordilleras provide different vantage points on what was likely a very similar system, with an essentially intact and still developing Cordillera in South America and a deeply exhumed Cordillera (in both the orogenic belt and the flanking basins) in North America (Allmendinger et al., 1997). Approaches to the search for cyclicity in Cordilleran orogenic systems would include structural geology, basin analysis, petrology, geochronology and thermochronology, paleoaltimetry, geodesy, passive and active source seismology, and numerical modeling of geodynamic and climatic processes.

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Surface processes, weathering fluxes and CO2 sinks in arc terranes

Chemical weathering of silicate rocks acts as a long-term sink of CO2. Modern conceptions of the geochemical carbon cycle are built around the hypothesis that CO2 consumption by weathering is sensitive to climate, providing a stabilizing feedback mechanism (Berner et al., 1983; Walker et al., 1981). At the watershed scale chemical weathering and CO2 consumption rates are generally believed to depend on lithology, temperature, runoff, uplift/erosion rate, and relief, among other variables. A number of recent studies have demonstrated that in granitic or cratonic terranes, the net influence of climate on weathering and CO2 consumption rates is not as strong as had been expected, as erosion rate, also plays an important role (Gaillardet et al., 1999; Riebe et al., 2004; West et al., 2005).

Whereas weathering rates in granitic and cratonic terranes have been well studied, information on weathering in volcanic terranes is sparse. Available data suggest that mafic – intermediate volcanic terranes play a disproportionately large role in the carbon cycle. They have high abundances of Ca and Mg silicates, the weathering of which results in much greater CO2 consumption rates than the weathering of the alkali silicates typical of continental crust, which is an inefficient CO2 sink (France-Lanord and Derry, 1997). They also have mineralogy (olivine, pyroxene, amphiboles) and texture (volcanic glass, ash) that weather much faster than those typical of most cratonic terranes. Additionally, most active volcanic centers are associated with arcs and hotspots that are adjacent to oceans where marine moisture and orographic effects can lead to high runoff and erosion rates, and many of the active island arcs today are located in the wet tropics (Vorosmarty et al., 2000). All of these features suggest that weathering and CO2 consumption rates of volcanics should be high. While there are relatively few published data from streams draining active arcs that permit estimation of CO2 consumption rates, there is evidence to support the hypothesis that arc weathering is an important CO2 sink (Figure 1).

Figure 1. Ca and Mg concentrations derived from silicate weathering [Ca+Mg]sil in Himalayan and Philippine streams vs. silica concentrations. [Ca+Mg]sil is a good estimate of CO2 consumption. The Philippine data has significantly higher [Ca+Mg]sil (ave 563 vs 125 µmol/L) and [SiO2] (ave 1032 vs 121 µmol/L).
Recent studies suggest that basalt weathering is climate-sensitive in the way required by models of the carbonate-silicate cycle (Dessert et al., 2003). Further, high islands in the Pacific are important sources of biogeochemically important constituents to the oceans (Lyons et al., 2005; Milliman et al., 1999; Sholkovitz et al., 1999), and weathering rates on basaltic islands are high (Louvat and Allegre, 1997). All these data suggest that volcanic terranes associated with volcanic arcs or plume-related island groups are a major component of global geochemical cycles. Yet despite the fundamental importance of weathering of volcanic rocks in the tropics, data on chemical fluxes from these terranes are sparse, and there are few process level studies that can place bounds on the long-term behavior of basaltic weathering systems in the way that recent work has done for granitic terranes.

The contribution of arc terranes to global weathering budgets is poorly known in part because rivers in these settings tend to be small and have not been sampled systematically (or in most cases at all) for geochemical purposes. Unlike major continental regions, where a single large river can give information about a large fraction of both the continental surface and total runoff, island arcs are a type of “non-point source” problem. Many smaller streams deliver large loads per unit basin area, and the aggregate flux can be quite large, but no one stream samples a large region. This effect was shown to be of enormous influence for sediment load by Milliman et al. (1999), but has yet to be quantified for chemical and CO$_2$ fluxes. Our overall hypothesis is that the weathering contribution from arc terranes, particularly those located at low latitudes, has been systematically underrepresented in current global weathering flux estimates.

Despite intriguing patterns seen in the available data, in point of fact the data sets on arc weathering are too limited to rigorously assess the hypotheses that 1) arc weathering is a quantitatively significant contribution to global CO$_2$ consumption, and 2) that weathering rates in arc terranes a sensitive to climate in a way that could provide a viable climate-weathering feedback on geological time scales. Several recent studies (cited above and Dessert et al., 2009) have added importantly to our knowledge, and we are now at the point that targeted studies could provide substantial insight into the role played by arc weathering in the global carbon cycle. Furthermore, the topic of coupling between the topographic evolution of arcs (via constructional volcanisms, tectonic uplift/subsidence, and erosion) and weathering fluxes is almost completely unexplored, yet this has been a fruitful area of research in continental systems. The time seems ripe to focus on the role of convergent margins as a volatile sink as well as a volatile source.

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**White Paper: Mapping a Mantle Wedge: Directly Constraining Mantle Flow, Melt Generation, and Volatiles Above the Subduction Zone**

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**Themes:** Subduction Zones, Rheology and Deformation, Fluids and Magmas

**Introduction**

Arcs and ridges are the most extensive volcanic systems on the planet, playing a major role in the global geochemical cycle. The two systems, however, are fundamentally different: ridges erupt tholeiitic basalt of remarkably uniform chemistry, while arc lavas range from primitive tholeiite similar to MORB, andesite, and alkaline basalts with silica contents ranging from <50% to >70% [Miyashiro, 1974]. This contrast is a fundamental manifestation of extensional versus convergent margin dynamics, the contrasting role of volatiles, and the underlying patterns of mantle flow. At ridges, a relatively dry lherzolitic mantle undergoes adiabatic decompression melting to produce MORB. At convergent margins, with the under-thrusting of sediments and altered ocean crust beneath the plate edge, dehydration of the down-going plate introduces water and slab derived melts into the overlying plate: inducing hydrous melting in the mantle wedge. While magma genesis beneath ocean ridges is relatively well understood, this is not the case at subduction zones due to their inherent complexity.

In particular, the relative contributions of the slab component derived from the down-going plate, and that from melting the overlying mantle in arcs is controversial. The pattern of mantle flow in the wedge both during and prior to melt generation above the slab is largely a matter of inference. Conventionally, the slab contribution problem is approached by inverting magma compositions: basalt, andesite, or whatever erupts in the many diverse arc environments (arc, fore-arc, back-arc, etc) involving a mass balance of putative slab to mantle components, often focusing on isotopic and incompatible trace element components enriched in the slab, such as B, Li, Rb, Cs, Sr, Th, Pb, and Ba (e.g. [Parkinson and Pearce, 1998]). This is intrinsically difficult due to the inherent complexity of a system involving a down-going reheated slab composed of sediment and variously altered crust and mantle, an overlying mantle wedge, and melt migration through the crust: all effecting final melt composition. This is clearly expressed by temporal variations in melt composition both across and within arcs (e.g.: [Kuno, 1966; Leeman et al., 2005; Miyashiro, 1974; Smith and Leeman, 2005]). Ophiolites, on the other hand, expose broad regions of mantle peridotite where many aspects of this complex process can be directly studied. Most ophiolites are believed, on the basis of their lavas and mantle residues, to have formed in, or passed through, a supra-subduction zone environment (SSZ) (e.g.: [Miyashiro, 1973; Alabaster et al., 1982; Shervais, 1982; Metcalf and Shervais 2008]). While the specific environment, back-arc, arc, fore-arc etc., is debated, it is clear that these peridotites offer the possibility of constraining the mechanisms by which water and hydrous melt interacts with the mantle wedge in the subduction factory as well as the accompanying patterns of mantle flow and deformation (e.g., [Choi et al 2008a,b; Jean et al 2009]).

**A Focus Study Site In An Exposed Mantle Wedge**

We propose, then, the designation of a large North American ophiolite peridotite massif as a MARGINS focus site for the study of subduction zone processes in the mantle wedge. Major questions that can be addressed by the study of such a massif include the nature and extent of mantle-slab interactions (e.g., addition of volatiles to the mantle from the down-going slab, either as fluids at shallow depth or as melts deeper in the asthenosphere), the nature, source, extent, and pattern of fluid/melt flow into and out of SSZ peridotites, the cumulative extent of melt extraction and the nature of the melts formed. Microstructures and macrostructures that document deformation processes the mantle wedge can constrain the pattern of mantle flow prior to and during mantle melting. With deep canyons cutting down to the base of the peridotite massif, patterns of alteration produced in a mantle wedge due to underthrust sediments can also be directly studied. In-situ seismic studies in such a massif will provide direct observations of mantle seismic anisotropy that will help interpretation of the new and emerging geophysical observations of...
mantle-wedge properties - much as such observations in the Oman Ophiolite have given us a decent model of anisotropic fabric in the uppermost mantle at fast spreading ridges.

The Josephine Peridotite in the western US, for example, offers an enormous peridotite massif that can be used to study geochemical fluxes in the mantle wedge above a subduction zone at a truly representative scale. The Josephine Ophiolite contrasts to the well-studied Oman Ophiolite in that it clearly does not represent a fast-spreading ridge environment, and its petrogenesis involved melting and crust formation in a hydrous supra-subduction zone environment with the formation of boninitic and andesitic magmas (Harper, 2003b). It encompasses a large swath of NW California and SW Oregon (Fig 1). Harper and coworkers have extensively mapped portions of the ophiolite (Harper 1984; 2003a, 2003b), documenting a complete crustal section overlain by a thin, siliceous volcanopelagic sequence and turbidites of the Galice formation. They interpret the ophiolite as initially formed in a back-arc basin crust, based on the observed rock associations, and on its position west of the Chetco arc complex (Harper 1984, 2003a, 2003b). The Josephine Peridotite forms the base of the ophiolite. This ~800 km² massif consists of harzburgite with less common dunite, wehrlite, pyroxenite, and chromitite that represent the residues of partial melting, melt transport, and magmatic deposits in a late hydrous melting environment (Dick, 1977; Dick & Bullen, 1984; Kelemen et al., 1992; Kelemen and Dick 1995). Several workers, however, have shown that dunite “dikes” and layers in the Josephine peridotite represent melt flow channels where pyroxene was dissolved and olivine precipitated at relatively low pressures in the mantle (Dick, 1976, 1977; Dick & Bullen, 1984; Kelemen et al., 1992; Kelemen and Dick 1995). An alternative site for such a focused study project could be the Paleozoic Bay of Islands Complex in Newfoundland, which also has an arguably arc affinity (e.g.: Elthon, 1991).

Project Proposal
We envision an initial 5-year project to map and systematically sample the entire mantle section at a scale of 1:12000 as well as a concurrent seismic study. This would establish foundation geologic, geochemical and geophysical datasets for a large community and that can provide a gateway into this focus site for investigators unfamiliar with the location and the basis for focused studies. Oriented samples would be taken on a closely spaced grid to allow detailed micro structural analysis, and these samples should be of sufficient size for correlated studies of whole rock major and trace element chemistry, mineral analyses, and in select cases, the physical separation of residual pyroxene for isotopic analysis. Detailed sampling at this scale in a peridotite massif has previously only occurred in the Oman ophiolite, and has directly constrained the processes of mantle flow, melt generation, and crust formation in a fast spreading ridge environment [e.g., Mée et al 2004]. A North American peridotite massif, clearly reflecting a SSZ setting, would also be easily accessible to the US research community. Full mapping of a massif, such as the Josephine Peridotite or Bay of Islands Ophiolite, however, will require extensive backpacking and helicopter support. This would require a large field effort likely involving 5 or more PhD projects as well as masters students. The primary goal of constraining the nature and extent of the geochemical fluxes, can be documented by systematic regional sampling of the massif using whole-rock major oxide and trace element analyses, electron microprobe, ion microprobe, and laser ablation ICP-MS mineral analysis, and
by isotopic analyses of hand-picked mineral separates. The full spectrum detailed study of micro fabrics, igneous and metamorphic petrology, and isotopic and trace element analyses across hundreds of km² of exposed mantle requires a large-scale multi-institutional laboratory effort well beyond anything that can be attempted under conventional NSF funding. For this purpose, all samples should be collected in a uniform manner, placed in a single repository, and all sampling done there by a qualified technician to insure equitable, and conservative use of the material, and future availability for studies by new P.I.’s.

References
The Role of Climate, Surface Processes, and Sedimentation in Continental Rifts and the Transition from Rifting to Seafloor Spreading

A White Paper for the MARGINS Successor Workshop
San Antonio, TX (February 15-18, 2010)
Topics: Sediment Transfer and Feedbacks; Rifted Margins

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Rift basins preserve long, high-fidelity records of the surficial response to tectonic deformation, climate change, and earth history. Because the generation of accommodation space in rift basins typically is rapid and prolonged, these settings are especially well suited for deciphering such records. We have made significant advances in understanding how sediments in rift settings record deformation and environmental conditions, but fundamental questions remain, especially with regard to contrasting rates of subaerial versus submarine processes and how they are linked across the shoreline. In addition, sediment accumulation appears to exert a direct control on the thermo-mechanical evolution of rifts. We recognize a suite of rate-related problems in which different components of the system operate on different timescales (e.g., erosion, subsidence, and basin filling in response to vertical and horizontal motions). Because of their natural tendency to capture and preserve a sedimentary record, rifts provide an ideal setting with which to advance understanding of these linkages. Below we summarize some leading scientific questions.

1. How do sediment input and loading affect crustal composition, thermal structure, rheology, rift architecture, magmatism, and structural evolution of rifts?

Accumulation of sediment has long been recognized as a mechanism of crustal formation in deep continental rifts (e.g., Moore, 1973; Fuis et al., 1984; Nicolas, 1985), but only recently has re-emerged as a primary control on rift evolution. Rapidly buried sediment is transformed in deep rift basins to form metasedimentary rock, possibly explaining: (1) the presence of “transitional crust” at many rifted margins; (2) changes in magmatism and buoyancy forces that favor an early transition to narrow rift mode (Lizarralde et al., 2007; Bialas and Buck, 2009); and (3) diffuse deformation following lithospheric rupture (Persaud et al., 2003). While these studies point to the influence of sediment input on rift processes, many aspects remain controversial and poorly understood. In addition, little is known about tectonic and climatic controls on source dynamics, sediment routing, erosion rates, and timing of regional scale drainage-capture events.

2. What are the dynamic feedbacks among crustal deformation, erosion, climate, and sedimentation in and adjacent to continental rifts?

Over the past ~20 years integrated studies of geomorphology, thermochronology, and mechanical modeling have investigated the effects of climate and erosion on the mechanics of thrust belts, crustal exhumation, and related orographic effects in convergent-margin settings (e.g., Willet, 1999; Montgomery et al., 2001; Whipple, 2009). However, these kinds of feedbacks are relatively little studied in rift settings. New studies indicate that even modest topographic elevation on rift flanks can have a substantial impact on atmospheric circulation and erosion of
source areas. Recent studies of low-T thermochronology (Spiegel et al., 2007), regional tectonics and climate change (Chapin, 2008), climatic controls on incision rate (Mack et al., 2009), climatic control on rift architecture (Kluesner et al., 2009), and sediment budgets (Dorsey, 2010) point to important but poorly understood feedbacks among rift-related deformation, climate change, erosion, subsidence, and transfer of sediments from eroding highlands to rift basins.

3. **How does evolving rift architecture, including rift segmentation, modify and interact with subaerial and submarine sediment-dispersal pathways through time?**

Prevailing models of erosion and sediment dispersal in rift settings involve transport away from the rift in the footwall of normal faults, and funneling of sediment into rifts via topographic lows in accommodation zones (e.g., Leeder and Jackson, 1993; Jackson and Leeder, 1994; Driscoll and Hogg, 1995; Gupta et al., 1999; Densmore et al., 2004). Some rifts experience sediment transport along the rift axis by fluvial, deltaic and submarine systems, while others are sediment-starved and receive input primarily from small footwall catchments. It is not well understood how 3-D sediment dispersal patterns change in space and through time in response to evolving structural controls such as fault migration and lateral linkages, how fluvial erosion modulates that response, and how these processes vary in marine versus nonmarine environments.

4. **How do sediment type and transport/depositional processes change when continental rifts are flooded by marine water?**

Many uncertainties exist regarding the nature and causes of the transition from nonmarine to marine environments involved in continental rupture and birth of an ocean. We wish to know how sediment-dispersal pathways, transport mechanisms, depositional environments and ecology change during the transition from fluvial/alluvial/lacustrine to marine-dominated. Different stratigraphic architectures can be expected for gradual versus rapid marine flooding, and sea-level change may significantly modulate this transition. Also poorly understood are the subsequent changes in currents, tides, and physical oceanography as a seaway expands during extension and subsidence. How does the production of biogenic and pelagic sediments develop after marine incursion, during expansion and deepening of a new ocean basin? How does the formation of a new ocean basin affect regional biosphere, hydrosphere, and atmospheric systems?

5. **How are break-up unconformities formed, and how is the timing of erosion related to lithospheric processes associated with continental rifting and rupture?**

Break-up unconformities are erosional angular unconformities across which syn-rift deposits and basin bounding faults are overlapped by flat lying “post-rift” deposits. Not all rifted margins display this kind of unconformity, but many do. To date, no model has successfully explained erosion that is required to produce this commonly observed feature. In-plane force (Cloetingh et al., 1985) is insufficient to produce the observed signal (Karner et al., 1993; Christie-Blick and Driscoll, 1995). Break-up unconformities may record an increase in mantle buoyancy or dynamic (i.e. flow-induced) forces associated with continental rupture (Lavier and Manatschal, 2006). Understanding the origin of such unconformities is central to deciphering the mechanisms that control continental extension and rupture at rifted and obliquely rifted margins.
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Mini-white paper proposal for a mini-focus site on specific volcanoes and plutons within a future MARGINS program.

We propose that one or two active volcanoes and plutons be targeted for multi-disciplinary study within a future MARGINS program. They could be anywhere but would be best if located within a focus site should one be part of the new program.

The idea is to enable an open-ended, multi-PI, multi-disciplinary, multi-year, multi-proposal project to tackle one or two specific volcanoes and ‘complementary’ plutons for a decade, in order to relate processes from slab through mantle, through crust, to eruption. The objective is to get people who might otherwise study such matters at different volcanoes and plutons, to subordinate the benefits they’d get by choosing a location best for their specific study in order to share the benefits of working together at the same place. We do not envision one big 3-year Collaborative Proposal of pre-selected PIs, but rather semi-random proposals by different groups over time that are informed by each others’ results. This might create opportunity for USGS and university scientists to work together. Mail reviews and panels would decide what gets funded, but over time we might build up more overlapping information than the status quo produces.

For the volcano, we propose integrated study of processes from the slab to the surface, to the extent possible. The goal is to understand how magma forms, evolves, and erupts in volcano-specific detail. For example, amidst the along-strike heterogeneity of slab seismicity, slab surface and mantle wedge thermal structure, mantle flow pattern, depth to Moho, and crustal velocity structure in that arc, what are these characteristics beneath this particular volcano and what is their influence? Where is there evidence of melt lenses within the crust now? What is the geological and geochemical history of eruptions and intrusion, and can they be tracked in minerals or xenoliths? What is the history of crystal fractionation, mixing, and assimilation, and at what time scales? What controls eruptions and associated hazards? How do all of these interact?

For the pluton, the objective is to understand the physical and chemical processes and history of intrusion. What is the volume of one crustal accretion event, what controls where it occurs within the pluton, and how is it accommodated structurally? How does the pluton evolve through time? How is it related to its surrounding hydrothermal system? Most of all, how is the pluton connected to its roots and to the surface, and how does this relate to the rates of, and relative volume partitioning between, extrusion and intrusion in subduction zones?

For example, if there is an arc focus site, and if it were the Cascades this time, then one example of a scientifically rich and hazardous volcano might be Rainier. A complementary Cascade pluton might be the Tatoosh. There are many other examples and many potential criteria for choosing amongst them.

This level of specificity would enable a new set of topics to be targeted within MARGINS and would attract new investigators. Rather than continuing to address
generalized processes and forcing functions, it would shift some of the effort to specific examples where one can test generalized models, and explore crustal-level processes.

Obviously the active volcanoes and the plutons must be in different places and ages, no volcano or pluton applies to all, and even a decade of multi-PI study at a few hundred $K/y would not suffice to answer the questions above. They are vast and complex but central to how continental crust evolves, volcanic hazards, and the formation of hydrothermal ore deposits. Subsets of them can be studied through EAR ± OCE core-funded projects, but integrated study of the geology, petrology, geochemistry, geochronology, and geophysics of one example by many research groups requires a MARGINS-like structure. To us, integrated case studies seem necessary to achieve a quantum step in understanding these topics.

Selection of the volcano and pluton, and of the criteria for choosing them, would be made democratically by the scientific community at a workshop devoted to the topic. Criteria for the volcano might include: wide range of rock types; isotopic contrast with surroundings; recent volcanic activity to enable study of melt location and migration; availability of background and complementary information, perhaps including an ongoing monitoring program; and high level of public risk. If the future MARGINS program has an active arc segment focus site, then it might make the most sense to select an active volcano within that segment but that is not necessary.

Signed (as of 12/22/09)
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Computational Infrastructure for a MARGINS Successor Program

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Computational infrastructure has played a significant role in MARGINS research and we believe that its potential as a tool for integrative studies will grow significantly in a successor program. A MARGINS successor program could benefit by strengthening linkages and interaction with existing efforts both within the geosciences and those that exist more broadly. Here, we describe the NSF supported Computational Infrastructure for Geodynamics (CIG), the lessons learned, and the opportunities that will unfold. The Computational Infrastructure for Geodynamics (CIG) is a facility that NSF supports for software development and maintenance in the geosciences. The resources provided by CIG are particularly useful for the MARGINS community given the goal of enhancing our understanding of plate margin processes through an interdisciplinary approach. As a community-governed organization, CIG has a small team of software engineers who provide software services to the community in terms of programming, documentation, training, and support. Guidance for the programmers comes from a Science Steering Committee. CIG commenced in 2004 with much of the software team housed at Caltech. In our currently pending with NSF, CIG will move to the University of California, Davis, while continuing to provide broad support to the community.

With a high level of community participation, CIG has leveraged the state of the art in scientific computing into a suite of open-source tools and codes. Many of the problems addressed generally in geodynamics are computationally challenging, often involving processes occurring over a wide range of time and spatial scales. Since existing solution methods are often not sufficiently robust to solve these problems, CIG has pursued a strategy of partnering with the larger world of computational science. In some cases, scalable, robust methods have yet to be discovered and new research is needed while in other cases methods can be imported from allied disciplines. CIG software is being developed collaboratively with investigators from national labs, software companies, and academics in applied mathematics.

The software is developed and maintained for problems ranging widely from mantle dynamics, crustal and earthquake dynamics, magma migration, seismology, and related topics, important components of the Seize, RCL, and SubFac initiatives. CIG has been able to introduce a number of important stand alone codes that has been used widely in margins-related research, such as CitcomS for thermal-chemical convection, PyLith for the entire earthquake cycle from tectonic loading and unloading to dynamic rupture, or Gale for the spontaneous initiation and evolution of faulted rift and compressional margins. In all cases, we have attempted to balance the needs of respecting the three-dimensional geometry of the geological environment and the strong variations in material properties that occur in tectonic problems, with the need to scale efficiently from desktops to the most massively parallel supercomputers available. In other cases, CIG has opted not to pursue the development of single stand-alone codes, such as in magma migration because the community has not been able to agree on the equations governing the underlying physics. In the case of magma migration, we have developed benchmarks and developed a test suite of codes for solving them.

One of the underlying computational challenges spanning nearly all of geodynamics is the need to resolve fine-scale features (such as faults or the sharp boundary of a
rising mantle plume) embedded in a larger domain (such as a plate or the mantle). The computational challenge is the need to resolve the fine features as they form, evolve and entirely disappear. Often, the fine scale features are associated with strong jumps in materials properties (such as jumps in viscosity over many orders of magnitude) making the problems highly ill conditioned. CIG has pursued a multiple approach to bring useful software to the geoscience community. The first is a collaboration with the developers of deal.II, a finite element library with a wide range of functionality in Adaptive Mesh Refinement (AMR), through the creation of a geodynamics, AMR test suite. We currently have tutorials for Stokes flow and mantle convection but will soon release examples in magma migration and visco-elastic deformation. We have also pursued a research strategy with the Institute of Computational Science and Engineering (ICES) at the University of Texas, Austin through which we have recently demonstrated global mantle convection problems having resolutions as fine as 1 km while scaling on tens of thousands of computational cores (processors). In terms of resolution and scalability, the applications are far reaching for all of geodynamics.

An entirely different strategy that CIG has pursued for the community has been the development and maintenance of Science Gateways to allow users to initiate and monitor simulations on the TeraGrid (the current incarnation of the NSF supercomputer centers and a powerful resource that is under utilized by the geosciences community). One portal applicable to the MARGINS community is CIG’s computational seismology gateway in which users can simulate seismic wave propagation in fully three-dimensional earth models using the versatile Specfem3D code. On the web, users can select the seismic sources and stations (with the data automatically retrieved), select the earth model, start the simulation on a remote parallel computer, and later download the results in the popular SAC format. The Gateway allows users to upload their own 3D earth model or to import the results of a global model of mantle convection.

The CIG vision for the future is on one of interoperable software that allows users to seamlessly move from data to dynamic models and back to data using computational models that are able to handle the extreme variations in material processes and multi-physics, while respecting the complex geometry of geological processes (Fig. 1). Strengthening the linkages between the MARGINS community and CIG is a clear route to expanding the use of computational models in a MARGINS successor program.
Figure 1: Examples of computations and data available to help us understand solid earth dynamics at a range of scales as envisioned in the next phase of CIG. In this case, the dynamics of plate boundary processes and their interaction with global mantle flow. RIGHT PANEL: Example output of computational codes for global mantle convection (CitcomS), midocean ridge flow with melting and melt transport, crustal scale magma injection and faulting (Gale), and small scale reactive melt channel formation. Each model was designed to consider a particular scale or set of processes. The challenge is how to permit users to combine these models, as needed, to explore the dynamics of the coupled interactions and use them to make inferences from geophysical and geochemical data. LEFT PANEL: Example data used to test and drive models, including seismic waveforms (SPECFEM), plate reconstructions (GPlates), and geochemistry (PetDB).

Additional information on CIG can be found at:
http://www.geodynamics.org/

The CIG-II proposal and the comprehensive document “Expanding Computational Infrastructure: The First Five Years of CIG” can be found at
http://www.geodynamics.org/cig/proposalsndocs/blogs/cig2-proposal/index_html
The Initiation of Subduction: From kinematics to dynamics
Theme: Subduction Zones

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Subduction initiation (SI), although only a transient phenomenon, is a vital phase of the plate tectonics cycle. Long-lived and well-developed subduction zones disappear and new subduction zones form. The initiation of subduction is arguably the last major component of the kinematics of plate tectonics that remains unsolved. Consequently, our understanding of SI dynamics is perhaps the least poorly developed part of geodynamics. However, since nearly half of all presently active subduction zones initiated during the Cenozoic (Fig. 1), we have an enormous opportunity for accelerated progress if we link field and geochemical studies of back-arcs, fore-arcs and ophiolites, detailed seismic images, and regional and global geodynamic modeling.

After a hiatus of a number of years, computational and synthesis models of subduction initiation are now being advanced that offer testable predictions [1,2]. Moreover, empirical studies from the MARGINS program show that the tempo of individual activities is increasing, including earlier work on the structure and morphology of the northern segment of the Macquarie Ridge Complex [3]; detailed thermochronology showing the detailed space-time pattern of rock uplift associated with SI in Fiordland, New Zealand [4]; the recognition that the world's largest ophiolites and their attendant ore deposits originate just after subduction initiation [5]; the discovery of widespread MORB-type basaltic volcanism just before boninitic volcanism in the IBM system [6]; and the recent discovery of compression and vertical motions associated with Tongan SI [7]. These studies indicate that a broadly based, empirical underpinning to a new understanding of SI is emerging.

That such a large proportion of subduction zones are young (Fig. 1) indicates that subduction initiation is a semi-continuous process in which the net force resisting SI is routinely overcome during the normal evolution of plates. Subduction initiation may have occurred in a variety of tectonic settings: old fracture zones, transform faults, and extinct spreading centers and through polarity reversal behind active subduction zones [1,2]. Although occurring within different tectonic settings, the four best-understood subduction initiation events (Izu-Bonin-Mariana (IBM) along a fracture zone, Tonga-Kermadec along an extinct subduction boundary, New Hebrides within a back arc, and Puysegur-Fiordland along a spreading center) were typified by major structural changes and vertical motions that reveal fundamental aspects of SI dynamics [2]. Detailed studies of the petrology and geochemistry of the IBM fore-arc reveal the evolution of melting conditions as the Pacific Plate first descended below the Philippine Sea Plate in the Eocene [5].

Subduction initiation is intimately linked to changes in plate motion (another frontier area of geodynamics). Understanding the putative change in Pacific Plate motion during the Eocene is critical for deciphering the dynamics of plate tectonics. Refined geochronology now suggests that the bend in the seamount chain started at ~50 Ma and occurred over a period of ~8 Myr [8]. The best examples where we know subduction started and has since evolved into fully self-sustaining subduction zones, including the Eocene initiation of the IBM and Tonga-Kermadec are likely intimately linked to this change in Pacific plate motion [9]. However, if SI preceded (and hence caused) changes in plate motion, or post-dated the change (and SI was forced) remains an outstanding but clearly solvable problem [1,2]. Recently, there have been important advances clarifying how these major SI events unfolded.

The eruption of boninites has long been associated with the initiation of the IBM subduction zone [10], but recent manned submersible diving in the IBM fore-arc has discovered that
MORB-like tholeiitic basalts crop out over large areas. These “fore-arc basalts” (FAB) underlie boninites and overlie gabbroic rocks (Fig.2). FAB trace element patterns are similar to those of MORB and most IBM back-arc lavas. However, Ti/V and Yb/V ratios are lower in FAB indicating that their mantle source experienced a distinctly higher oxygen fugacity compared to the source of basalts from mid-ocean ridges and back-arc basins. The most likely origin of FAB is that they were the first lavas to erupt when the Pacific Plate began sinking beneath the Philippine Plate at about 51 Ma. FAB magmas were generated by mantle decompression during near-trench spreading with little or no mass transfer from the subducting plate. Boninites were generated later when the residual, highly depleted mantle melted at shallow levels after fluxing by a water-rich fluid derived from the sinking Pacific Plate. This magmatic stratigraphy (Fig. 2) of MORB-like tholeiites overlain by boninites is similar to that found in ophiolites, suggesting that the latter were also generated by fore-arc volcanism in association with subduction initiation.

The Tonga-Kermadec subduction may also have initiated in the Eocene and be associated with the change in Pacific Plate motion. Recently, seismic-reflection (Fig. 3) 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 [7]. 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 [7].

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. Indeed, despite the numerous links that have been made between mantle melting and flow within the mantle wedge, there are, as of yet, no dynamic models linking melting to SI. Finally, dynamic models of global mantle flow are capable of resolving details of subduction zones at scales as small as 500 meters [11] (Fig. 4). This suggests the possibility of linking structural details to the dynamics of changes in plate motion.

The MARGINS Successor Program can advance this effort by marshalling and coordinating on-land studies of ophiolites, marine studies of back-arcs and fore-arcs, and geodynamic and petrogenetic modeling to explain how these nucleating and fossil SI features form. Accelerated progress toward distinguishing between SI hypotheses can be achieved though a focus site approach. For example, sites could be selected that span different phases of SI from nascent (Macquarie ridge), early stage (Puysegur), to fully developed (IBM) or that elucidate SI events that occurred synchronously but in widely-separated and different tectonic settings (IBM versus Tonga). An integrated MARGINS program with well-defined focus sites provides us with an outstanding opportunity to test the competing self-nucleation and forced subduction initiation hypotheses.
Fig. 1. Age of initiation of subduction zones showing the Western Pacific as a natural laboratory for studying subduction initiation, especially in the critical period 0-50 Ma where there is a geochemical and structural record partially deciphered that can be linked to changed in Pacific Plate motion. From [2].

Fig. 2. Inferred cross section from petrographic and geochemical analysis of samples recovered from recent deep sea dives in the Mariana fore-arc near Guam. There is a time span of only a few Myr between initial basaltic and boninitic outpourings. Based on the analysis in [6].

Fig. 3. Detailed seismic stratigraphy showing compressions (thrusts in c) and vertical motions (drowned terraces in a) in the New Caledonia Basin that have been linked to the initiation of the Tonga subduction zone. From [7].

Fig. 4. Zoom in to the Lau Basin & Tonga Slab from a global model of mantle convection and plate tectonics. The fine-scale details at < 1 km can now be linked to the full dynamics of global plate motion. From [11].

Preservation of Samples Utilized in Geoscience Research

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Topics: Inclusive of all the predefined topics

Keywords: Samples, preservation, curation
**Preservation of Samples Utilized in Geoscience Research**

The MARGINS Subduction Factory initiative has involved many dimensions of geoscience, from modeling, to experimentation, to expeditions, to petrology and geochemistry. The program mandates archiving of metadata in various repositories (see http://www.nsf-margins.org/XLS/DataArchives.xls) including a couple of repositories for samples (e.g., Scripps, Oregon State, and LDEO). Certainly retention of and ready-access to data are necessary for continued robust inquiry and synthesis of the topics encompassed in MARGINS. However, distinct from marine cores and perhaps dredge samples, there are no rock sample repositories at institutions with a specific mandate for preserving physical samples, whether rocks, sediments, or experimental products. Individual investigators are expected to retain physical samples, however, there is considerable evidence that individual responsibility alone is not a reliable mechanism for preservation of samples. Notably, NSF has not uniformly mandated preservation of samples in nationally recognized repositories from sponsored petrological or experimental research.

Natural history samples are preserved, in particular, in research museums of natural history and natural science. This role is well appreciated in the sciences related to living and fossil organisms. It is opportune to address the need to preserve samples studied as part of the successor to MARGINS in institutions with a mandate and record for preservation, care, and disclosed-lending policies of research collections. Several of these institutions also preserve synthetic and experimental samples as well, recognizing that experimental products are as critical to the scientific edifice as are natural samples.

Consequently, a mandate for retention of samples studied as a part of funded research should include the ultimate destination of these samples in institutions with collections policies that address long-term preservation and equitable loan procedures. Ultimately, considerations should include funding for sample preservation and curation at these institutions actively serving the sample-oriented research community.
Continental Breakup and Formation of Rifted Margins: The Gulf of Mexico as a Natural Laboratory

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Identifying Theme: Rifted Margins

Rifted continental margins capture the full pre-rift through post-rift process of continental breakup. As such, studying rifted continental margins should be a central focus of the MARGINS Successor Program (Stern and Klemperer, 2008). Based on four workshops held during the past year (GSA Southeast Section and Annual Meetings, AGU Fall Meeting, and Workshop for Earthscope Science Plan meeting), we argue on behalf of >100 participants that the Gulf of Mexico (GOM) is an ideal place for such studies (Fig. 1). The GOM formed during a brief (~25 m.y.) period in Late Jurassic time when Pangea broke up to form the Tethys seaway (Dickinson, 2009). Rifting exploited the Paleozoic Ouachita orogenic belt in the northern Gulf, which formed during the final stages of assembly of Pangea, and on the west involved an extensive Mesozoic magmatic arc system formed by subduction along the western North American plate boundary (Torres et al., 1999; Barboza-Gudiño et al., 2008). Prior events include formation of a segmented south Laurentian rift and transform margin during the Cambrian, which followed the trend of the Mesoproterozoic Grenville orogenic belt (Mosher 1998). During rifting, Yucatan separated from Texas-Louisiana and slid south along the Tehuantepec transform (Marton and Buffler, 1994) allowing variations on the Yucatan margin to be compared with those of the NW Gulf.

The GOM basin presents several opportunities to study fundamental processes associated with continental breakup. We briefly outline 8 of these opportunities:

1) **Tectonic Inheritance.** Rift style and location are strongly influenced by preexisting lithospheric fabric, with continental breakup commonly occurring along the trend of the last orogen (Dunbar and Sawyer, 1989; Thomas, 2006). The GOM provides an opportunity to study the influence of two end-member cases: a “soft” collisional orogen in the central and eastern Gulf (eastern Ouachitas - thin-skinned deformation and minimal syn-orogenic telescoping of the crust, which results in relatively shallow mantle and a strong lithosphere), and a “hard” collision in the western Gulf (western Ouachitas - thick skinned deformation and a great deal of crustal telescoping, which generates both thick crust and a lithospheric weakness (Harry and Londono, 2004). In the GOM, we can evaluate how these two tectonic fabrics affect subsequent rifting under similar lithologies, thermal conditions, and extension rates.

2) **Rift Segmentation.** What controls whether transitional crust is broad (among the broadest in the world in the eastern GOM) or narrow (as in the western GOM)? How do along-strike variations in the nature of transitional crust and lithosphere segmentation impact the subsidence history and thermal evolution of the GOM margins? Rifted margins also vary from magma-rich (volcanic rifted margins, e.g. Norway) to magma poor (e.g. Iberia). Such variations are inferred along strike in the central Gulf of Mexico, from magma-rich beneath the Texas Gulf Coast (Mickus et al., 2009) to magma-poor beneath Louisiana-Mississippi (Harry and Londono, 2004). Do magma supply variations control the width of transitional crust, or do these variations reflect control by inherited tectonic fabrics? Although much of the syn-rift magmatic evidence in the GOM is deeply buried under late Mesozoic and younger sediments, a possibly unique opportunity to examine the GOM rift magmatic record is presented by xenoliths recovered from salt diapirs, some of which contain 160 Ma syn-rift alkaline lavas (Ren et al., 2009) picked up from underlying rift-related lavas.
3) **Mantle Fabrics.** What is the nature of mantle lithosphere and how does this change from continent, across the transitional crust, and into the center of the basin? Mantle xenoliths from central Texas (Young and Lee, 2009) indicate that the mantle lithosphere here is composed of slightly depleted spinel peridotite. Limited studies indicate strong, margin-parallel shear-wave splitting beneath the Texas Gulf coastal plain (Gao et al., 2008). Do the shear wave studies reflect crystal orientations developed during Jurassic rifting, or are they remnants of older events (e.g., the Ouachita orogeny)? This question speaks to how long mantle fabrics are preserved, and to whether orogeny or rifting may dominate mantle fabrics. Shear wave splitting beneath oceanic crust is generally perpendicular to the spreading ridge; because the spreading ridge is thought to have trended ~E-W, associated mantle fabrics would be oriented ~N-S, perpendicular to that observed beneath the coastal plain. How does the transition from rift-parallel to rift-normal fabric occur, and what does this signify about lithospheric evolution beneath the rift?

4) **Lithospheric Reactivation.** The Gulf coastal plain was magmatically and tectonically reactivated after the Jurassic, as revealed by Cretaceous low-degree asthenospheric melts (Griffin et al., 2010) and ongoing faulting. The landward extent of Cenozoic faulting and Cretaceous magmatism is generally associated with the landward limit of the Louann Salt. Is this reactivation a result of regional or plate-scale stresses? Local salt movement and/or eustatic rebound?

5) **Sedimentation, Eustasy, and Coastal Subsidence.** Sediments accumulated around the GOM range up to 18 km in thickness and are among the thickest of any continental margin. The NW GOM receives an extraordinary load of sediments from rivers draining southern Canada and the continental U.S., from east of the Rockies to west of the Appalachians as well as eastern central Mexico. This presents an opportunity to study source to sink depositional systems at a continental scale over a wide range of depositional environments, how rift architecture controls subsidence and thus sediment accumulation, and how sedimentation influences rift margin evolution. Evolution of this thick sedimentary section is also reflected in migration of the GOM shoreline. Position of the shoreline records the interplay between eustasy, sediment supply, tectonic subsidence and flexure. Understanding these variables has broad societal implications, from possible coastal flooding associated with sea level rise, to predictions of relative subsidence in important population centers like New Orleans.

6) **Salt Tectonics.** The GOM provides an ideal opportunity to study the connections between active faulting and salt movement on the scale of the coastal plain to continental slope, as well as more detailed studies of salt tectonic movements in environments ranging from shallow burial near the landward pinchout, deep burial beneath the shelf, and extrusion onto the abyssal plain. The GOM basin also provides world-class examples of a variety of salt tectonic styles (salt domes, ridges, welds, minibasins, etc.).

7) **Fluid Evolution and Migration.** The GOM is a factory for generating a wide variety of fluids: CO$_2$, brines, and a wide range of hydrocarbons. These are generated in different ways, including mantle flux (CO$_2$), sediment compaction (brines), biologic activity (biogenic methane), and diagentic/metamorphic reactions (fresh water, oil, thermogenic methane). The GOM provides an opportunity for understanding how these fluids form, migrate, and interact.

8) **Synergies:** The MARGINS successor program provides a timely opportunity to advance understanding of rifted margins in collaboration with other NSF initiatives as well as industry. These include EARTHSCOPE, which will conduct onshore broadband seismic, GPS, and magnetotelluric studies adjacent to rifted margins of the U.S. in the next decade; the Computational Infrastructure for Geodynamics (CIG), which provides computational tools to examine geodynamic problems related to continental breakup; and the Oceans Observatory Initiative, which will install a wide range of seafloor sensors. Participation by the hydrocarbon industry also is likely and should be encouraged. We expect that the MARGINS Successor Program will continue to stress geoscientific studies that cross the shoreline and will be well-positioned to lead the effort to study GOM evolution.
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Fig. 1. Present day tectonic map of the Gulf of Mexico region (Pindell and Kennan, in press 2010).
An important accomplishment of the Suduction Factory Initiative has been the development of thermal structure models of subduction zones that are consistent with geophysical observations and accessible to the MARGINS community. At the Subduction Factory TEI in Eugene, OR (2000) it became clear that the constant viscosity slab/wedge thermal structure models widely-used in the subduction factory community were not consistent with a number of geophysical observations, including heat flow, gravity, and geochemical constraints of slab surface temperature. After the meeting, a number of groups developed high-resolution temperature- and stress-dependent rheology models showing that the rheology of the wedge critically controls the slab-wedge thermal environment due to the difference between isoviscous and temperature-dependent viscosity mantle wedge flow patterns (1-3). This new class of kinematic-dynamic slab thermal models has been extensively benchmarked (4) and extended to consider compressible convection (5), time-dependent flow (6), and 3D wedge flow (7-8). Additionally, slab thermal structure models have been linked with petrologic models to predict arc lava compositions (9-13).

While significant progress has been made over the last decade, the majority of the thermal models are 2D and only partly dynamic (i.e., the downgoing slab does not deform). Most models also neglect the generation or transport of fluids/magma. Shear-wave splitting observations (e.g., 14-15) and the along-strike variation of arc petrology and subduction zone geometry show that subduction dynamics are 3D and time-dependent and these effects are only beginning to be explored (7-8,16-18). Shear-wave splitting observations have lead to the development of a conceptual model where trench-parallel flow in the mantle wedge results from mantle material flowing around the edges of the slab driven by slab rollback (19). Kneller and van Keken (7-8) examined another mode of trench parallel flow driven by the pressure gradient due to wedge geometry with a fixed slab. Both laboratory (20-22) and numerical studies (23) have examined slab-rollback and trench migration however, the thermal and wedge structures from these calculations have not been examined at the same level of detail as the thermal structure calculations described in the first paragraph. The results presented by Schmeling et al. document the importance of the free surface for dynamic slab evolution. This has not been investigated in the current generation of slab thermal structure models and whether the free surface formulation impacts slab and wedge thermal structure is unknown.

Testing whether trench parallel flow results from trench migration, the hypothesis developed to explain the shear wave splitting observations, has proven to be quite challenging (23). At present, the resolution of the 3D calculations is significantly coarser than the grids used in 2D calculations, raising concerns that the thermal structure in the 3D models is not as well resolved. A decade ago a number of codes...
capable of solving 2D non-Newtonian wedge flow were already in use and had been
benchmarked. It still took most of the decade to complete a subduction zone thermal
structure benchmark that most codes could reproduce because the geometry of the
wedge was something many codes were not designed to handle and, the nature of the
coupling at the top of the slab in the seismogenic zone proved challenging for many
codes. The current state of benchmarking of 3D convection codes is not as advanced as
was the case for the 2D codes in 2000 and there are significantly fewer 3D codes
available.

Adding to the challenges described above, subduction flow calculations need to couple
melt, water (volatiles), and solid flow (9,24-25). This is important understanding the
hydrous state of the mantle wedge and for better integration of geochemical data with
godynamic models. Inclusion of fluids are critical for understanding the development
of serpentine in the corner of the mantle wedge and identifying the proper deformation
mechanism for olivine (i.e., hydrous or anhydrous conditions), which is critical to
interpret the shear wave splitting observations (26). Transport and reactive flow of
fluid and magmas in the wedge also control geochemical cycling through the subduction
system and into the deep mantle as well as the fundamental observation of the location,
composition and volume of arc volcanics.

Presently most slab thermal structure calculations assume a rheological structure in the
wedge that is loosely based on seismic and EM observations and the interpretation that
these indicate a significant component of serpentine in the corner of the wedge. This is
translated into reduced viscosity a priori. Topography and geoid can be used to
constrain the rheological structure of the wedge (16-17) and future calculations could
be used to test various assumptions regarding regions of serpentinization. At present
dynamic topography and geoid are underutilized observational constraints.

The next generation of MARGINS will require a significant contribution from
godynamic modeling. This will require supporting geodynamics projects, such as
coupling melt, volatile, and solid flow and may require coordination between MARGINS
and CIG (Computational Infrastructure for Geodynamics) to ensure that critical
functionality necessary to address goals relevant to the MARGINS program is
incorporated into geodynamic tools.
Figure 1 (a) 2D high-resolution calculation with dislocation creep in the mantle wedge from (4). (b) Fluid distribution (color contours), fluid flow (black lines) and solid flow (white lines) from a 2D wedge calculation from (9). C) Cross-section through New Hebrides and Tonga from 3D global model with variable resolution (27).


Selection Criteria for Future Geohazards-Motivated Research under the NSF MARGINS Successor Program

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Subduction zones by far present the greatest hazards to populations along continental margins, whether active or passive. During the last century giant (M \textgreater 8.5) subduction earthquakes and the regional and ocean-crossing tsunami waves that they spawn rank at the top in social impacts among geohazard events that occur off ocean margins. These impacts are likely to increase with time as population grows in coastal areas and as sea level rises during global warming.

Focus should therefore be directed to subduction zones that have produced giant ruptures during the seismic-instrumental and historical eras because earthquakes with established dates and magnitudes are reference events needed to compare with the actual consequent distribution and geochronologies of marine turbidite systems and on-land coastal tsunami deposits. Subduction systems that have produced mega-events during the instrumental and historical eras include Chile, Colombia, the central Kuriles and Kamchatka, the Indian-Ocean margin of Indonesia, Cascadia, continental Alaska and the Aleutians. The sediment record of these source regions provides the critical chronological record necessary for probabilistic hazard assessment. These records can be acquired by onshore sampling and offshore coring, drilling, and seismic reflection data.

Giant subduction earthquakes represent rupture zones that are elongate parallel to their respective trenches and resultant tsunamis tend to be of greatest wave amplitudes along azimuths perpendicular to the trench. This “beaming” effect is well known. Together with the detailed bathymetry along pathways between sources and receiving coastlines, and the distribution of coastal population and infrastructure, beaming largely dictates the potential human impacts of tsunami sources that cause ocean-crossing tsunamis. Tsunami modeling that identifies tsunami source regions threatening populated and built shorelines, an approach known as disaggregation, shows that certain subduction-zone sectors pose greatest danger to US coastal communities and their infrastructure. But little is known about the frequency of these events, evidence for which is stored in onshore and offshore sedimentary deposits and fault growth structures.

An important factor critical to dating turbidite and tsunami deposits is the presence of widespread tephra deposits from frequent caldera-forming arc eruptions, especially
during Holocene times. Active explosive activity is therefore an important selection criterion that permits dating of offshore turbidite-and coastal tsunami deposits. A related factor relevant to dating coastal tsunami deposits is the degree to which biological activity disturbs or breaks down organic carbon needed for radiocarbon dating. This factor of preservation is not a concern for cool, high latitude subduction zones but may diminish the suitability of subduction systems in some tropical regions.

Another criterion to consider is whether large ‘slow-rupture” or tsunami earthquakes have occurred in a particular margin. It is presently unclear if particular geologic settings are required for these enigmatic events to occur or whether tsunami earthquakes occur over time in most subduction systems as part of the statistical variability of subduction rupture. Detailed investigations of the source zones of great destructive tsunami earthquakes in the instrumental era are therefore called for.

Most of the source regions of giant subduction earthquakes are dominated by sediment influx from land areas, trench-axis sediment transport and accumulation, and likely sediment ingestion into subduction channels. Thickly sedimented subduction channels are thought to smooth subduction-slip interfaces and promote long-runout, great-earthquake ruptures. Conditions that favor large sediment influx are not uniform over geologic time or space. In particular, climate, mountain building, and geography appear to be important in establishing modern sediment-dominated subduction systems. High rainfall in the tropics or high snowfall and glaciation at high latitudes combined with late-Cenozoic mountain building in subduction or collisional environments and high and sustained delivery of sediments to continental margins by rivers and glaciers appear to be factors that control whether a sediment-dominated subduction system develops. Submarine fan formation and long-distance down-trench sediment transport by turbidity currents, are processes that are evident in most of the subduction systems that have produced giant plate-boundary earthquakes.

Important questions about this classic sediment source-to-sink problem include: What is the time scale of sediment flux from source to seismogenic depths in subduction channels? Does sediment ingestion along subduction channels affect other physical expressions of the subduction processes, such as the structure of forearc basins, the eruptive activity, chemistry, spacing and eruptive style of arc volcanoes, and the fine structure of the Wadati-Benioff zone? Do giant subduction earthquakes themselves trigger long-run-out turbidite flows? Are these events essential for long-distance along-trench sediment transport? This climate/mountain-building/sediment/earthquake problem is truly a systems-level one with potential for engaging collaborative research with most components of the NSF MARGINS Program, for example S2S, Subduction Factory, and SEIZE, collaborative liaison studies are envisioned with NSF support of climate change research, and government agencies such as NOAA and the USGS and non-U.S. university and governmental partners.
The French Margin Group, “Action Marge”
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Rifted continental margins form by the interplay of tectonic, magmatic and hydrothermal processes leading to continental break-up and seafloor spreading. Research into the formation of deep-water rifted margins is currently undergoing a paradigm shift. The discovery of exhumed sub continental mantle and hyper-extended crust devoid of significant normal faulting directly overlain by shallow marine sediments is proving fundamental in defining how continents rupture and oceans form. These new observations challenge existing plate tectonic concepts and question the concepts presently used to describe and quantify isostatic movements and the rheology of the extending lithosphere.

Rifted margins also represent archives of the past and present climate changes and related environmental changes recorded in the thick sedimentary sequences. More recent studies suggest that magmatism and serpentinization related to continental break-up may have a strong environmental impact.

Last but not least, rifted margins host hydrocarbon resources on which modern societies and industry rely and may also represent the locus for future CO2 sequestration. The discovery of some of the world biggest oil fields in deep water rifted margins shows that they may also represent one of the last frontiers in the hydrocarbon exploration.

For all these reasons, research on rifted margins is of societal, economic and scientific importance. Due to the development of new imaging techniques and numerical modelling approaches the research at rifted margins became more quantitative and therefore also more predictive. These new developments are, however, only possible in successful joint ventures between academia and industry. Modern research on rifted margins includes all different communities within Earth Sciences, develops collaborations with Biological, Oceanographic and Engineering Sciences, and links basic and applied research in order to better understand and make use of our resources and protect our environment.

Scientific themes:

The “Action Marges” promotes research activities and collaborations between researchers working on rifted margins within the French community. Two major scientific questions guide the research of the program:
1) How do tectonic, magmatic and hydrothermal processes interact during continental rifting and break-up and how are they recorded in the syn-to post-rift sedimentary record of rifted margins

2) How and when do sediments form, how do they travel and how, when and where are they finally deposited (source to think) within rifted margins”

Finding answers to these questions are critical to understand, interpret and predict geological processes that are of societal and economic importance such as distribution of mineral and hydrocarbon resources, earthquakes and predictions of climate and environmental changes.

In order to successfully answer to these questions and to develop technically ambitious research projects and foster collaborations between the French research groups, the “Action Marges” focus their research initiative into two sites (western Mediterranean and the Aden-Afar) and four “themes”.
Glacial-Marine Sedimentation as a Recorder of Tectonic, Climatic and Sea-Level Dynamics on Active Continental Margins

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Keywords: tidewater glaciers, fjords, sediments, tectonics, climate, sea level, continental margin

a) Overview Statement
Glacial-marine sedimentation responds to and provides sedimentary archives for a diversity of important processes associated with continental-margin dynamics. Tectonic convergence and subduction on active margins lead to uplift and volcanism that commonly (in temperate and high latitudes) create coastal mountain ranges with sufficient elevation to be ice covered. Glaciers are extremely effective in eroding mountains, transferring much ice and sediment to the sea, and aiding continued uplift. In areas with high coastal mountains, the ice commonly extends to sea level as tidewater glaciers (e.g.: southern Alaska; Patagonia; south island New Zealand; Antarctic Peninsula). Today, in these settings, the glacial sediments are typically released into a fjord (Fig. 1) with nearly complete entrapment of erosion products, forming a well-preserved sedimentary record of uplift, ice build-up, associated climatic variations, erosion, and transfer events. These under-studied coastal glaciers and sedimentary settings are also gaining attention for their control over sea-level rise (e.g., Overpeck et al. 2006), which is one of the largest potential threats of future climate change. On a global scale, the complex behavior of outlet glaciers and rapid ice-marginal changes are prime factors limiting confidence in predictions of impending sea-level rise. So, in these sites, the record of recent history and the prediction of future events (e.g., next century) have great scientific, environmental and human value. Our understanding of the linkages between glacial erosion and tidewater sedimentation would benefit greatly from an integrated investigation.

b) Tectonics, Subduction and Uplift
On active margins, ocean crust collides with and is subducted beneath continental crust. Spectacular coastal mountain ranges, including the St. Elias mountains in the NE Pacific, can form where continental terranes coupled to oceanic crust converge with continental plates. Based on much work in this area, Berger et al. (2008) hypothesize that “alpine glaciation in late Cenozoic time modified denudation and deformation within numerous mountain belts worldwide. This is consistent with climate as the driver of observed changes in exhumation rates, sedimentation rates and relief within many orogenic systems over the past few million years. Where present, glaciation may thus have a significant role in the internal processes of mountain building, empirically supporting the paradigm that orogenic architecture, kinematics and evolution may be heavily influenced by external climatic processes.”
c) **Glacial Erosion**

Glacial erosion is receiving increased attention due to: 1) the high erosion rates documented for many active glaciers (e.g., Hallet et al., 1996; Delmas et al., 2009); 2) its role in curtailing the height of mountain ranges, the “glacier buzzsaw” (see Fig. 2; Egholm et al., 2009); and 3) alpine glaciers being widespread during Plio-Pleistocene climate (e.g., Berger et al., 2008). Many active orogens have been extensively glaciated in the past (e.g., Himalayas, Andes, European Alps, Southern Alps in New Zealand, northwestern Cordillera of North America), but most of these regions currently contain only small alpine glaciers and remnants of larger ice fields. Consequently, the studies of coupling between glacial erosion and tectonic processes are based on the geomorphic studies of formerly glaciated landscapes and on conceptual, analytical, and numerical models (Tomkin and Roe, 2007). Direct field investigations of tectonically active regions that are currently glacier covered have only recently gained attention (e.g., Enkelmann et al., 2009).

d) **Tidewater Glacial-Marine Sedimentation**

Sedimentation proximal to the calving ice front impacts glacial advance and retreat, and the distal sedimentation records their history. Many tidewater glaciers advance slowly into deep water over a period of centuries with little sensitivity to climate variability, by keeping before them a moraine shoal that drastically reduces ice loss by calving (Meier and Post, 1987). This shoal, which can buttress not only a tidewater glacier but the massive ice sheet behind it, is slowly moved forward by erosion on the glacier side and deposition on the far side.

Sedimentation in proglacial portions of fjords is complicated by englacial and subglacial discharge and by oceanographic factors (temperature, salinity and bathymetry), which impact melting of glacial ice and mixing in fjord water. Sediment supply and accumulation on the seabed decrease with distance from the ice front (Syvitski, 1989; Cowan and Powell, 1991; Domack and Ishman, 1993; Jaeger and Nittrouer, 1999). The gradient of decrease and the detailed sedimentary signatures record assorted histories of ice and sediment supply and release.

e) **Sea-Level Rise**

Glacial retreat around the world has been used as dramatic and visible evidence of climate change, and has considerable practical importance because it directly contributes to global sea-level rise. However, the controls on the fluctuations of some of the most important outlet glaciers are only partly related to climate variability (Fig. 1), and these controls remain poorly understood. An innovative merger of glaciology and oceanography could provide a valuable understanding of retreat by tidewater glaciers.

f) **Concluding Statement**

The linkages described in this white paper are very common, and are found on many margins surrounding the Pacific Ocean. Therefore, gains in knowledge about the intrinsic processes will significantly improve our understanding of active continental margins. The writers’ expertises are centered in glacial erosion, tectonics and marine sedimentation, however, they have tried to demonstrate the broader linkages to other aspects of the MARGINS initiative. As mentioned in the overview, relevant study areas abound (e.g.: southern Alaska; Patagonia; south island New Zealand; Antarctic Peninsula). In addition, this research lends itself to numerical modeling, and can be readily integrated with diverse Earth system studies ranging from orogenesis to ice-sheet stability and their impact on continental-margin sedimentation and sea-level rise.
References

Fig. 1 – One example of a tidewater glacier from a coastal mountain source is Columbia Glacier, a massive (1000 km²; 60 km long) calving glacier in south-central Alaska that flows into Prince William Sound. During the 1980s, it began a rapid retreat controlled largely by factors affecting ice loss at its marine terminus (modified from Pfeffer, 2007).

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

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The Aleutian arc extends about 3,000 km westward from central Alaska, and has often been described as being structurally simple, with downdip subduction velocity nearly constant over the majority of its length; a reasonably homogeneous subducted plate; and no complications from intra-arc or back arc rifting or spreading. Enough new data from diverse subdisciplines have accumulated to warrant reevaluation of our previous view and a new look at links between geology, geophysics and volcanology.

The classic view that the arc is structurally simple first started to change in the 1980’s, with the demonstration that the western arc was broken up into a series of blocks which rotate clockwise and translate westward as convergence becomes more oblique and transpressional forces became more important (cf. Geist et al. 1988, Tectonics 7:327-341). New information about ongoing deformation, via GPS (Freymueller et al. 2009, AGU Monograph 179:1-42), and integrated over geologic time (cf. Redfield et al., 2007, Geology 35:1039-1042) shows that the entire arc is undergoing arc-parallel deformation related to westward extrusion caused by the accretion of the Yakutat Block at the eastern end of the arc.

The classic view was also that the presence of an upper plate which is continental in the east and oceanic in the west presents a good opportunity to investigate the influence of the upper plate on volcanism because so many of the other variables are controlled. However, an along-arc seismic profile across this junction shows that the Moho is at essentially the same depth in the oceanic and continental arcs (cf. Fliedner and Klemperer 1999, JGR 104:10,667-10,694), calling into question the role of “thickened continental crust”. Additionally abundant new geochemical data have not found a geochemical offset associated with the transition from oceanic to continental crust, although some systematic along-arc variations exist.

Figure 1a shows major tectonic elements of the arc as they are currently understood. Figure 1b is at the same scale and projection and shows only known volcanic vents. The removal of all other information from Figure 1b facilitates the identification of major disjoints in the volcanic chain (smaller-scale segmentation of the arc has been addressed by others, notably the Kays, and Marsh).

The disruption of the volcanic chain at 173.3W longitude (I in Figure 1b) coincides with a change in structural style in the forearc (seen in seismic reflection data) from compressional to the west to extensional to the east. An abrupt change in the number of earthquakes at this transition suggests that the forearc is more strongly coupled to the subducting Pacific plate to the west. A mirror disruption of the volcanic chain occurs at 156.5W longitude (II in Figure 1b). To the east geologic evidence for most recent offset on the Bruin Bay Fault is thrusting, marking compression near the arc crest. To the west, geologic evidence shows that crestal arc-parallel faulting changes to normal. This also marks the eastward limit of the North Aleutian basin, a kilometers-thick Cenozoic extensional sedimentary basin immediately north of the arc crest.
The two disruptions in the volcanic front at I and II (Figure 1b) divide the arc into three first-order segments. The outer two typically have small-volume, crystal-rich calcalkaline magmas which are andesite to dacite in whole-rock composition with dacite to rhyolite groundmass glass. The central region contains those volcanoes which are larger, basaltic-andesite to andesite, tholeiitic, have dramatically lower crystal contents and more mafic groundmass glass. There are modulations of these first-order features. The central segment also has small crystal-rich calcalkaline andesite volcanoes -- it’s the presence of the large mafic tholeiitic volcanoes, rather than the absence of smaller crystal-rich andesite volcanoes which is defining. West of I the average composition of individual volcanoes is more variable than east of II, perhaps reflecting stress heterogeneity associated with block rotation. (See Kay and Kay 1994, Alaska DNAG 687-722, and Singer and Myers 1992, Geology 18 1050-1053, and references therein for additional discussion of the relation between upper plate stress and volcanism.)

*Figure 1a (top panel).* Major tectonic and structural features of the Aleutian arc. Black arrows are current day plate motions relative to North American, with lengths proportional to velocities given by the scale in the lower left-hand corner. White arrows indicate geologically constrained movement and are not proportional to rate. Other symbols are black lines, major faults; YB, Yukutat Block; triangles, major Quaternary arc volcanic centers; circles, non-arc Quaternary volcanic centers; squares, Wrangell volcanoes (arc volcanoes displaced from the Aleutian arc. *Figure 1b (bottom panel).* Aleutian arc volcanic vents at the same scale, projection, and orientation as the top panel. I, II, and III are first order spatial dislocations discussed in the text.
I and II also mark major topographic irregularities on the subducting Pacific Plate – the Amelia Fracture Zone at I and the chain of seamounts derived from the Cobb hotspot at II. Because these are oblique with respect to plate motion their intersection with the trench migrates, the former to the west, and the latter to the east. They may be acting to decouple the subducted plate from the overriding plate as they migrate outward, causing the transition from a forearc and arc that is compressional to one that is extensional. This change may in turn allow easier passage of magmas to the surface in the central arc. Thus the stress regime in the upper plate may be an essential factor in modification of parental magmas and in the origin of calcalkaline vs. tholeiitic magmas (as previously discussed on sub-regional scales, cf. Kay and Kay 1994 and Singer and others 1992). An extreme case of compression limiting volcanism is seen at III (Figure 1b), where there is a 330-km long gap in volcanism spatially associated with the uplift of the Alaska Range. The presence of Holocene and Pleistocene arc volcanism NE of this gap (north of the Denail Fault), as well as various geophysical evidence suggest that this is only a volcanic gap, not a magmatic gap, and not a cessation of arc magmatism at the eastern edge of the subduction system.

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**Figure 2.** Tectonic and petrologic features of the Aleutian subduction system. Geochemical data are from the literature as well as ongoing AVO projects. Tectonic data are from (or derived from) Syracuse and Abers 2006, G3 doi:10.1029/2005GC001045. Vertical lines I and II are the breaks in the arc from Figure 1. Note that I and II do not coincide with major changes in subduction parameters.
Metamorphic processes in the subducting slab and overlying mantle wedge

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The MARGINS Subduction Factory initiative to date has focused on probing the depths of *active* subduction zones. Much progress has been made towards addressing the three fundamental science themes proposed by the science plan: (1) How do forcing functions such as convergence rate and upper plate thickness regulate production of magma and fluid from the Subduction Factory? (2) How does the volatile cycle (H₂O and CO₂) impact biological, physical and chemical processes from trench to deep mantle? (3) What is the mass balance of chemical species and material across the Subduction Factory, and how does this balance affect continental growth and evolution? Clearer understanding of processes occurring deep in active subduction zones requires further investigation of *fossil* subduction zones: including the metamorphic rocks that were once parts of the subducting slab or overlying mantle that directly experienced those processes. Field-based studies of subduction-zone metamorphism, and allied experimental work, can address key questions raised by the Subduction Factory community and these types of studies should figure more prominently in future MARGINS initiatives.

Research that addresses MARGINS science themes includes modeling of subduction-zone thermal evolution (e.g. van Keken et al., 2002) and related dehydration histories (e.g. Schmidt and Poli, 1998, 2003; Hacker, 2008) with the goal of providing estimates of fluid fluxes within subduction zones. These models can be tested by petrologic and geochemical constraints from subduction-related metamorphic rocks (e.g. Bebout, 1995, 2007; Breeding and Ague, 2002). The models can be refined by better constraints on model inputs, such as the degree of hydration of oceanic lithosphere and by inclusion of (de)hydration of overlying mantle wedge. Recent studies of arc volcanic degassing have begun to incorporate insights gained through study of metamorphic suites (Elkins et al., 2006; Mitchell et al., in press) and studies of geochemical trends in forearc serpentinite seamounts (and associated peridotites) and in arc volcanic rocks incorporate and complement information gained through study of forearc metamorphic suites (Morris and Ryan, 2003; Mottl et al., 2004; Savov et al., 2005; 2007). Theoretical models for devolatilization thus far mostly consider dehydration; greater focus on CO₂, especially in mixed carbonate-silicate sediments, and on halogens, S, and N, will place important additional constraints on volatile budgets in subduction zones. Studies of metamorphic rocks are just beginning to scratch the surface in the understanding of how components other than H₂O behave during devolatilization reactions.

Element mobility and processes of mass transfer are other topics that have begun to be addressed by studies of metamorphic rocks. Investigation of features such as veins and metasomatized rocks, including hybridized rocks found in mélange zones, provides insight into mechanisms of fluid transport, fluid flow pathways, mobility of elements, and mixing processes within subduction zones (e.g. Bebout and Barton, 2002; Ague, 2007; Bebout, 2007; King et al., 2007; John et al., 2008; Miller et al., 2009). Examination of serpentinites from mélange complexes and from the eruptive deposits of serpentine mud volcanoes of the Mariana subduction system constrains both the mobility of elements at low P-T conditions during subduction and the material transport requirements of arc systems (Mottl et al., 2004; Savov et al., 2007; Hattori and Guillot, 2007). Mineral solubility experiments have demonstrated large solubility increases with increasing pressure while phase equilibria and *in situ* experiments are beginning to demonstrate the importance of silica and alumina polymerization under sub-arc conditions (see summary in Manning, 2004). The role of polymers in controlling the composition of subduction zone fluids and also the effects of chlorine and other ligands need to be investigated.

The physical properties of subduction-zone rocks are also understudied. Particularly critical is improving our ability to use geophysical observables, like seismic wave speeds and attenuation, to inform our understanding of compositional and structural variation within subduction zones (and vice versa) (e.g., Abers et al., 2003; Hacker et al., 2003). Of critical importance is the measurement or calculation of shear moduli—and their variation with pressure and temperature—in crustal minerals.

Studies of metamorphic rocks that reached various depths in ancient subduction zones are critical to understanding processes at modern convergent plate boundaries. It is important to combine efforts from experiments, geochemical observations, petrologic observations, modeling, and field investigations to ground truth ideas of what happens in the subducting slab and overlying mantle wedge during subduction.
We have identified the following key issues to address:

1) What is the alteration state of a slab as it enters a subduction zone?
2) What metamorphic reactions occur in the downgoing slab and mantle wedge and what metamorphic assemblages form? What volatile and non-volatile elements are released by those reactions?
3) What are the rates and timescales of devolatilization reactions during subduction and how do these rates affect rock rheology? What is the role of reaction kinetics during fluid release? Do reactions occur at near-equilibrium or are reactions significantly "overstepped"?
4) What is the nature of the slab-mantle wedge interface and how does it change with depth? 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 and its physical, chemical, and seismic properties?
5) How do major and trace elements partition among minerals and between minerals and fluid in subduction zones and where do these elements reside in minerals? Similarly, how do isotopes fractionate and how do these fractionations evolve with changing pressure and temperature?
6) What are the compositions and physical characteristics of fluids (e.g. aqueous COHSN fluids, hydrous silicate melts) within subduction zones and how do they evolve? How do fluid compositions affect element mobility in fluids? What are the fluid fluxes, including fluxes of CO₂, during metamorphic processes? What are the fluid-flow pathways (fractures, 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?
7) How do processes in the forearc affect the overall budget of elements in the subduction zone? To what extent does recycling of elements at shallow levels affect the overall budget within subduction zones? What contributions do forearcs make to arc magma source regions?
8) What are the implications (both physical and for volatile cycling) of serpentinization in the outer rise of the subducting slab (e.g. Ranero et al., 2005) and in the forearc mantle wedge?
9) What velocity structure is expected for the slab and wedge based on metamorphic processes? How are seismic images of the slab and wedge best interpreted from a petrologic perspective?

Sketch of a subduction zone showing locations corresponding to key questions identified above.
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Drilling below the salt in the Western Mediterranean Sea: the GOLD (Gulf of Lion Drilling) Project.

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In recent years the Gulf of Lion within the Occidental Mediterranean Sea has become a unique natural laboratory for the study both the evolution and interaction of deep processes (geodynamics, tectonics, subsidence, isostasy) and surficial processes (river behavior, sedimentary fluxes, sea-level changes, climatic impacts). Here, representing a large group of international researchers, we present the main objectives for a deep drilling project at the foot of the continental slope (2400 m water depth) in the Gulf of Lion. This position is the only place in the Gulf of Lion where the sedimentary column is expected to be complete without major erosional hiatuses or time gaps. It is located sufficiently far from the shelf and slope to not have been affected by the extraordinarily erosional event of the Messinian, and at the same time be free from salt-related faulting and diapirism. At this position we have recorded nearly a complete high-resolution history of the last 23 through 30 Ma of Mediterranean history in some 7.7 km of sedimentary archive. From the petroleum exploration perspective the deepest part of the margin remain underexplored since all existing wells were drilled on the shelf and slope GLP1 & 2 being the deepest one (Fig. 1). New interpretations in the region (especially concerning the Messinian event) have considerably changed earlier views of potential hydrocarbon reservoirs.

New results expected from deep drilling are numerous:

1) For the substratum, seismic reflexion data (ECORS and SARDINIA) quite clearly image the limit between continental crust and transitional substratum at the toe of the slope. Here highly reflective lower crust that is clearly visible below the shelf disappears. Refraction data confirm those observations: the upper continental crust thins to less than 5 km, and changes laterally to a relatively thin crust with high velocities whose precise nature is still undetermined (Gailler et al., 2009). Magnetic maps also indicate a large smooth domain as is sometimes observed at the foot of the margins around the world. The aim of the drilling is to reach this crucial information on the puzzle of the nature of this crust which, in association with precise kinematic and paloebathymetric reconstructions, is essential for the understanding of the evolution of the sedimentary basin (Aslanian et al., 2009).
2) The Gulf of Lion receives most of its sediment eroded from the Alps and transported through the Rhône River. The amount of sediment is expected to vary significantly depending on the existence or the absence of glaciation. The drilling will allow the dating and characterization of the impact of the initiation and changes in glacioeustatic cyclicity in alpine glaciers and ultimately on sedimentation in the deep basin during Plio-Quaternary interval. For the Miocene and older sediments the drilling, combined with seismic reflection data, will yield information about the nature, paleoenvironments and age of deposits enabling an astronomically-tuned Neogene time scale to be refined for the period of Aquitanian through Langhian interval. Sampling these deposits will also provide key elements to reconstruct the early history of margin formation and subsidence testing recent work that suggested that this margin stayed in a high position during early phase of rifting (Bache, 2008).

3) The Messinian extreme event represents a unique sedimentological, hydrological, oceanographic, biological and probably climatological crisis in Earth history. It is a unique case to study the impact of sea-level drop (more than 1000 m, one order of magnitude greater than Late Quaternary glaciations) on sedimentary river behavior, deltaic and evaporitic deposition and ensuing biotic crisis. Furthermore, the amount of Messinian deposits (detritics, evaporites and salt) have been inferred to have reached more than 3000 m in thickness which corresponds to a massive depositional rate. Such rapid and vast erosional and sedimentation rates must affect continental margin dynamics (isostatic readjustment, behaviour of the upper mantle) in a significant way. So far old DSDP and IODP drilling have reached only the upper part of the evaporites, and thus the beginning of the crisis is still a matter of intense debate and conjectures. Our observations suggest a thick series of “lower evaporates” under the halite resting above a major detritic series (Bache et al., 2009). Other interpretations suggest
less amount of Messinian detritics and pre-Messinian canyons (Lofi & Berné, 2008) or evaporite deposition before major the detritic phase and without a sea-level drop (Krijgsman, 1999). Deep drilling with the R/V Chikyu is the only way to go through the complete series of evaporites in the Provence Basin, sample the initiation and evolution of the crises, the first deposits related to the lowering of sea-level on the one hand and to the salinity crisis on the other.

4) Finally, this drilling will represent the first opportunity to study the composition and functioning (metabolic processes and products, regulation of populations, etc.) of the microbial communities (bacteria, Archaea, viruses, fungi and protists) from the deep biosphere of the Mediterranean Sea. This site is particularly relevant to address the question of life’s tolerance to environmental extremes since extreme conditions such as high P, high T°, salt layers (are there organisms in salt inclusions?) and particular organic matter content were prevailing. The ultra-deep drilling should reach 7700 mbsf while the current deepest detection for molecular signatures of microbes is at 1626 mbsf (Roussel et al. 2008). Consequently, it would represent an opportunity to determine the limits of life in terms of depth and physico-chemical constraints. This drilling is also relevant to study of dispersal and evolution (isolation during Messinian salinity crisis) and the interaction biosphere with geosphere.

We invite all interested scientists to join us in planning and promoting this drilling project. We are proposing an IODP Magellan workshop in Banyuls on 3-5 March, 2010 to bring together all interested scientists and stake-holders around this proposal and other drilling projects in the Mediterranean Sea. Please contat us at the earliest opportunity.

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The “GOLD” IODP Project

Global Climate & Sea-level Changes, Extreme Events, Margin formation and the Limits of Life

Proposants : Marina RABINEAU & Internationals (marina.rabineau@univ-brest.fr)

For the Miocene: (>1600 m) Sed Rate = 1mm/ky
- Paleoclimate sensitive to astronomic oscillations
- Sea level history
- Early history of margin evolution (palaeoenvironments)
IODP Theme : 2 and 3

For the Oligocene:
- Nature of transitional crust
- Full story of margin formation and vertical evolution
- Understanding crust mantle dynamic
IODP Theme : 1
REFERENCES:


Towards a 4-D understanding of subduction zone geodynamics

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1 A diverse population of subduction zones

A wealth of geochemical and geophysical observations on many aspects of subduction zones have been compiled in an attempt to quantitatively describe the processes that occur within them. Focus initiatives of the MARGINS program have allowed a few subduction zones to be particularly well-studied, namely, the Nankai, Central America and Izu-Bonin-Mariana subduction zones. However, the modern Earth hosts a diverse population of subduction zones, of which only a fraction have been studied in such great detail.

A study by Schellart et al. [2007] identifies 24 subduction zones defined as unique by virtue of being composed of a coherent system of trenches attached to a single downgoing slab. From a geodynamical viewpoint, this definition is useful in the sense that each individual subduction zone shares a common source of negative buoyancy in the associated slab that drives the system. These 24 subducting systems actually consist of 45 distinct segments, differentiated by the arcuate cusps and associated island arcs (including 4 segments that were formerly subducting but have evolved into collision zones, but are still attached to downgoing slab). At a smaller scale, recent studies [Lallemand et al., 2005, Wu et al., 2008] have updated the compilation of subduction zone parameters started by Jarrard [1986] with trench-perpendicular transects. These sample between 65-85% of the world’s trenches, after having filtered for whether the tectonic setting is perturbed by proximity to a collision zone or bathymetric highs such as aseismic ridges, oceanic plateaus, and seamount chains. The remaining population of "nonperturbed" transects still exhibit a large degree of along-trench variations in plate age, convergence azimuth, stress state of the upper plate, dip angle, and proximity to a slab edge. With the exception that shallow dip angles correspond to compressive states in the back-arc while steep dip angles correspond with extensional stresses in the back-arc, statistical analyses of these data sets show virtually no correlations exist between parameters. This is because simple statistical correlations contain no physics and can in no way substitute for a dynamical theory with predictive capability.

Furthermore, each individual subduction zone on Earth represents a snapshot in time of a dynamic and continuously evolving system. The seminal paper by Uyeda and Kanamori [1979] proposed that two end-members (Chilean type and Mariana type) represent the beginning and end stages of subduction evolution. This classification distinguishes subduction modes based on the observed stress state in the back-arc and slab dip, and while it has been influencing the thinking about subduction zone geodynamics for three decades, the conceptual model does not contain any dynamics. Additionally, it has now been sufficiently demonstrated that the dynamics of subduction zones are inherently three-dimensional by nature [Schellart et al., 2007]. This issue of classification urgently needs revisiting and can be greatly informed by computational geodynamics.
2 The need for a new global classification of subduction zones

An updated classification of subduction zones, based on the temporal evolution of fully-dynamic three-dimensional models, would be an important step towards being able to meaningfully address how one subduction zone is different from another. A subduction zone is a complex system comprising of the subducting plate, its associated slab, and the overriding plate which are all coupled together through the upper mantle which surrounds the entire system (and includes the mantle wedge). From a geodynamics perspective, it is not possible to consider any one part of this complex system in isolation from any of the components to which it is coupled. Similarly, such strong interconnectivity suggests that the inherent properties of the system (the age and net buoyancy of subducting lithosphere, for example) control the dynamics which are expressed in the emergent properties of the system (dip angle, trench retreat rate, etc).

In terms of geodynamics of subduction zones, what are the distinguishing characteristics of a subduction zone that control its evolution? One important aspect is the nature of the overriding plate, and whether it is continental or oceanic lithosphere. It has been found that the presence of a continental upper plate can profoundly influence the dip angle [Lallemand et al., 2005] and kinematics [Capitanio et al., 2010 (in press)] relative to when the overriding plate is simply oceanic lithosphere. Another factor that appears to be a defining quality of subduction zones is the lateral extent of the subducting plate and associated downgoing slab, with subduction motions of narrow plates ( <1500 km in width) primarily accommodated by trench retreat and slab rollback while wider plates ( >4000 km) preferentially subduct through forward plate advance through a stationary trench [Schellart et al., 2007, 2009]. The nature of the plate contact, including the extent and strength of the plate bounding fault as well as the presence of a subduction channel, is another primary control on this coupled system. Subduction zones distinguished as either erosive or accretionary exhibit a varying nature of this plate contact which may play a role in limiting the maximum moment of earthquakes that can be produced (Figure 1) [De Franco et al., 2008]. At present, we are only in the initial stages of developing an understanding about how such emergent features respond to these controlling factors, but this research avenue leads to an ability for explaining some of the observed lateral variations of subduction zones. Continued effort on this front will produce a geodynamic classification capable of providing a suite of reference models from which certain subduction zones on Earth may be identified.

3 Development of a geodynamic subduction zone reference model

The state of knowledge for understanding these systems is in its infancy. Even simplified models exhibit large variations in plate kinematics, mantle flow patterns, seismic coupling, accretionary style and stress patterns both on the surface and within the slab. For example, the arc, back-arc and fore-arc regions can simultaneously express compression and extension, depending upon the particular point in time during the evolution. Understanding these varying states of (uncomplicated) reference models is a vital step required before addressing scientific questions regarding those subduction zones clearly complicated by other dynamical influences such as seamounts/ridges/plateaus, small sub-vertical slab tears (Ryukyu), gaps or slab windows (Costa Rica, Solomon Islands), or places where the slab seems to have broken off entirely (Baja).

Considering that many existing observations are not adequately explained at present, the choice of which data to collect (and where) is crucial for connecting the dots. On the basis of having availability to a vast collection of recently or yet-to-be acquired, high-quality data, we propose a three-tiered approach for advancing science in this area: 1) development of a global classification of subduction zones based on temporal evolution of geodynamic models and constrained by observations such as seismic imaging, earthquake focal mechanisms, bathymetry/topography, gravity, structural mapping, and tectonic reconstructions; 2) identification of archetypical examples of subduction zone segments which may serve as geodynamic reference models, and 3) supporting a large-scale computational program for integrated modeling and simulation.
These populations may each have a particular type of plate deformation and seismic moment release, only one of which appears capable of producing great earthquakes. According to Capitanio et al., 2010, there are different classes of subduction zones that can be identified based on the type of plate contact and the nature of the margin.

**References**


White Paper for MARGINS Successor workshop, San Antonio, February 2009

ELEMENTAL ARC OUTFLUX AND ARC GROWTH RATES
Theme: Subduction Factory
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In order to understand the impact of subduction zone magmatism on the broader global geochemical cycles, the MARGINS Subduction Factory Science Plan (pg. 75-77, 86-87) emphasized the necessity of quantifying the elemental outflux (‘material output rate’) of volcanic arcs. Despite major strides towards understanding subduction processes, the progress towards the quantification of the arc fluxes has remained slow. This is due to the uncertainties inherent to the key variables in the arc outflux equation such as the arc growth rates and petrological variables.

The elemental outflux of volcanic arc is calculated as follows:

\[ \text{elemental outflux} = \text{element abundance} \times \text{arc density} \times \text{arc growth rate} \]

The arc density is the density of the melts and has a limited range of (~2.3-2.8 g/cm³). The elemental abundance is the concentration of an element in the primary mantle melt, as a function of the extent of mantle melting and the solid/liquid partition coefficients of the relevant mantle lithologies. While the abundances of most elements in primary arc melts can now be estimated with roughly a factor of 2, larger uncertainties remain with respect to the extent of melting and the nature of primary arc melts (basaltic vs andesitic). The arc growth rate is the mass of melt added per unit time (or gain of arc mass per unit time). It is commonly given in units of km³/per km of arc length/Myr (shortened to km³/Myr). The arc growth rate is least well known. Estimates may vary about a factor of 5 and more within single arcs and between different arc settings.

In general, two methods are used to determine arc growth rates. The methodology of Reymer and Schubert (1984) estimates the increase in net crustal growth per unit time from geophysical measurements of the present-day crustal thickness, the duration of volcanism and simplified models of crustal accretion. Average numbers for net arc growth rate range between 20-40 km²/Myr, but higher values of 90-180 km²/Myr have also been calculated, with or without accounting for crustal loss by erosion (Stern and Bloomer, 1992; Dimalanta et al., 2002; Jicha et al., 2006). The second method determines the volcanic output rates by dividing the volcanic output volumes by the duration of the activity (Crisp, 1984; White et al., 2006). Assuming an average arc length of 1000 km, values between 10 and 100 km²/Myr are derived that are then converted to arc growth rates by estimates of the intrusive:extrusive ratios.

Either method has shortfalls. The Reymer and Schubert (1984) approach depends on the crustal accretion model and does not account for crustal loss by erosion, delamination or tectonic thinning, nor for episodic growth during the lifespan of arcs. Arc growth rates derived from volcanic output volumes are limited to young volcanic
arcs and are subject to considerable uncertainty owing as the intrusive: extrusive ratios may vary between 1:1 and 1:200 (White et al., 2006).

The current data on arc growth rates allows for first-order estimates of the arc outflux, but remain overall limited in their potential by the sum of inherent uncertainties. Because of the nature of these uncertainties, there is no easy way out. However, a concerted effort of towards better determining the variables in the arc outflux equation will likely make progress. Owing to its overall importance for the quantification of arc fluxes, the issue of elemental fluxes and arc growth rates should deserved a thematic focus in the successor program to the MARGINS ‘Subduction Factory’.

An important aspect of the elemental outflux and arc growth rates equations is that their variables are interrelated. This is because the volumes of the extrusive series are directly related to the magma volume generated by partial melting that in turn plays a vital role in controlling the magnitude of outfluxes of volcanic arcs. The extent of melting is influenced by tectonic parameters, such as crustal thickness, convergence rate, distance from trench, but it is also reflected in the major element compositions of arc magmas that make up the bulk of the magma volume produced. Understanding the interrelation of compositional, physical and structural variables that influence the major element composition of arc magmas should result in better constrained rates of the arc outfluxes through time.

Thus, this problem can be addressed by closer integration of geochemistry with geology and volume of extrusive series emplaced through time. One way to proceed could be a comprehensive, regional (per subduction zone) and global evaluation of existing data, now partly pre-compiled in the online data bases accessible through EarthChem (http://www.earthchem.org/). Such data evaluation could weigh known arc growth rates against the most recent data on arc crustal thickness and composition, as well as compositional and volumetric data of intrusive and extrusive series and a broader variety of subduction zones parameters. Another important avenue is to conclusively identify the processes that control arc magma formation and differentiation. The composition of arc magmas is globally unique despite the physical and thermal diversity of subduction settings worldwide (Plank and Langmuir, 1988). Yet, there is no consensus on the key processes of arc magma genesis (slab melting, mantle melting, mantle metasomatism, melt-rock reaction, crustal contamination and assimilation). Understanding the dominant processes of arc magma genesis will provide better constraints on the intrusive:extrusive ratio of magmatic rock series and improve quantification of the relative contributions from slab, crustal and mantle reservoirs. When combined with extrusive volumes, improved estimates of material flux rates will result from well-chosen study areas.
References
White Paper for MARGINS Successor workshop, San Antonio, February 2009

SUBDUCTION VOLCANISM AND ENVIRONMENTAL CHANGE
Theme: Subduction Factory
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Volcanism links the vast reservoir of greenhouses gases (H₂O, CO₂, sulfur, CH₄) stored in the solid Earth with the cycles of the ocean-atmosphere system. It is well-documented from historical major eruptions of arc volcanoes that the explosive eruption of volatile-rich arc magmas can trigger devastating tsunamis (e.g. Krakatoa 1883) and can influence the global climate with far-reaching consequences for humankind (e.g. global cooling and famine following Tambora 1815).

While the effects of single eruptions are short-lived (a few years), the potential role of arc volcanism as player in the evolution of Cenozoic Earth is a longstanding issue of research. The existence of causal links between arc volcanism and the Earth’s Cenozoic surface systems were first postulated by Kennett and Thunell (1975) who observed that variations in the frequency of arc-derived marine fallout tephra layers - and implicate episodic variations of arc volcanism - coincided with the onset of the Quaternary glaciation and potentially an earlier mid-Miocene period of cooling. Several subsequent studies, that built on the improved core recovery of technically more advanced drilling expeditions, confirmed these results (Cambray and Cadet, 1994; Prueher and Rea, 1998; Straub and Schmincke, 1998; Sigurdsson, 2000; Prueher and Rea, 2001). A recent compilation of eruption dates of four circum-Pacific arcs indicates that arc episodicity extends farther back in time, and may be linked to major climate changes of the early Cenozoic (e.g. Eocene-Oligocene cooling, Jicha et al., 2009).

The temporal coincidence between arc volcanism and periods of environmental change has lead to many speculations and models as to cause-and-effect relationships and ensuing feedbacks. An obvious cause of global cooling is the injection of climatically-active gases and aerosols into the atmosphere. Atmospheric cooling may lead to positive feedbacks, such as an increased albedo as snow cover and ice sheets expand, or the biological drawdown of CO₂ driven by the release of nutrients from dissolving ash into the oceans (see Jicha et al. (2009)). Other speculations link arc episodicity to mid-ocean ridge spreading rates (Kennett and Thunell, 1975), and consider sporadic plate tectonic reorganization as driving force of simultaneous arc initiation (e.g. Whittaker et al., 2007). A recent study by Huybers and Langmuir (2009), not limited to arc volcanism, proposed that glacial load of icecaps and glaciers regulate the melt fraction in the upper mantle. Whereas the melt fraction and hence magma production rate increased by mantle decompression during deglaciation, the waxing of the glacial loads reduced the melt fraction and suppressed magmatic activity.
Importantly, Huybers and Langmuir (2009) provided a quantitative estimate of the increased contribution of magmatic CO₂ to the increase in worldwide atmospheric CO₂ during the last deglaciation. They estimated amount of ~30-40 ppm of magmatic CO₂...
relative to the overall ~100 ppm natural variability during glacial/interglacial periods. This number suggests that magmatism exerts a significant influence on climate evolution together with the mechanisms of the ocean-atmosphere systems.

There is now a critical mass of information and models that warrants a work focus of the MARGINS subduction community towards elucidating causal relationships between arc volcanism and global environmental change. Albeit only a part of global volcanism, subduction volcanism plays a unique role because through the recycling of surface materials it provides a rapid and efficient link between the Earth’s exterior and interior processes. Moreover, explosive arc volcanism is famed for leaving a time-precise and temporally highly resolved ash record in marine and lacustrine sediments that cover intermediate (10^3-10^5 yrs) and tectonic (≥10^6 yrs) time scales. Through composition and temporal distribution, these marine tephras are unique recorders of arc evolution as well of changes in intensity and frequency of arc volcanism (Lee et al., 1995; Bryant et al., 1999; Straub et al., 2009). An extended temporal ash record obtained from suitable sediments may allow for testing the Huybers and Langmuir (2009) hypothesis beyond the last glaciation. The sediment is accessible by drilling, whereby the excellent recovery rates (~100%) of oceanic drilling now allow for an uninterrupted correlation of the ash record with other archives of environmental change (e.g. oxygen stratigraphy, Sigurdsson, 2000).

Exploring links between arc volcanism and the oceanic cycles requires a multi-disciplinary approach. Judicious choice of study areas is needed where a confluence of favorable conditions exists. The influence of glacial loading and unloading is strongest at high latitudes, and thus arc settings like Kamchatka, the Aleutians and the South Sandwich arc should offer the most favorable conditions. Abundant ashes have already been recovered outside Kamchatka and Aleutian trenches. A high background sedimentation rate of non-volcanic datable biogenic sediment will provide a highly-resolved link to other marine climate archives (e.g. Sigurdsson, 2000). Even a temporally incomplete, but longer tephra record may allow for linking arc volcanisms to plate tectonic change (e.g. Straub et al., 2009). Such deep-time studies could further be complemented by studies whether and how the evolution of individual arc volcanoes was related to the glacial/interglaciation cycles.

References


THE AFRICAN PASSIVE CONTINENTAL MARGIN IN THE GULF OF GUINEA: GEOSCIENTIFIC PROBLEMS

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The Gulf of Guinea is a part of the passive margin of the Atlantic Ocean near to the Equator in Central Africa. The Gulf of Guinea is characterized by the presence of a volcanic field forming the oceanic segment of the active Cameroon Volcanic Line (CVL), a line extending over 1500km from the Atlantic Ocean to the Africa continent in Cameroon with its oceanic segment underlined by the following volcanic islands: Bioko, Principe, Sao Tome, Annobon. The continental segment of the CVL starts at Mt, Cameroon (4100m) which is the main active volcano along the CVL with at least 17 eruptions since the 19th century. Mt. Cameroon Eruptions of 1922 and 1999 stretched over several km, entering the Atlantic Ocean at Bibundi for the first and ending about 300 m from the ocean for the second. Mt Cameroon area is the most seismically active zone of the CVL but little information is available for seismic activity within the oceanic segment of the CVL. A volcanic eruption or an earthquake within the Gulf of Guinea may provoke huge damage in coastal areas with are characterized by high population concentrations (07 cities with more than one million inhabitants). The Gulf of Guinea geology is completed by sedimentary formations currently undergoing massive hydrocarbons exploitation.

In the framework of future MARGINS activities main problems challenges concerning the Gulf of Guinea in Central Africa thus include:
- The building up of a comprehensive theory for the origin and nature of the Cameroon Volcanic Line, a unique example on Earth of an active intraplate alkaline tectonomagmatic alignment simultaneously developed into both oceanic and continental domains (Fitton, 1987; Halliday et al., 1990; Burke, 2001; Caldeira et al., 2002; Deruelle et al. 2007).
- The integration of the gulf of Guinea in an initiative for a the building up of a global warning system for tsunamis.
- The effects of massive hydrocarbons exploitation on climate change.
In conclusion, the Gulf of Guinea comprises diversified geological environments formed by volcanic islands which are part of the active Cameroon Volcanic Line and sedimentary formations currently under heavy hydrocarbons development. Related geohazards to be investigated include oceanic volcanoes and earthquakes survey, study of potential effects of massive hydrocarbons exploitation on global climate change.

Summary references

MARGINS Successor Program White Paper: Roots of Arc Volcanoes

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Topics/Themes: Subduction Zones, Fluids and Magmas

We propose the fundamental topic of "Roots of Arc Volcanoes" (RAV) as a major theme for the MARGINS Successor program. This theme is specifically identified in the MARGINS 2009 Review. We envision this initiative as encompassing the arc volcano system from the slab to the surface, involving a comprehensive suite of geophysical, geochemical, and geological studies of submarine and subaerial arc volcanoes over a broad range of spatial and temporal scales. This initiative embodies some of the elements of the original MARGINS program (magma genesis, fluids, and volcanism), but with a change in focus to a specific theme of how arc volcanoes work, from bottom to top. A broad analogy can be made to the vast suite of multidisciplinary, multi-scale studies of the Hawaiian volcanoes and hotspot, funded by multiple NSF programs, and involving: "passive" seismic studies from the scale of Halema'uma'u crater to the mantle plume track; marine seismic profiling and offshore-onshore imaging; deep drilling; petrology and geochemistry of lavas; gravity, magnetic, and electromagnetic field studies; geodesy; and much more. Thus, there is great potential for synergistic work on this theme across disciplinary boundaries. Studies in Cascadia and Alaska can take advantage of recent ARRA initiatives, future USArray deployments, and cooperation with U.S. volcano observatories. The "roots of arc volcanoes" theme also has direct societal relevance in terms of providing a deeper understanding of volcano behavior and hence volcanic hazards and environmental impacts.

The potential components of the RAV initiative cut across many earth science disciplines. Overall, the research components for the RAV initiative would largely mirror those of the Subduction Factory, but with a different focus: experimental and theoretical analyses; bathymetry, swath mapping, and dredging; active- and passive-source seismology; drilling; magnetotellurics; heat flow; geodesy; field studies; petrologic, geochemical and isotopic analyses; and database development. The suite of studies would of course vary for submarine volcanoes versus subaerial volcanoes.

Considerable debate exists, especially in Cascadia and Alaska, regarding the role of the subducting slab during magma genesis. Geochemical studies of primitive lavas in these arcs indicate that magmas are generated via fluid-flux melting, adiabatic decompression melting of hot, nearly anhydrous mantle, partial melting of the slab, or some combination of these processes. The recent work by Grove et al. (2009) on the primary control that slab dip has on arc volcano location is an example of the type of fundamental issue that requires cross-cutting research that could be supported by the RAV initiative. In this case, a combination of experimental work on chlorite stability, geodynamic modeling of subduction zone thermal structure, and seismic estimates of slab dip led to the conclusion that the melting zone is controlled by the intersection of zones of chlorite dehydration with the (vapor-saturated) peridotite solidus, which in turn is controlled primarily by slab dip and, to a lesser degree, by convergence rate. An ultimate goal is to understand how slab petrology (Figure 1) is linked to its seismic structure and seismicity (Figure 2). Given the recent advances in locating non-volcanic tremor on plate interfaces and relating tremor to fluids, earthquakes, and aseismic slip, there is...
currently a rich dataset available to explore the link between seismicity and magma generation processes in subduction zones.

Another example of a critical issue that requires multi-disciplinary research is the spatial and temporal characterization of crustal magma storage. Key aspects related to mitigating volcanic hazards include identifying conditions and processes that trigger magmatic ascent, improving our ability to recognize and interpret real-time signs of magma ascent, and discriminating between the movement of magma versus aqueous fluids. From the geophysics side, seismology (passive and active, on-land and ocean-bottom), geodesy, and potential field and electromagnetic studies can provide information on the depth and geometry of magma storage zones at a variety of spatial scales, and they can also detect various aspects of temporal changes. Determination of regional and local stress fields, via focal mechanisms and shear wave splitting, will be valuable for monitoring temporal changes and evaluating the dynamical effects of regional tectonics (i.e., large earthquakes or aseismic slip) on magma reservoirs. Another key element is studies that would improve our ability to identify and understand the tell-tale signs of fluid and magma movement such as long-period and very-long-period earthquakes, volcanic tremor, and repetitive or "drum-beat" earthquakes. From the geochemistry side, petrologic, isotopic, and experimental studies of minerals within individual lavas and tephras can quantify crystal residence times and magma storage depths. Coupling these constraints with geophysical observations would provide unprecedented spatial characterization of magma storage in the crust. Moreover, geochemical investigation of a geochronologically constrained suite of lavas from an active arc volcano can constrain the long-term record of eruptive and crustal processes and provides an opportunity to quantify the timescales and kinetics of these processes.

We also identify the lower crust as a key area where we can hope to make some advances. One hazards-related issue is the basaltic magmas thought to trigger some eruptions through injection into a mid- or upper-crustal magma chamber, for example in the recent eruptions at Augustine and Redoubt volcanoes. Where are the sources of these magmas and what are the characteristics of these source zones? Can deep long-period earthquakes or detailed geochemical studies provide clues? It has recently been hypothesized that "deep crustal hot zones" (Annen et al., 2006) are the source of two distinct magma types, one from partial crystallization of basalt sills producing H₂O-rich melts, and the other from partial melting of pre-existing crustal rocks. Studies of young submarine volcanoes may have the potential for providing insight into the lower crust, combining active-source seismology, passive OBS studies, petrologic and geochemical analyses of drilling and dredging samples, etc.

The RAV initiative can be built upon a broad range of established research paradigms in geophysics, geochemistry, and geology. Perhaps as importantly, close collaboration among the scientists in these disciplines may lead to new avenues for exploring and understanding arc volcanoes and their roots.

References

**Figure 1.** Petrologic view of a generic subduction zone, indicating major processes governing subduction zone dynamics. Mineral labels represent the potential stability fields of volatile-bearing phases. The location of the partially molten region (pink zone) is constrained by seismic tomography (Iwamori and Zhao, 2000). From Poli and Schmidt (2002).

**Figure 2.** Seismic view of the Japan subduction zone. In this cross-section of shear wave velocity beneath northern Honshu at 39° N (Zhang et al., 2004), we see the dipping high-velocity subducting slab with two planes of seismicity. Note the significant heterogeneity in structure and seismicity within the slab, which are presumed to reflect the dehydration reactions that ultimately lead to arc volcanism. Above the slab on the left, low velocities in the mantle wedge (Vs < 4.3 km/s, 40-80 km depth) underlie the arc volcanoes, with the higher velocities of the "cold nose" (Vs > 4.3 km/s) evident between X = -40 and -10 km.