4. Subduction Cycles and Deformation

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

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

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

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

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

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

4.7 What are the critical feedbacks between surface processes and subduction zone mechanics and dynamics?

4.8 SCD in the Next Decade
4. Subduction Cycles and Deformation

Subducting margins are the loci of many of the most fundamental Earth processes, from the accretion of island arcs to their eventual modification into continental crust, and the fluxing of fluids and volatiles from the surface into the mantle and back through arc volcanoes. The largest earthquakes on Earth occur on subduction zone megathrusts, and their occurrence and magnitude are strongly influenced by material properties, metamorphic and geodynamic processes, and rheology of the crust and mantle. Many of these processes can be perceived as cyclic, for example, the seismic cycle, material cycling through the Earth, and even long-term tectonic cycles, e.g., the Wilson cycle. These processes are also critical to understanding the feedbacks between volcanism, long-term climate change, and the thermal evolution of the Earth’s interior. The research directions of the Subduction Cycles and Deformation (SCD) Initiative are closely linked to the overarching themes outlined in Section 3, and demonstrate the interconnectedness of surficial, crustal, and deep Earth processes and their roles in plate boundary deformation, megathrust seismicity, mantle rheology, magmatic processes, and elemental fluxes, particularly volatile and fluid-mobile elements, many of which are important for ore-formation.

The key questions that will be addressed within SCD include:

- What governs the size, location and frequency of great subduction zone earthquakes and how is this related to the spatial and temporal variation of slip behaviors observed along subduction faults?
- How does deformation across the subduction plate boundary evolve in space and time, through the seismic cycle and beyond?
- How do volatile release and transfer affect the rheology and dynamics of the plate interface, from the incoming plate and trench through to the arc and backarc?
- How are volatiles, fluids, and melts stored, transferred, and released through the subduction system?
- What are the geochemical products of subduction zones, from mantle geochemical reservoirs to the architecture of arc lithosphere, and how do these influence the formation of new continental crust?
- What are the physical and chemical conditions that control subduction zone initiation and the development of mature arc systems?
- What are the critical feedbacks between surface processes and subduction zone mechanics and dynamics?

The successful resolution of these questions will require strong interdisciplinary research teams, including experts in surface processes, structural geology and geodynamics, rheology, geochemistry and geophysics, who will examine the full subduction system from the trench to the sub-arc, arc, and back-arc regions. High resolution geodynamic models, incorporating complex rheologic and thermodynamic data, will provide important tests of data-driven hypotheses, providing an integrated understanding of the long-term mechanical, thermal, and chemical evolution of the Earth. These models, in turn, will guide the future collection of data to advance the frontier of subduction zone knowledge. This approach builds on the SEIZE and SubFac initiatives of MARGINS as envisioned by the Decadal Review Committee, but extends them in new directions that are driven by discoveries over the last decade.

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

Recent large damaging earthquakes, such as the 2004 Sumatra and 2010 Chile events, not only demonstrate the societal importance of understanding the subduction megathrust, but also provide unprecedented new datasets to understand fault behavior. In addition, many exciting discoveries in the last ten years have revealed that subduction zone
faults show a wide range of previously unknown fault slip behaviors and rates, from coseismic slip to silent earthquakes, slow slip events (SSE), episodic tremor and slip (ETS), low frequency earthquakes (LFE), and very low frequency earthquakes (VLF), in addition to “normal” fast-slip earthquakes. Although our community has made some progress in characterizing these phenomena, we do not know if these new observations represent a fundamentally new type of seismic moment release, or fall along a continuum between normal earthquakes to creep [e.g. Ide et al., 2007] (Figure 4.1). We also do not fully understand the underlying physical processes that give rise to these slip phenomena, in terms of intrinsic fault rock properties, fault architecture, and conditions (e.g., pore pressure, stress state, and temperature) on the fault interface, or how these other slip processes may influence great earthquake occurrence.

Figure 4.1. Highlights from observations of new slip processes made in the last decade. (A) Episodic tremor and slip observed over 7 years along the Cascadia margin shows correlation between the slow slip events observed in the geodetic record (upper) and timing of tremor activity during periods of slow slip [Rogers and Dragert, 2003]. (B) Time scale for ETS and slow earthquakes relative to “regular earthquakes” suggests a different scaling law and different behavior for these slip events with longer time constants [Ide et al., 2007]. (C) Moment release during May 2008 ETS episode with earthquake locations (1960-2008, pink and green circles near and away from subduction interface), showing that the tremor patches occur in areas without earthquakes [Ghosh et al., 2009].
A major focus of the Subduction Cycles and Deformation Initiative will be obtaining key observational and experimental constraints on faulting processes across the entire range of slip conditions and sampling these at various stages over the earthquake cycle. This effort will require a combination of: (1) new seismic, geodetic, and other geophysical field observations; (2) long-term observations of in situ mechanical, geochemical, thermal, and hydrologic conditions relevant to these slip processes; (3) theoretical and laboratory-based experimental approaches that link observations and the underlying physical mechanisms; and (4) integration of observations across multiple study sites to sample the full range of slip behaviors and/or stages in the seismic cycle (as discussed in Section 4.2).

What controls the magnitude and recurrence interval of earthquakes?

Large megathrust earthquakes, such as the recent 2010 Chile earthquake (Figure 4.2), capture the public’s attention like few other natural events. How and why do some subduction zones, such as Sumatra, Chile, and Cascadia, produce magnitude 9+ earthquakes whereas others such as Central Mariana are apparently limited to magnitudes <7 remains a major unanswered question of profound societal importance. Connections have been suggested between the occurrence and size of locked regions, and other subduction zone parameters, such as convergence rate [e.g. Ruff and Kanamori, 1980; Stein and Okal, 2007], incoming plate thermal structure and sediment content [e.g. Hyndman et al., 1997; Spinelli and Saffer, 2004, Lay and Bilek, 2007], upper plate structures [e.g., Wells et al., 2003; Collet et al., 2004; Brudzinski and Allen, 2007], hydration and weakening of the overriding forearc [Peacock and Hyndman, 1999; Hyndman and Peacock, 2003], and inhomogeneities such as subducting basement relief [e.g. Bilek, 2007; Bangs et al., 2006; Burgmann et al. 2005; McIntosh et al., 2007].

Although it has been widely held that both the updip and downdip limits of seismicity are controlled by temperature along the megathrust [e.g., Hyndman et al., 1997; Oleskevich et al., 1999] identifying the underlying processes in terms of fault material physical properties, composition, or state variables, such as pore pressure or effective stress, has proven elusive [e.g., Moore and Saffer, 2001]. Furthermore, at some margins, recent observations indicate significant along-strike variability in both the updip and downdip limits of interseismic locking, suggesting that the association of the updip and downdip limits of interseismic locking with particular temperature...
ranges is probably oversimplified [e.g., McCaffrey et al., 2008]. A second issue in correlating slip and locking behaviors with inferred fault conditions at depth is that considerable uncertainty remains in thermal and hydrologic models that are typically used to estimate temperatures and pore pressure. Quantifying these relationships will require seismic and geodetic studies to identify the locked sections of the faults combined with modeling studies to (1) define thermal and hydrologic state of the fault and (2) explore how variable fault zone conditions affect seismic rupture processes.

A significant new proposition in the last decade for understanding subduction zone seismogenesis, which needs to be verified by more observations, is that large earthquakes are correlated with large negative gravity anomalies and forearc basins [Song and Simons, 2003; Wells et al., 2003] and that maximum coseismic moment release tends to occur in local gravity minima, with slip decreasing along positive gravity gradients [Llenos and McGuire, 2007]. A theoretical understanding of the observed correlations is still in development – are the large earthquakes in some sense caused by the forearc basins [e.g., Fuller et al., 2006] or are these basins a consequence of the nature of plate coupling [e.g., Wells et al., 2003]? Are the correlations robust with respect to uncertainties in moment release distributions? Further progress will be enabled by detailed seismic and geodetic observations of large earthquakes and the geologic structure of forearc basins, as well as by theoretical models relating basins and earthquakes over many earthquake cycles.

What mechanical properties and/or fault zone conditions control the wide spectrum of slip rates observed on subduction megathrusts?

Recent observations from MARGINS and MARGINS-related studies have documented a wide spectrum of slip processes beyond simply aseismic creep and earthquake slip. These include tsunami earthquakes, very low frequency and slow slip events that occur in the outer forearc [Ito and Obara, 2006], episodic tremor and slip (ETS) and associated non-volcanic tremor activity (NVT) (Figure 4.1). A clearer picture of the physics controlling these processes and the conditions necessary for their occurrence will provide critical clues about the mechanics and moment release on subduction megathrusts, but our understanding of these phenomena is in its infancy. ETS, for example, has been observed in several subduction zones [e.g. Rogers and Dragert, 2003; Obara, 2002; Shelly et al., 2007], however, the fault zone conditions and intrinsic rock properties that are required to produce these events are not well understood. Tremor in particular has been observed in a wide variety of locations including both the downdip and updip limits of the subduction megathrust [e.g. Schwartz and Rokosky, 2007; Brown et al., 2009] and is proposed to be linked to the downdip edge of great earthquakes [Chapman and Melbourne, 2009]. The same is true for VLF events in the outer forearc, which may signal slip activity on major, potentially tsunamigenic, splay faults [e.g., Ito and Obara, 2006]. The effort to understand the connections between fault conditions and slip behavior will require additional seismic and geodetic observations of these signals, as well as laboratory and modeling efforts. Furthermore, many of the physical mechanisms that have been hypothesized to explain the occurrence of these phenomena involve linking fluid pressure variations with different frictional slip regimes [Wada et al., 2008; Liu and Rice, 2007; Peacock, 2009]. Thus a key component of the research in this area will involve investigating the interactions between subduction inputs (sediments and hydrothermally altered lithosphere), thermal structure, and metamorphism as described in Section 4.3.

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

Although the subduction megathrust is a dynamic and important component of the subduction zone (Section 4.1), it is not the only locus of deformation in the subduction system. For example, secondary faults in the upper and lower plates exhibit coseismic slip and may accommodate substantial interseismic
What is the time history of surface displacements throughout the seismic cycle, and what are the respective contributions from mantle flow, upper and lower plate deformation, and the plate boundary interface?

Geodetic observations of plate boundary displacements demonstrate that relative plate motions vary with location and time, even along a single subduction zone. To first order, these differences can be understood within the context of the earthquake cycle and the variable decay of post-seismic deformation with time depending on the specific earthquake history and the subsurface rheology of an area (Figure 4.3) [e.g., Wang, 2007]. In practice, it is not possible to document the full time evolution of the deformation cycle due to the long recurrence time between earthquakes at any given margin. However, global comparisons
of subducting margins at different stages in their seismic cycle offer the opportunity to construct a comprehensive picture of deformation throughout the entire cycle, and to relate these patterns to the responses of key components of the system – the megathrust fault, the oceanic and forearc crust, and the viscoelastic mantle. Although only a few such comparisons have been made to date [e.g., Savage and Thatcher, 1992; Cohen, 1996], the availability of inexpensive, but highly precise continuous geodetic instruments on land, and improvements in similar measurements offshore, now make if possible to fully constrain the patterns of deformation that accompany the full seismic cycle within a decadal time frame by working in several subduction zones simultaneously. Defining this framework will enable us to clarify the second order factors that govern the distribution and magnitudes of large earthquakes in these settings, including the spatial and temporal variations in strength and locking behavior of the megathrust fault, and the intracrustal deformation that may diffuse stress build up that drives fault slip.

As one example of the relevance of understanding plate boundary deformation throughout the seismic cycle, we note that discrepancies between observed geodetic displacements and predicted plate convergence rates have been interpreted to reflect partial locking of the plate interface during interseismic periods [e.g., Wang and Dixon, 2004; Norabuena et al., 2004, Burgmann et al., 2005; Chlieh et al., 2008] with implications for the potential size of megathrust earthquakes. In other settings, e.g., parts of Alaska [e.g. Fournier and Freymueller, 2007] and Sumatra [Chlieh et al., 2008], the plate boundary appears to be fully locked. The physical mechanisms behind this variability are still poorly defined. Is partial locking an indication of slow creep along the entire interface, at a rate slower than plate convergence, or is it a manifestation of a heterogeneous fault surface, parts of which are fully locked, and others fully creeping? How much interseismic strain is accommodated by faulting or folding within the forearc and how does it vary along and across strike, particularly in complexly faulted forearcs? Dense continuous geodetic data with broad spatial coverage over a range of convergent margins can offer critical observations to address these questions. The recent earthquakes in both Sumatra and Chile, and increasing attention applied to the Cascadia margin, make this a unique time to fulfill this objective, within the next decade of GeoPRISMS.

What is the role of secondary faulting in the upper and lower plates in accommodating strain accumulation and what are the potential earthquake and tsunami hazards from earthquakes on these faults?

At many subduction zones, numerous “secondary” faults both onshore and offshore, and in both the upper and lower plates, may slip coseismically and/or accommodate an appreciable fraction of plate motion. Understanding the roles and slip rates of these faults is crucial to understanding the associated hazards. For example, major splay faults in the upper plate (Figure 4.4) may rupture coseismically during great earthquakes, and by efficiently transferring slip to the seafloor, could generate large tsunami [e.g., Moore et al., 2007; Henstock et al., 2006]. Normal faulting in the subducting plate is thought to have generated the large tsunami that inundated Samoa in 2009 [Lay et al., 2009]. Oblique convergence at subducting margins is commonly manifest by significant slip partitioning within the forearc, accounting for large seismogenic strike-slip faults, e.g., Chile’s LOFZ and the Sumatra Fault. Complex forearc structures and kinematics both onshore and offshore, for example in Central America [e.g., LaFemina et al., 2002], Cascadia [e.g., Goldfinger et al., 1997; Pratt et al., 1997], Sumatra [Mosher et al., 2008], and the Aleutians [e.g., Ave Lallemant and Oldow, 2000], complicate the interpretations of strain accumulation and release on the megathrust fault [e.g., Collot et al., 2004; McCaffrey, 1992], and may also host slip triggered by megathrust earthquakes [e.g., Delouis et al., 1998]. Many of these structures cross the shoreline, and due to their proximity to populated areas, raise significant concern regarding seismic and tsunami hazards. Studies of these faults are important for developing a complete understanding of the long-term strain accumulation in the subduction system.
and seismogenesis on the megathrust. This can be accomplished through a combination of offshore seismic imaging and bathymetric surveys, onshore and offshore geodetic surveys, and geologic and paleoseismic studies.

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

Volatiles and melts play important roles in the dynamics of subduction systems from the shallowest levels of the plate interface to the greatest depths of arc melting source region (Figure 4.5). Numerous theoretical, experimental, and field campaigns over the last decade point to fundamental links between devolatilization, deformation, and fluid/melt transport. Several key questions have emerged from these studies: How does devolatilization affect the frictional properties and slip behavior of the shallow subduction interface where earthquakes occur, and does it modulate episodic tremor and slip? How do volatile release and serpentinization impact the rheology and the width of the slab-mantle wedge boundary? What are the relative importance of temperature, water content and melt content in controlling the viscosity of the mantle wedge? How does fluid move from the slab interface into the melting regime beneath arc volcanoes? A few selected examples of these exciting emerging questions are described below, followed by a description of evolving problems in linking slab volatile release to understanding geochemical fluxes in Section 4.4.

*How does volatile release from the subducting sediments and igneous ocean crust affect the slip behavior of the subduction megathrust?*

Fluids are known to affect the strength of faults in the brittle crust because they modulate the effective normal stress [e.g., *Hubbert and Rubey*, 1959]. However, only recently have fluids been recognized as potential controls on the nature of slip on faults. For example, at or near the down-dip edge of the seismogenic zone, where estimated temperatures are 350-450 °C, numerical models suggest that the occurrence of slow slip events (SSE) and non-volcanic tremor (NVT) may arise owing to extremely low effective stresses, and thus elevated pore pressure [e.g., *Liu and Rice*, 2007]. The location of these processes may also coincide with slab dehydration reactions [Wada *et al.*, 2008; Wada and Wang, 2009; Rondenay *et al.*, 2008; Abers *et al.*, 2009]. Near the trench, the low stress drops associated with very low frequency earthquakes (VLF) and SSE have also been attributed to elevated
frictional behavior as diagenetic and metamorphic reactions alter sediment in the subduction zone, spurring compositional changes and/or fluid release. Fluid production can modify pore pressures that in turn affect fault strength and sliding behavior [Moore and Saffer, 2001; Spinelli and Saffer, 2004]. Mechanical behavior and diagenetic reactions are also related to subduction zone thermal structure [Moore and Vrolijk, 1992; Spinelli and Wang, 2008]. Some observations and theoretical reasoning suggest that the updip and downdip limits of the fast earthquake slip region correspond to about 150° C and 350-450° C (or where the slab encounters the upper plate Moho), respectively [e.g. Hyndman and...
For example, geochemical signals of serpentine dehydration [Savov et al., 2007; Barnes and Sharp, 2006] may be observed in arc lavas [Eiler et al., 2005; Straub and Layne, 2003]. Although evidence for serpentinization of both the mantle wedge [e.g., Bostock et al., 2002] and the incoming oceanic plate upper mantle [e.g., Ranero et al., 2003] has been documented, the extent of alteration and its effects on the mechanics of the subduction system are poorly constrained. For example, does serpentinization of the incoming plate mantle significantly change its mechanical strength [e.g., Faccenda et al., 2009] and its subsequent dehydration control the location of some intermediate depth seismicity? Likewise, serpentinization of the mantle wedge above the subducting slab has been hypothesized to partially control the downdip limit of interplate seismicity [Hyndman et al. 1997]. By combining constraints from seismic imaging, seismicity studies, and modeling informed by new experimental results, our community can make significant advances in understanding the links between serpentinization and subduction dynamics.

**How does dehydration of the slab influence mantle wedge dynamics?**

The strength or viscosity of the slab-wedge interface controls coupling of displacement between the mantle wedge and the downgoing slab. Integrative studies demonstrate that the degree of coupling is a key factor for controlling the thermal structure of the slab at depth and the mantle wedge beneath the arc. To match observed heat flow and to explain a range of other geophysical and geochemical observations, the interface must be mechanically decoupled to depths significantly beyond the down-dip limit of seismicity [e.g., Wada et al., 2008; Wada and Wang, 2009]; fluids released through dehydration reactions may play a role in this phenomenon. However, the deformation processes and thermodynamic conditions that control the location of the “decoupled-coupled” transition are not understood. Another key aspect of subduction dynamics is the apparent requirement for a low viscosity mantle wedge [e.g., Billen and Gurnis, 2001]. Thus, the introduction of fluids into the wedge likely plays a key role, owing...
to the strong effect of water on the viscosity of the mantle. However, key questions remain regarding the path that fluids take from dehydration to melting [e.g., Cagnioncle et al., 2007]. How distributed is the fluid flow? Do fluids migrate along fractures? Are fluids advected via buoyant diapirs along the slab interface [e.g., Gerya and Yuan, 2003]? How is the change in water content during melting reflected in melt composition and recorded in melt inclusions? Multidisciplinary investigations of these problems will be significantly improved by new advancements in our understanding of the role of water on the seismic properties of the mantle [e.g., Karato, 2003; Karato et al., 2008] and geochemical constraints on the conditions of dehydration of the slab and hydrous melting in the wedge.

What physical processes are associated with intermediate and deep earthquakes?

Fault slip that occurs under high pressures corresponding to depths greater than ~70 km (i.e., where normal stresses should prohibit fault movement) have puzzled seismologists for decades. Based on constraints from deformation experiments, metamorphic phase equilibrium and thermal models of subduction zones, intermediate depth earthquakes (70-300 km depth) are related to dehydration reactions in the subducting slab [e.g., Kirby et al., 1996; Hacker et al., 2003; Abers et al., 2006]. However, the mechanical process of dehydration embrittlement and the widespread applicability of this model is still uncertain due to uncertainties in the feedbacks between reaction rate, permeability and the evolution of pore-fluid pressure [e.g., Wong et al., 1997; Rutter et al., 2009]. Alternatively, these earthquakes may arise owing to the viscous instabilities that nucleate within locally weak layers resulting from variations in temperature or grain size (which may actually be produced by dehydration reactions) [Kelemen and Hirth, 2007; John et al., 2009]. Resolution between these possibilities awaits new observational and theoretical constraints on the thermal and hydration state of the slab, the kinetics of dehydration reactions [e.g., Rutter et al., 2009; Perrillat et al., 2005] and their roles on the mechanics of faulting.

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

The efficiency of mass cycling through subduction zones is controlled by the composition of the subducting lithologies and the processes by which volatiles are released from the subducting slab and

Figure 4.6. Modeled CO₂ and H₂O fluxes from the top of the subducting slab for Central America, assuming pervasive fluid flow [Gorman et al., 2006]. Note that the predicted CO₂ flux from the fore-arc region is significantly higher than the flux from the sub-arc region.
transferred to the surface. Significant progress has been made over the last decade in quantifying sediment and crustal inputs at various subduction zones [e.g., Plank and Langmuir, 1998; Kelley et al., 2003; Sadofsky and Bebout, 2004; Plank et al., 2007], the extent of devolatilization during subduction [e.g., Hacker, 2008; Shaw et al., 2008], the geochemical, petrologic, and dynamic relationships between slab volatile fluxes and generation of magmas in the mantle wedge [e.g., Grove et al. 2006; Kelley et al. 2006, Cagnioncle et al. 2008], and the volcanic outputs of arcs [e.g., Hilton et al., 2002; Fischer et al., 2002; Shaw et al., 2003; Gorman et al., 2006] (Figure 4.6). These advances have raised a number of fundamental new questions about subduction volatile fluxes and cycling.

**What is the role of serpentine in subduction and release of H\textsubscript{2}O?**

Recent work has suggested that serpentine may be a major carrier of volatiles and other trace elements into the subduction system [e.g., Ranero et al., 2003]. Serpentine can hold up to ~14 wt% H\textsubscript{2}O [O’Hanley, 1996] - a factor of ~3 more than crustal and sedimentary lithologies [Hacker, 2008]. This has led to the recognition that serpentine dehydration may play a major role in mass transfer and arc magmatism. Serpentization reactions also lead to carbonation of the downgoing plate and thus have the potential to influence the carbon budget of subduction zones. However, the extent of serpentization of the incoming plate is largely unquantified. Likewise, the concentration of several major volatile components (e.g., C, S, F, Cl) in subducting mantle remain poorly characterized. Quantifying these inputs through geochemical analyses of drill cores on the incoming plate or studies of ancient lithospheric sections, or by seismological or other geophysical imaging, such as MT, is essential toward assessing volatile budgets through the subduction system.

Some of the subducted serpentine contributes to the flux of volatiles that returns to the surface through island arcs, but some may convert to high pressure hydrous phases, delivering H\textsubscript{2}O to the deeper mantle [Ohtani et al. 2002; Rupke et al. 2004]. The fate of H\textsubscript{2}O subducted in serpentine is therefore critical to the operation of the deep Earth H\textsubscript{2}O cycle. Along with considerations of the proportion of subducted serpentine and its depth in the subducting plate, key considerations in evaluating the fate of subducted serpentine include improved understanding of temperature-depth trajectories of subducting slabs, experimental studies of phase equilibria and kinetics associated with dehydration reactions in subducting peridotite, seismic and other geophysical detection of the extent of hydration in subducting plates, and geochemical studies of tracers of serpentine in arc magmas, such as B and other light elements.

**What is the relationship between dehydration reactions and the release of fluids and/or melts from the slab?**

A range of techniques has been exploited to quantify the output flux of volatiles from subduction systems. These include remote sensing techniques to quantify present-day gas fluxes from some arc volcanoes (those with sufficiently large gas plumes), geochemical gas studies that have provided new insights into the sources of volatiles [e.g., Snyder et al., 2001; Hilton et al., 2002; Fischer et al., 2002; Shaw et al., 2003; Hilton et al., 2007], and new micro-analytical tools such as SIMS that allow the direct analysis of melt inclusions to constrain volatile compositions in relatively primitive melts [e.g., Benjamin et al., 2007; Shaw et al., 2008; Sadofsky et al., 2008] and clinopyroxene to infer volatile contents indirectly [Wade et al., 2008]. Comparison of water contents in olivine-hosted melt inclusions from Central America to slab fluid proxies such as Ba/La and B/La shows relatively good agreement and thus yields insight into fluid release processes [Sadofsky et al., 2008] (Figure 4.7). Likewise, through studies of the isotopic composition of subduction-related water trapped in melt inclusions, we have learned further details of slab dehydration and how water is exchanged between the mantle and its exospheric reservoirs over time [Shaw et al., 2008] (Figure 4.8). Significant progress has been made in understanding the role that water plays in...
generating arc and back arc melts and linking these melts to geophysical observables [e.g., Wade et al., 2006; Wiens et al., 2006; Benjamin et al., 2007; Shaw et al., 2008; Sadofsky et al., 2008]. However, calculating volatile fluxes has been hindered by our inability to reliably estimate magma production rates at individual arcs. New research opportunities include: (1) integrating melt inclusion studies with better estimates of arc magma production rates, (2) estimating volatile fluxes in forearc and back arc regions, (3) determining fluxes of volatile species that have not been previously quantified (e.g., S, F, Cl, etc.) in a range of subducting settings, and (4) linking volcanic fluxes to climate models.

**What are the melting reactions and loci and melt pathways from the mantle wedge to the surface?**

The processes and pathways by which volatiles are released from the downgoing slab, and the extent to which they contribute to melting, are important new avenues for future study. Evidence for high temperatures at the slab-wedge interface from both geodynamic simulations [van Keken, 2003; Kelemen et al., 2003; Syracuse et al., 2010] and novel slab-top thermometers applied to arc lavas [Plank et al., 2009] suggest that slab-derived fluxes are melts or silicate-rich fluids. Yet, melting reactions for slab-top lithologies and the compositions and properties of the fluids produced are incompletely known. New measurements of Fe$^{3+}$/Fe$^{2+}$ ratios...
in arc magmas indicate that upward migration of slab-derived fluids promotes relatively oxidizing conditions in the mantle wedge [Kelley and Cottrell, 2009], although alternative tracers of mantle wedge oxidation state, such as V/Sc ratios of arc magmas [Lee et al. 2005] yield conflicting conclusions. The effect of subduction fluids on wedge oxidation state therefore requires further investigation. New experiments are needed to constrain the petrologic and geochemical character of fluids and melts in equilibrium with appropriate lithologies over a range of oxidation conditions. Coupled with sophisticated models incorporating reaction kinetics, multiphase flow, and re-hydration of the overlying mantle, such work will fully characterize mass transport from the slab to the overlying mantle wedge.

Studies of arc and back arc lavas show that the proportion of melting of the wedge is a complex function of slab-derived H₂O, temperature, and pressure of melting, but that individual arcs have distinct, nearly-linear relationships between extents of melting and proportions of water in the wedge sources. These relationships have have been interpreted either as fluid addition to a nearly isothermal mantle or as mixing between two distinct melting regimes within the wedge [e.g., Stolper and Newman, 1994; Gribble et al. 1998; Kelley et al., 2006; Langmuir et al., 2006] (Figure 4.9). Increasingly realistic 2-D dynamic models of melt generation in the mantle wedge now incorporate inputs from the slab, as well as solid and melt transport [Cagnioncle et al. 2007] (Figure 4.10). However, the locus of melting in the mantle wedge remains highly uncertain and the models do not yet reproduce the linear H₂O-melt fraction trends or resolve their origin. New experiments [Grove et al., 2006] locate the H₂O-saturated peridotite solidus near 840°C, expanding considerably the area of the mantle wedge where partial melting is permissible, and suggesting that melting could initiate through breakdown of hydrous minerals such as chlorite. Melting reactions and mechanisms thus remain incompletely understood, opening new avenues

Figure 4.9. Melt fraction vs. H₂O content of the mantle source beneath the Mariana and Manus back-arc basins, modeled from erupted melt compositions [from Kelley et al., 2006]. The slope of each trend, which is an indicator of the productivity of hydrous melting, coincides with a contrast in mantle potential temperature, suggesting that the differing P-T conditions of melting beneath each basin relates to melt productivity.

Figure 4.10. Geodynamic model of melting in the mantle wedge from Cagnioncle et al. [2007], demonstrating the interaction between fluid release from the slab, the temperatures and flow in the mantle wedge, and the production and segregation of partial melt.
Once magma ascends into the lithosphere, crystallization and differentiation creates feedbacks between thermal and rheological evolution, leading to variable amounts of sequestration in the crust and influencing the dynamics of melt transport, storage, and eruption. Seismic, geodetic, and potential field studies of arc volcanoes, including monitoring volcanic tremor and low frequency seismicity [e.g., Konstantinou and Schlindwein, 2003] and satellite-based observations of volcano inflation [e.g., Pritchard and Simons, 2002; Hooper et al., 2004], provide new opportunities to document location and movement of magma from the base of the lithosphere to sub-volcanic conduits. Integrating these with studies of erupted volcanic rocks, crystals, and melt inclusions to determine storage depths, volatile contents, and residence times of volcanic products may provide exciting opportunities for new cross-disciplinary understanding of the transport and storage of magma in the crust and shallow mantle.

Melt in the mantle beneath volcanic centers can be imaged seismically using Vp/Vs tomography [Syracuse et al. 2008] and it is clear that partially molten zones beneath volcanic centers extend through the mantle to the slab/wedge interface (Figure 4.11). Coupling of geophysical detection with petrologic documentation of the depths of formation and segregation of mantle-derived arc magmas from phase equilibria experiments [e.g., Grove et al. 2002] or using new petrologic geobarometers [Lee et al. 2009] will provide new constraints on the depths of origin of arc magmas. Dynamic models combined with petrologic and experimental investigations are also needed to better understand the parameters that determine the plutonic versus volcanic fates of arc magmas.

Figure 4.11. Seismic images of the mantle wedge in subduction zones, from MARGINS studies. (left) Vp/Vs tomography beneath Central America, imaging regions of melt beneath volcanic centers all the way down to the slab/wedge interface [Syracuse et al. 2008]. (right) Spatially averaged shear-wave splitting indicating anisotropy beneath the Central Mariana arc [Pozgay et al., 2007].
What are the fluxes of volatiles delivered to the mantle from the subducting slab and how are fluids and melts focused to the volcanic front?

Improved (although by no means complete) understanding of fluid release from the subducting slab to the overlying wedge [Hacker, 2008] demonstrates that fluxing components are added to the wedge over a range of depths and that these are not necessarily located directly below the volcanic front. Concentration of melt beneath volcanoes therefore requires significant melt focusing. Although it is clear that such focusing responds largely to the spatial distribution of fluid sources and the pressure and permeability fields, there is at present no robust predictive model that can be compared to observed volcanic outputs. Furthermore, understanding the pathways of melt ascent in the mantle wedge—in particular the 3-D and 4-D aspects—remains a challenging problem in mesoscale physics, as it requires dynamical models of interactions between solid and fluid flow in the wedge, as well as experimental and theoretical models of the influence of deformation on wedge permeability [e.g., Holtzman et al., 2003].

On a longer time scale, delivery of volatile-rich sediments to oceanic trenches followed by subduction may be an important contributor to the flux of subducting volatiles. Consequently, the formation, transport, storage, and ultimately the delivery of sediments from the upper reaches of volcanic terranes to forearcs to trenches have direct influence on the subducting volatile fluxes. Quantifying the volumes and rates of material transfer, and mapping them through space and time in different settings, will clarify the magnitudes of such fluxes for mass balance calculations. This will require not only better inventories of subducted and volcanic volatile fluxes, but also improved accounting for subduction devolatilization in forearcs and its relationship to volatiles vented to the oceans and surface via submarine and terrestrial hydrologic systems [e.g., Füri et al., 2010].

How do surface processes and climate modulate volatile inputs and outputs at subducting margins, and vice versa?

The surfaces of island and continental arcs are dynamic regions in which significant, but poorly quantified, mass transfer occurs. Arcs represent the largest fraction of juvenile volcanic exposures on Earth and, in particular, the largest proportion of such terranes in tropical and sub-tropical regions. Weathering of these terranes is of substantial importance to terrestrial weathering processes [Allegre et al., 2010], including those leading to fixing of atmospheric CO$_2$. The storage of CO$_2$ in weathered arc terranes, as well as its transport to the ocean via riverine fluxes, is as yet poorly quantified, as is the influence of climate on these processes.

Other surface processes including erosion and glaciation/deglaciation on central volcanoes may also have significant influence on volcanic outputs owing to decompression/compression of underlying mantle and/or of magma chambers, and these in turn may influence arc volatile fluxes and therefore climate. For example, Huybers and Langmuir [2009] showed a temporal correlation between arc volcanic eruptions and the end of the last glacial cycle and argued that enhanced volcanic output from deglaciation of arc stratovolcanoes was a significant source of atmospheric CO$_2$, an important feedback to the climatic shifts at glacial/interglacial transitions. Further quantification of the flux of CO$_2$ from arc volcanoes, improved chronometry of volcanic eruptions, and modeling of the feedbacks between deglaciation, eruption dynamics, and climatic effects are needed to explore this intriguing hypothesis.

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

A principal focus of the MARGINS program was the functioning of the Subduction Factory, which aimed to examine how materials processed in subduction zones contributed to the ongoing large-scale geochemical differentiation of the Earth,
including fluxes to the deeper mantle and formation of the continental crust. Improved understanding of the workings of the Subduction Factory was one of the principal achievements of the MARGINS program, but significant questions remain.

**What are the geochemical characteristics of the materials that subduction returns to the Earth’s mantle, and how are these related to the development of long-term mantle heterogeneity?**

Subduction zones create a range of petrological products in the mantle, including multiple residual lithologies (metasediments, metabasalt, metaperidotite) in the subducted plate, depleted and metasomatized peridotite in the mantle wedge, and potentially, an ultramafic lower arc crust that may descend into the Earth’s mantle but be geochemically distinct from it. The contributions of these lithologies to mantle geochemical evolution remains unclear. Following long residence times in the mantle, some of these lithologies may evolve into mantle isotopic heterogeneities that are detected at modern ocean island volcanoes [e.g., Hoffman and White, 1982]. Although coarse linkages can be drawn between isotopic signatures and hypothesized residues of subduction [e.g., Jackson et al., 2007; Workman et al., 2008; Weaver, 1991] (Figure 4.12), the elemental fractionations required to generate the oceanic island sources are potentially attributable to subduction processes, but are largely unconstrained and untested against actual geochemical characterizations of subduction zone mass transfer processes. Recent models show that subduction processes may be sufficient to explain certain mantle end-members [e.g., HIMU; Kelley et al., 2005], but significant uncertainties remain. Advancement of our understanding of the role of subduction in creating long-term mantle heterogeneity requires improved element budgets of altered gabbro and lithospheric mantle in the subducting plate, accurate constraints on arc crustal growth rates, high-precision geochemical analyses of arc volcanic and plutonic rocks, and petrological/geochemical studies of exhumed sections of subducted slabs, mantle wedges, and lower arc crust. These data will provide essential constraints on the magnitudes of elemental fluxes through subduction zones, and the critical geochemical fractionations that take place during subduction, in order to construct accurate mass balances that allow the long-term imprint of subducted residues to be quantitatively assessed.

**What are the rates and processes of arc crust growth and differentiation and how is arc crust transformed to continental crust?**

The formation and differentiation of arc crust is one of the central geochemical fluxes on Earth, but
the dynamic and petrologic evolution of magma in the crust promotes or inhibits magma eruption versus in situ crystallization. Along with growth of arc crust, a complementary set of problems pertains to the rates and processes of differentiation of arc crust and creation of juvenile continental crust. The continental crust shares many geochemical signatures with arc lavas, and the two have long been thought to be genetically linked. Yet the continents are andesitic in composition (~60 wt.% SiO$_2$) whereas the primary mantle-derived magmas at most mature subduction zones are basalts (~50 wt.% SiO$_2$). Intracrustal differentiation takes place over a range of spatial and temporal scales, from the local evolution of individual magmatic centers to large-scale development of distinct compositions of upper, middle, and lower continental crust. Intracrustal differentiation processes in arcs can create silicic or intermediate mid-crust, such as that documented in the rates at which arc crust forms and at which it matures towards continental crust remain poorly known. Studies of the growth of volcanic edifices may be insufficient to characterize the rates of arc growth, as significant outputs take the form of tephra deposited far from volcanic sources [Kutterolf et al. 2008] (Figure 4.13) or large portions of arc magmas that do not erupt, but cool and crystallize as plutons. As arc crust differentiates and matures, some fraction is thought to transform to juvenile continental crust, although the rates and processes of this transformation in modern arcs are poorly understood. Exhumed sections of arc crust show that significant fractions of arc magmas crystallize as plutons rather than erupting as volcanic products [Bard et al., 1980; DeBari and Coleman, 1989]. Some portions of arc plutonic rocks represent cumulates from differentiated magmas that ultimately erupt, and with estimates of the extent of differentiation, cumulate masses may potentially be computed from compositions and volumes of volcanic rocks [e.g., Kutterolf et al. 2008] (Figure 4.13) or from comparisons between growth rates of volcanic edifices and tracers of subduction fluxes such as SO$_2$ [Sadofsky et al. 2008]. Not all arc plutons are dominated by cumulates, however, and the magmas that solidify within arc crust may be a substantial fraction of juvenile arc crust. Estimates of the growth rates of plutonic arc crust, therefore, must be approached either from field-based observations of sections of exhumed arc crust, including geochemical characterization and geochronometry, or from a combination of geophysical, geochemical, and geochronologic studies of active arcs. The former depends in part on developments in high precision geochronometry, chiefly from accessory minerals such as zircon. The latter may include seismic documentation of the volumes of arc crust of known age, or more focused geophysical and geochemical efforts to characterize the deep magmatic roots of modern volcanic systems as described in Section 4.4. A critical parameter to be sought is the ratio of erupted versus plutonic crustal material and constraints on how this ratio varies in different arc settings, which requires an understanding of how

![Figure 4.13. Average magmatic flux over the last 200 kyr at Central American volcanic centers as reconstructed from combining geologic mapping of exposed volcanic edifices with the offshore tephra record, with corrections for the proportion of cumulates required to account for the compositional differentiation evident in the volcanic compositions [Kutterolf et al. 2008].](image-url)
the Izu-Bonin arc [Suyehiro et al., 1996; Koidaira et al. 2007] (Figure 4.14) and those evident from exposed crustal sections [Bard et al., 1980; DeBari and Coleman, 1989]. Intracrustal differentiation, however, cannot be solely responsible for formation of juvenile continental crust, and intermediate compositions are not seismically indicated at all modern arcs (e.g., the Aleutians [Shillington et al., 2004]). Many recent hypotheses attempt to explain continental compositions by invoking, for example, unique primary melts [e.g., Kelemen et al., 2003], co-evolving geophysical properties and petrological architecture of arc crust [e.g., Tatsumi et al., 2008], removal of ultramafic lower crust [e.g., Rudnick and Fountain, 1995], or geochemical evolution associated with surface processes such as weathering (as discussed below) to create continental crust from the magmatic products of subduction zones. Although there are models that can account for the return of cumulates to the mantle [e.g., Jull and Kelemen 2001], better petrologic and geophysical tools are required to document their formation and their impact on magmatic and crustal differentiation and on the structure of the Moho beneath arcs. Understanding creation of continental crust in arcs also requires careful trace element and isotopic discrimination between true juvenile components and those recycled from subducted sediments [Plank, 2005]. Moreover, although recent models offer a broad spectrum of hypotheses to explain the physical and petrological processes that may produce continental crust in arc settings, these remain largely untested against petrological, geochemical, and geochronological data of direct samples of exhumed or in situ arc crust, experimental/natural constraints on the petrological evolution of volatile-rich arc magmas in general or at individual volcanoes, or high-resolution investigations of the geophysical properties of mature arc crust.

Figure 4.14. (A) Along-strike seismic velocity structure of arc crust in the Izu-Bonin arc [Kodaira et al., 2007], showing finely-resolved variations in crustal thickness. (B) The composition of lavas erupted at Izu-Bonin frontal arc volcanoes correlates with (C) the thickness of the low-velocity (Vp=6.0-6.5) middle crust beneath each volcanic center.
How does the initial tectonic state control the initiation and subsequent evolution of subduction, and how do plate kinematics, deformation, and petrology change before, during, and after initiation of subduction?

The cold thermal structure and the formation of dense eclogite in the descending lithosphere may be primary drivers of plate motions, but these are counter-balanced by the strength of the bending oceanic plate, which could be the locus of the primary resisting force to plate tectonics [Buffett and Rowley, 2006]. The driving force behind the earliest inception stages of new subduction zones, whether by far-field forces or in situ with local forces (Figure 4.15), is unknown [Gurnis et al., 2004; Stern, 2004]. Indeed, whether the Eocene change in Pacific plate motion either caused or was caused by initiation of IBM and Tonga-Kermadec subduction zones is one of the most outstanding unsolved problems in plate tectonics. The question of how and why subduction initiates and then evolves into an arc involves substantial geophysical and petrological unknowns. These questions can only be answered through comparative studies between subduction zones at different phases of development (precursory to nascent through to fully developed). Such integrated studies will involve the interpretation of the petrological, structural, and stratigraphic history in terms of experimental and computational constraints on mineral equilibria and metamorphic phase transitions, plate motions, and dynamic modeling. Numerical models will play a key role in linking far-field plate dynamics and the initial tectonic state of a margin to the expected structural, stratigraphic, and petrological signatures in time and space. Already, dynamic models predict different vertical motion and volcanic histories for the far-field and in-situ nucleation hypotheses (Figure 4.15).

How do the early products of island arc magmatism relate to the dynamics and conditions of subduction initiation?

The fore-arc basalts (FABs) and boninites that characterize the earliest lavas erupted at subduction...
zones are also fundamentally different from the arc tholeiites, calc-alkaline basalts, and more silicic lavas that typify volcanism at most modern subduction zones. The first magmatic products of subduction are likely to be FABs (Figure 4.16; [Reagan et al., 2010]), which are chemically similar to mid-ocean ridge basalts and require decompression-driven melting of the mantle during the early stages of subduction. Following the FABs, boninites are hydrous melts of highly depleted mantle, which require a H$_2$O flux from the subducted plate. These early magmas are the products of unique mantle melting processes that occur predominately during subduction zone infancy [e.g., Crawford et al., 1989; Stern and Bloomer, 1992; Reagan et al., 2010], yet the relationship of these distinctive magmas to the physical state of the mantle and slab as subduction begins is unknown. Stratigraphic sequences of early arc lavas preserve the age progression of these key magmatic transitions, thus petrological, geochemical, and geochronological studies of early arc lavas will provide important data for constraining the magmatic evolution during the early stages of subduction. Such data will also place important constraints on the presence and timing of physical processes active in the mantle wedge through the early stages of subduction (e.g., decompression-driven melting and the timing of the appearance of slab-derived fluxes in the mantle wedge). The relationships between the initiation of subduction, the onset of magmatism, and the very early co-evolution of subduction zone structure and magma composition are also central to constraining the origins and early architecture of arc crust.

Figure 4.15. Dynamic model of initiation of a subduction zone at a pre-existing fracture zone that separates 10 Ma lithosphere from 40 Ma at four instants in time (with stress shown in the left column and temperature in the right). The new subduction zone is driven by a combination of convergence perpendicular to strike of the fracture zone and the buoyancy differences. The initial driving forces must first overcome substantial elastic bending before sufficient buoyancy exists beneath the plate to remain self-sustaining. The model predicts a distinct phase of rapid uplift of the margin before subsidence and subsequent rapid back-arc opening. (From Gurnis et al., [2004]).
What controls the rate of subduction and the 3-D structure and geometry of a subduction zone over time, and how are these related to magmatism at the surface?

To what extent an initially descending, forced slab affects the physical properties of the juvenile mantle wedge, how the initial melting and volatile release affect the properties of the plate (strength and buoyancy), and how these factors relate to volcanic expressions at the surface are entirely unknown. Dynamic models show that the rates of subduction and slab dip are controlled not only by the age of the incoming plate but also by the duration of subduction and the characteristics of the mantle wedge [Manea and Gurnis, 2007; Billen, 2008]. Moreover, volatile release from the slab changes the physical properties of the mantle wedge, such as effective viscosity, which also affects slab dip angle [e.g., Manea and Gurnis, 2007]. The rate of plate motion and subduction are potentially controlled by the strength of the bending plate [Buffett and Rowley, 2006], which may be governed not only by the initiation and growth of normal faults in the trench but also by the serpentinization of the mantle lithosphere. The recent correlation of mantle lithosphere seismic velocities with normal faulting on the outer rise [e.g., Ivandic et al., 2008] opens up new opportunities to determine the role of serpentinization in controlling the strength of the plate when combined with other geophysical observations. Seismic observations also suggest a significant component of 3-D, along-strike mantle wedge flow at many modern subduction zones [e.g., Russo and Silver, 1994; Fouch and Fischer, 1998; Pozgay et al., 2007; Hoernle et al., 2008; Long and Silver, 2009], yet most current models of subduction are 2-D. The structure and geometry of subduction zones in 3-D through time, may result from an intimate balance between volatile fluxing, melting in the wedge, and larger-scale geodynamic forces. Studies of the volatile and magmatic output of the arc in time and space augmented with constraints on the mechanical properties of the incoming lithosphere will prove essential in deconvolving the specific roles of each of these factors. Future dynamical models will need to be 3-D, incorporate melting and melt migration in a thermodynamically self-consistent way, and allow the plates to dynamically interact, and geophysical studies will provide 3-D snapshots of the structure and flow vectors of modern subduction zones that can be tested against dynamical models (e.g., Figure 4.11b).

**Figure 4.16.** Schematic cross-section of volcanic stratigraphy in the Mariana fore-arc, showing the age progression of lava types from FAB to transitional lavas, to boninites (compiled by Reagan et al. [2010]).
What controls the distribution of volcanoes in space and time?

Recent studies examining the positioning of arc volcanoes above subducting plates suggest that volcano location may be related to the slab dip and descent rate [e.g., England et al., 2004; Syracuse and Abers, 2006], but may also relate to the thermal structure of the mantle wedge [e.g., Schmidt and Poli, 1998; Grove et al., 2009] and extensional forces in the overriding plate [e.g., Alaniz-Alvarez et al., 1998]. Volcanic centers might not be permanent features of arcs, but may be replaced by newer centers elsewhere along the arc as subduction and arc kinematics evolve [e.g., Honda et al., 2007]. Understanding the distribution of volcanic centers along arcs in space and time requires improved understanding of the 3-D and 4-D dynamics of subduction and the overlying plate at scales ranging from entire arcs to single volcanoes, and to volatile and melt pathways in the mantle wedge. Geophysical imaging of “hot fingers” in the mantle beneath Japan [Tamura et al., 2002] shows that magma may be concentrated beneath major volcanic centers, and seismic studies of the crust in Izu-Bonin reveal significant along-strike variations in crustal structure that correlate with volcanic expressions at the surface (Figure 4.14) [Kodaira et al., 2007], suggesting that the roots of volcanic centers remain stationary. Similar features have not yet been identified in other arcs, although recent studies suggest that significant focusing to volcanic centers may also occur in the crust [Karlstrom et al., 2009]. Achieving a 4-D perspective on the evolution of melt focusing beneath volcanic arcs requires combining geodynamic modeling of the interactions between solid and fluid flow in mantle wedges with high-resolution geophysical documentation of the deep crustal and mantle roots of whole arcs and individual volcanic centers and geochemical and petrologic constraints on the depths and temperatures of primitive magmas.

4.7. What are the critical feedbacks between surface processes and subduction zone mechanics and dynamics?

The dynamics and resulting structural evolution of convergent margins is governed by the balance between tectonic and magmatic processes that build up the margin, and erosive and sediment dispersal processes that tear it down. The resulting distributions of sediments of different types also influence the distributions, geometries, and mechanisms of deformation and fault slip across the boundary, which in turn influence rates of uplift.
and exhumation. Clarifying the interplay between surficial and deep-seated processes at subducting margins is fundamental to understanding the long-term evolution of plate boundaries, and interpreting ancient analogs. This approach follows the recommendation by the DRC to explicitly incorporate surface processes in the subduction studies. The key questions include:

**How do erosion, sediment transfer, and deposition interact with deformation and subduction geometry during plate boundary evolution?**

Field studies of active [e.g., Koons, 1990, 1994] and ancient [e.g., Hoffman and Grotzinger, 1993] mountain ranges reveal how orographic precipitation and consequent erosion impact the distribution of deformation in mountain belts. These processes can now be understood in the context of critical Coulomb wedge theory [Davis et al., 1983; Dahlen et al., 1990; Beaumont et al., 1992; Willett, 1999]: forearc erosion and recycling back into the trench favors frontal accretion and uplift, whereas retroarc erosion enhances the exhumation of deep crustal material. Sediment deposition also influences the dynamic behavior of a margin. The addition of sediments above or in front of an active thrust belt restricts the initiation of new frontal thrusts in an attempt to balance the critical stresses [Storti and McClay, 1995; Simpson, 2006; Berger et al., 2008].

Most of these models have assumed steady-state conditions in 2-D. However, the Earth is 3-D and subject to variable conditions over time and space, which impact the evolution of convergent margins. We are only just beginning to understand this behavior. For example, climatic variations influence erosion rates through time, which can control the width of mountain belts [McQuarrie et al., 2008] and limit the convergence rate between plates [Meade and Conrad, 2008]. Complex 3-D landforms result from the formation and evolution of drainage systems and glaciation, which are themselves driven by tectonic uplift [e.g., Whipple, 2004; Tomkin and Roe, 2007; Egholm et al., 2009]. The time dependent evolution of these landforms significantly affects both local and regional stress conditions and resultant deformation patterns. Integrated onshore and offshore studies are necessary to more fully clarify these relationships, and to relate landform evolution, 3-D sediment dispersal patterns and accumulations within the stratigraphic record, and uplift and erosion rates within the forearc, arc, and back-arc regions. Comparative studies at contrasting margins will be needed to discern the relative importance of climatic and tectonic factors under different conditions.

**How do sediment dispersal patterns influence forearc evolution?**

In the offshore region, depositional processes impact the dynamics of the accretionary prism and the underlying megathrust fault. The thickness, texture, composition, facies distribution, and rate of sediments entering trenches are highly variable, which results in a heterogeneous distribution of strata that are accreted or underplated (Figure 4.17). This configuration impacts pore fluid pressure, stress state, wedge geometry, and the strength of the plate boundary fault [Morley, 2007; Underwood, 2007]. As a result, the form of accretionary prisms may be controlled in 4-D by the heterogeneous properties of sediment input [Saffer and Bekins, 2002]. To understand this heterogeneity, we must understand how surface processes and accommodation space interact to form stratigraphy in convergent settings. For example: (1) What defines the size, spacing, and location of submarine canyons, and how does this impact the distribution of sediment types? (2) Do canyons debouch in mid-slope forearc basins or continue to the base of slope? (3) Are sandy trench-wedge facies spatially restricted to channel-levee complexes or evolve into broad sheet-flow systems? (4) How does sedimentation interact with basement topography? The evolution of forearc basins and smaller trench slope basins may also be intimately coupled to the initiation of slip and subsequent uplift history along imbricate thrusts and major out-of-sequence thrust faults (e.g., megasplays) within the accretionary prism [Underwood et al., 2003; Strasser et al., 2009; Simpson, 2010]. In turn, the thickness of sediment in a forearc basin, itself driven
by surface processes, may control the degree of mechanical coupling between the upper and lower plate and hence the magnitude of subduction zone earthquakes [Fuller et al., 2006; Wells et al., 2003]. Detailed 3-D seismic data combined with direct sampling and in-situ measurement (e.g., through coring and logging) will be necessary to map out the stratigraphic and structural packages that control this system, while coupled 3-D numerical models can test these dynamic feedbacks.

4.8. SCD in the Next Decade

The Subduction Cycles and Deformation Initiative is poised to make rapid progress on the questions outlined above, by building on the successes of both the SEIZE and SubFac Initiatives, capitalizing on the realized connections between the two original initiatives, and entraining new participation from other communities to examine the role of surface processes and sedimentation at subducting margins. The integration of communities will promote strong collaborative investigations of both shallow and deep controls on plate boundary deformation and megathrust seismogenesis, and the role of sediments, fluids, and volatiles in mass transfer, fault processes, and crustal growth. Substantial data already have been collected at the three main focus sites for the two initiatives: Nankai, Central America, and Izu-Bonin Marianas. As noted in Section 6.1, future research will probably take place in different locations, either newly defined focus sites (i.e., primary sites) or a broader array of sites selected for comparative studies. Joint EarthScope-MARGINS deployments of seismometers and GPS stations at Cascadia, and the migration of the USAArray Transportable Array to Alaska in 2014, define clear opportunities for more focused studies (Section 6.3). The quality and volume of observations at the current MARGINS focus sites define a baseline of knowledge that will transfer into the new program, allowing for important comparisons to test the significance of the observations made at the focus sites.

Additionally, the MARGINS subduction community has established strong international collaborations, in particular, with Japanese, German, and Central American researchers, and IODP drilling efforts (Section 8.2). In fact, IODP drilling is entering its third phase at Nankai (NanTroSEIZE), and is projected to continue well into the next decade, providing key constraints on the physical state and behavior of the megathrust. IODP drilling offshore Costa Rica (CRISP) is entering its first phase, augmented by observatories both on land and offshore, which will continue to provide geodetic, hydrologic, and seismological data for the Middle America subduction zone. Thus, both SEIZE focus sites will continue to attract researchers within or outside of GeoPRISMS, contributing to our growing understanding of seismogenic zone processes in both locations. IBM drilling has also been proposed, addressing some of the crustal objectives of the SubFac community highly relevant to GeoPRISMS.

The structure of the GeoPRISMS program fosters interdisciplinary studies that can take advantage of the latest advances in numerical modeling, integrated geophysical observations (seismic structure, earthquake parameters, geodesy gravity/geoid, electrical conductivity, bathymetry, magnetics and heat flow), integrated geochemical and petrological studies using state of the art analytical equipment of both subduction inputs (i.e., sediments, fluids, altered oceanic crust), and outputs (plutonic rocks, lavas, and gasses). The GeoPRISMS structure will also provide the motivation for new experimental studies on both key physical and chemical properties of subduction zone materials. Finally, the advancements made in MARGINS provide the context for focused studies on unique exposures of plutonic lower crustal and mantle rocks, ultra-high-pressure metamorphic rocks, and accretionary prism exposures that can help constrain key parameters inferred from observational and experimental studies.