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

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

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

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

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

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

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

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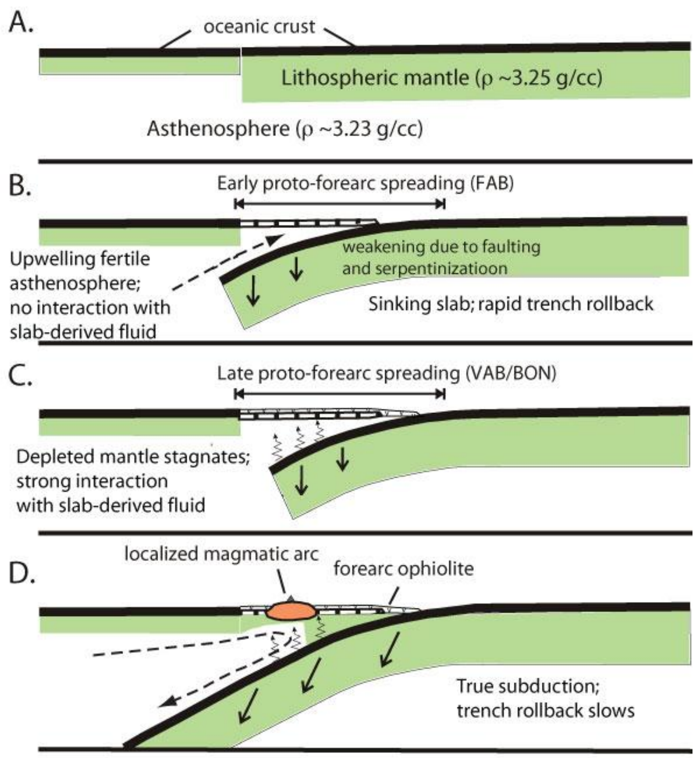

Fig. 1: Subduction initiation, formation of the forearc, and evolution of magmatic systems. A) Older, thicker, colder, and denser lithosphere (right) is juxtaposed with young, thinner, hotter, and more buoyant lithosphere across a zone of weakness (e.g. fracture zone). B) subsidence of old lithosphere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