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

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

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

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

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

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

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

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

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

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

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

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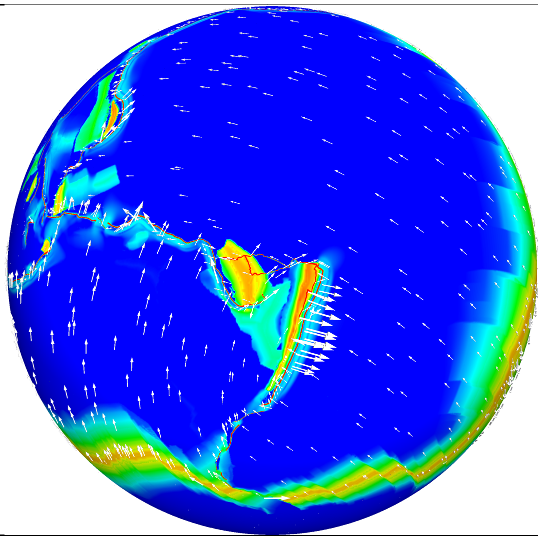

Fig. 1. A new generation of global models of plate motions and mantle flow that capitalize on the latest advances in computational science [6,7] from Stadler *et al*. [8] and Alisic *et al*. [9]. This model of the whole solid earth is used to predict a variety of quantities, including plate motions shown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

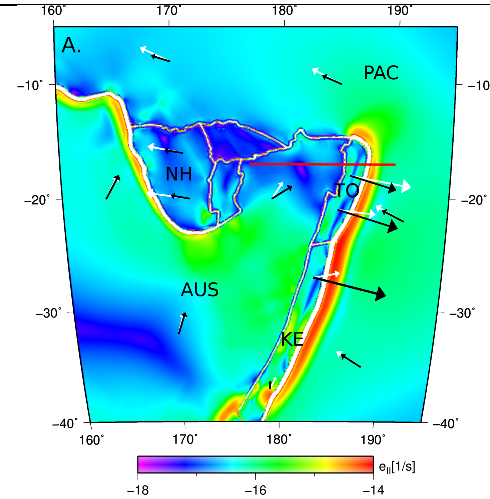

Fig. 2. The new global motion models, for the first time predict not just the motion of the major plates but also micro-plates. Indeed, Statdler *et al*. [8] recently demonstrated that rapid back arc motion, like that seen for the Tonga-Kermadec and New Hebrides subduction zones was an emergent consequence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

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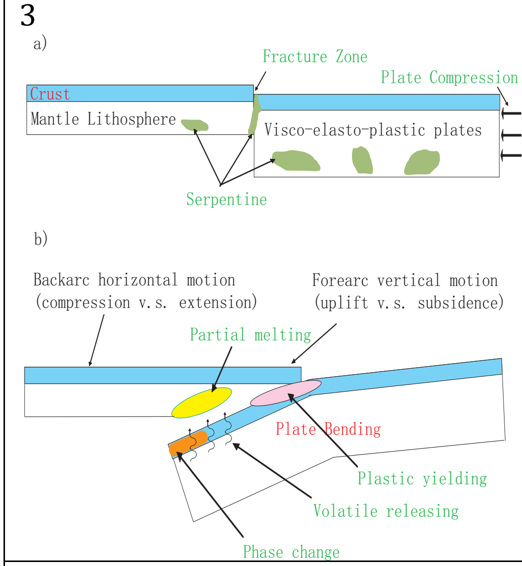

Fig, 3. The different physical properties that enhance (in green letters) and retard (in red letters) the growth of Subduction Initiation that will be incorporated into a new generation of 3-D regional, multi-physics models.

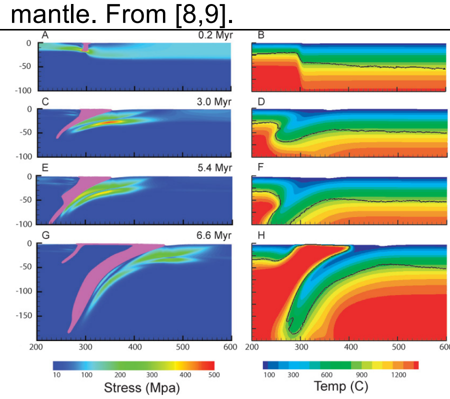

Fig. 4. An earlier, time-dependent model of SI at a fracture zones in medium with visco-elasto plastic plates. The models showed a phase of rapid back arc extension following SI -- consistent with the evolution of SI and back arc extension in the Western Pacific. From Gurnis *et al*. [2].