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

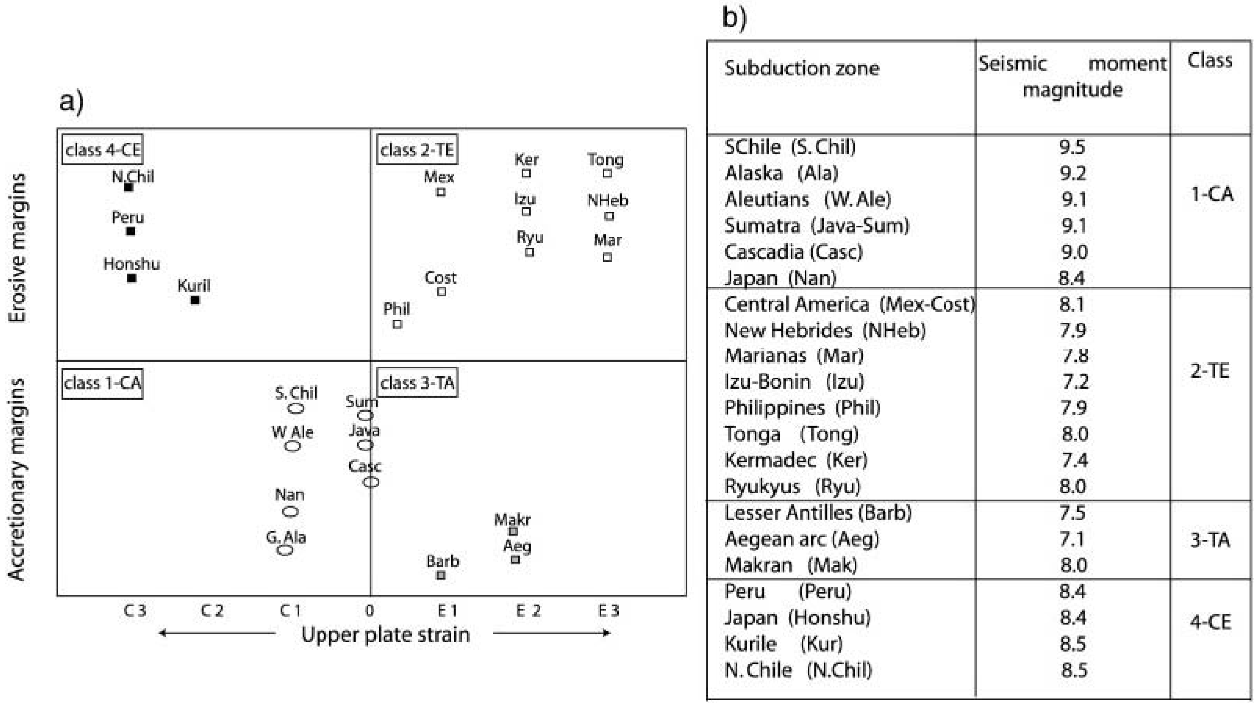
An updated classification of subduction zones, based on the temporal evolution of fully-dynamic three-dimensional models, would be an important step towards being able to meaningfully address how one subduction zone is different from another. A subduction zone is a complex system comprising of the subducting 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.



Subduction zone	Seismic moment magnitude	Class
SChile (S.Chil)	9.5	1-CA
Alaska (Ala)	9.2	
Aleutians (W.Ale)	9.1	
Sumatra (Java-Sum)	9.1	
Cascadia (Casc)	9.0	
Japan (Nan)	8.4	
Central America (Mex-Cost)	8.1	2-TE
New Hebrides (NHeb)	7.9	
Marianas (Mar)	7.8	
Izu-Bonin (Izu)	7.2	
Philippines (Phil)	7.9	
Tonga (Tong)	8.0	
Kermadec (Ker)	7.4	
Ryukyus (Ryu)	8.0	
Lesser Antilles (Barb)	7.5	3-TA
Aegean arc (Aeg)	7.1	
Makran (Mak)	8.0	
Peru (Peru)	8.4	4-CE
Japan (Honshu)	8.4	
Kurile (Kur)	8.5	
N.Chile (N.Chil)	8.5	

Figure 1: from [De Franco et al., 2008] (a) Using the classification of upper plate strain [Jarrard, 1986, Lallemand et al., 2005] and differentiating by erosive or accretionary nature of the margin, four distinct populations of subduction zones are identified, (b) these populations may each have a particular type of plate contact which controls the maximum seismic moment release, only one of which appears capable of producing great earthquakes.

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