High-resolution numerical modeling of outer-rise fault development and evolution

Magali Billen, John Naliboff

The complexity of deformation patterns found within subduction zones reflects the competition between forces driving and resisting subduction. In the outer-rise region of subduction zones, slab-pull forces and bending stresses overcome compressional stresses generated at the plate boundary interface, giving rise to extensional stresses and subsequent normal faulting. On the seismic timescale, such faulting may generate significant magnitude earthquakes (e.g. Lynnes and Lay, 1988) and serve as a potential indicator earthquake for larger underthrusting events (Christensen and Ruff, 1988). Over longer timescales, observational (e.g., Ranero et al. 2003) and numerical (Faccenda et al., 2009, 2012) studies suggest that outer-rise normal faults provide pathways for fluid migration deep into slabs and consequently a mechanism for volatile recycling into the deep mantle. Building on these studies, this investigation aims to discern the relationship between outer-rise deformation, plate driving forces and lithospheric rheology at both short- (<10,000 years) and long-term (> 10 Myr) time scales.

Our approach to examining the factors controlling outer-rise deformation combines high-resolution numerical modeling with global observations of subduction dynamics, flexural rigidity and seafloor faulting. On a global scale, outer rise faulting patterns show little to no correlation with slab pull magnitudes, convergence rates or oceanic plate ages despite wide variations in these parameters across modern subduction systems (Naliboff et al., 2013). 2-D numerical models of long-term (> 10 Myr) outer-rise deformation in oceanic-continental

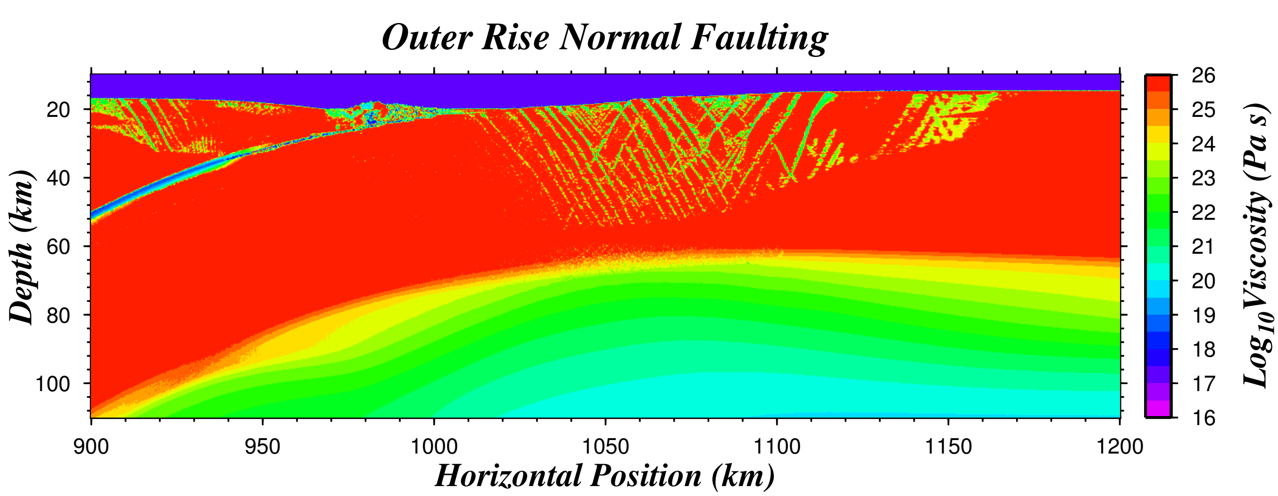

Figure 1. Viscosity structure of the overriding- (upper left) and downgoing-plate after ~ 400,000 years of deformation. Normal faults (brittle shear zones) develop seaward of the trench in the outer rise region in response to extensional bending stresses and slab pull forces.

systems suggest that this lack of correlation likely reflects that downgoing plate age and velocity, slab pull magnitude and plate boundary coupling all significantly affect outer-rise faulting patterns (Naliboff et al., 2013). Conversely, variations in the brittle rheology of downgoing oceanic lithosphere produce little to no changes in time-averaged outer-rise faulting patterns.

To further elucidate any connection between the rheology of downgoing oceanic lithosphere, plate boundary interface strength and outer rise faulting patterns, we have developed 2-D models of the Tonga subduction system incorporating observations of slab geometry, bathymetry and overriding plate structure. Rather than develop a subduction system through time-dependent processes, these experiments impose a 'cross-sectional' slice of the modern Tonga subduction system as an initial condition that approximates the modern forces driving and resisting subduction. In addition, high numerical resolutions in the vicinity of the trench (200 m) permit the definition of a narrow (1 km), rheologically distinct shear zone marking the plate boundary interface. The resulting models thus allow for direct comparisons to observed regional patterns of outer-rise deformation and an assessment of their relationship to plate boundary rheology. Preliminary results show the development of outer-rise normal faults penetrating deep into the mantle lithosphere after ~ 400,000 years of deformation (Fig. 1)).