Quantitative Estimates of Interplate Coupling Inferred from Outer Rise Earthquakes

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Abstract — Interplate coupling plays an important role in the seismogenesis of great interplate earthquakes at subduction zones. The spatial and temporal variations of such coupling control the patterns of subduction zone seismicity. We calculate stresses in the outer rise based on a model of oceanic plate bending and coupling at the interplate contact, to quantitatively estimate the degree of interplate coupling for the Tonga, New Hebrides, Kurile, Kamchatka, and Marianas subduction zones. Depths and focal mechanisms of outer rise earthquakes are used to constrain the stress models. We perform waveform modeling of body waves from the GDSN network to obtain reliable focal depth estimates for 24 outer rise earthquakes. A propagator matrix technique is used to calculate outer rise stresses in a bending 2-D elastic plate floating on a weak mantle. The modeling of normal and tangential loads simulates the total vertical and shear forces acting on the subducting plate. We estimate the interplate coupling by searching for an optimal tangential load at the plate interface that causes the corresponding stress regime within the plate to best fit the earthquake mechanisms in depth and location.

We find the estimated mean tangential load \( f_t \) over 125-200 km width ranging between 166 and 671 bars for Tonga, the New Hebrides, the Kuriles, and Kamchatka. This magnitude of the coupling stress is generally compatible with the predicted shear stress at the plate contact from thermal-mechanical plate models by MOLNAR and ENGLAND (1990), and VAN DEN BUEKEL and WORTEL (1988). The estimated tectonic coupling, \( F_t \), is on the order of \( 10^{12} - 10^{13} \) N/m for all the subduction zones. \( F_t \) for Tonga and New Hebrides is about twice as high as in the Kurile and Kamchatka arcs. The corresponding earthquake coupling force \( F_e \) appears to be 1-10% of the tectonic coupling from our estimates. There seems to be no definite correlation of the degree of seismic coupling with the estimated tectonic coupling. We find that outer rise earthquakes in the Marianas can be modeled using zero tangential load.

Key words: Interplate coupling, outer rise earthquakes, stress modeling, subduction zones.

Introduction

Two approaches are often adopted for plate tectonic studies. One is to study earthquakes occurring at the plate boundaries, which helps us to identify the shape and extent of a plate, to detect the degree of plate interaction, and to acquire information about the state of stress at the plate boundaries. Another approach is to construct mechanical models for plate motion, stresses, and evolution. Surface
plate motion data sometimes are used to constrain the models, along with gravity and bathymetric data, and, occasionally, some earthquake and heat flow data as well. Results from the former approach often give only qualitative assessments of the parameters controlling the subduction dynamics, whereas quantitative results from the latter approach generally suffer from large uncertainties due to the need for many assumptions. Here, we combine the two approaches, using the information of earthquake depths and mechanisms to constrain the stress distribution in the plate, and attempt to obtain quantitative estimates of the parameters controlling the plate dynamics. In particular, we are interested in outer rise earthquakes and their relationship to subduction dynamics.

An important aspect of subduction zone dynamics is the degree of interplate coupling, which is related to the shear stress and coupling width at the interplate contact between the downgoing and overriding plates. Estimation of the shear stresses at the interplate contact is difficult, but the stress drops due to great underthrusting earthquakes can be estimated from seismological studies. Ruff and Kanamori (1980, 1983) used the maximum moment magnitude of the characteristic underthrusting earthquakes in different regions to classify seismic coupling at subduction zones. They concluded that younger plates with faster convergence rates tend to have stronger seismic coupling. The Southern Chile subduction zone represents the end-member with strong seismic coupling. The Marianas, an old plate with a slower convergence rate, is an example of the other extreme, a weakly coupled subduction zone. Such general characterizations of seismic coupling are useful, but do not provide quantitative information about the degree of interplate coupling.

Outer rise earthquakes are oceanic intraplate events, occurring within the bending plate before it subducts into the trench. These earthquakes are rare compared with subduction zone interplate and intermediate depth intraplate seismicity. Approximately 20 outer rise earthquakes with magnitudes from 5 to 7 occur worldwide each year. The depths and focal mechanisms of outer rise earthquakes contain valuable information about the stress distribution with depth in the oceanic lithosphere near the trench. This distribution is related to the mechanical coupling at the interplate contact.

In general, the observation that tensional outer rise events tend to be shallower, while compressional outer rise events tend to be deeper, supports the association of these earthquakes with bending of the subducting plate (Stauder, 1968a,b, 1973). However, variations in the degree of interplate coupling may modulate the stress in the outer rise from one subduction zone to another. Furthermore, temporal variations in interplate coupling related to great underthrusting earthquakes may superimpose time-dependent changes in the outer rise seismicity (Ward, 1983, 1984; Christensen and Ruff, 1983, 1988; Dmowska et al., 1988; Lay et al., 1989). Spatial and temporal changes in stress inferred from outer rise earthquakes may thus provide constraints on the interplate coupling at subduction zones. The