Can Interseismic Geodetic Observations Resolve Persistent Rupture Asperities? A study of the Japan trench off Tohoku

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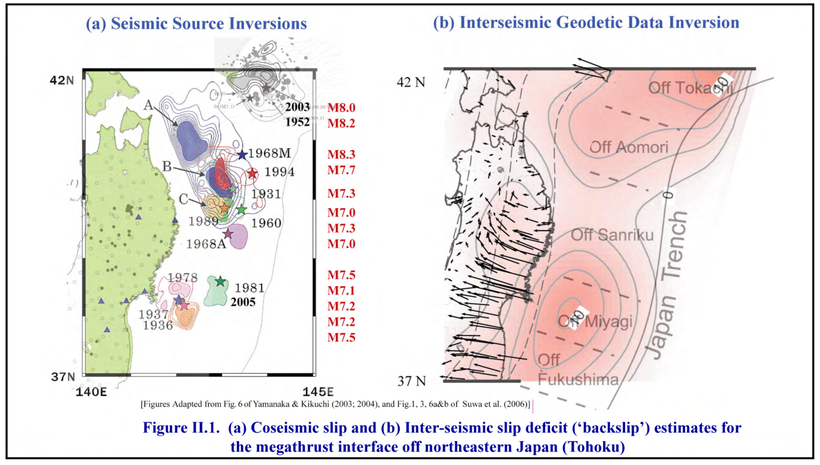
I. Abstract

In the last century, several large (M > 7) earthquakes have occured on the megathrust interface along the Japan Trench, offshore of Japan's Tohoku region. Published earthquake source inversions based on seismological data suggest that some of these earthquakes have repeatedly ruptured the same region of the fault (i.e., asperities), while others have ruptured closely clustered asperities (e.g., Yamanaka and Kikuchi, 2004, Panel II). For instance, the 1978, M 7.4 and the 2005, M 7.2 Miyagi-oki events are inferred to have ruptured the same asperity, while the 1968, M 7.9 Tokachi-oki event, and the 1994, M 7.5 Sanriku-oki event ruptured distinct asperities that are close to each other. In contrast, inversions of geodetic data from interseismic periods produce models that are locked over more spatially extensive regions (e.g., Suwa et al, 2003, Panel II). These broad and smooth regions are in contrast to the smaller discrete asperities indicated by earthquake source studies, and may be a consequence of lack of model resolution and a resulting need for regularization that is inherent to the use of onshore geodetic data. Alternatively, the differences may imply the potential for a large earthquake in the future. Thus, the different levels of apparent coupling implied by these two classes of models have very different implications for regional seismic hazard. In this project, we want to test the hypothesis that mechanical coupling on inferred asperities alone is sufficient to explain available geodetic observations or alternatively, that these data require additional regions on the megathrust to be coupled. To address this question, we are using a 3-D mechanical model of stress-dependent interseismic creep along the megathrust, that is consistent with a given frictional rheology and the known spatio-temporal distribution of large earthquakes (Hetland et al. 2009, Panels III & IV). These mechanical models predict that asperities are surrounded by a "halo" of very low creep-rates (a "stress-shadow" effect) late in the seismic cycle, which also results in a relatively smooth and long wavelength surface velocity field. We want to test if this "physical" smoothing preserves any signature of the original asperities, in comparison to the artificial smoothing produced by model regularization in inversions of interseismic geodetic data. Underlying this analysis is the assumption that known asperities persist across multiple earthquake cycles, and that portions of the megathrust that slip co- or post-seismically do not slip interseismically. Originally written in Matlab, we are currently migrating the software to a Python-based modular architecture using generalized numerical algorithms in order to (a) handle complex realistic 3D plate interface geometries, (b) facilitate distributed computing for the resulting large problem sizes, and (c) visually compare theoretical predictions with geodetic data.

II. Motivation



[Figures Adapted from Fig. 6 of Yamanaka & Kikuchi (2003; 2004), and Fig.1, 3, 6a&b of Suwa et al. (2006)]

Figure II.1. (a) Coseismic slip and (b) Inter-seismic slip deficit ('backslip') estimates for the megathrust interface off northeastern Japan (Tohoku)

Previous work on kinematic modeling of intersismic deformation has shown that distributions of interseismic creep inferred from backslip models is roughly anti-correlated with the location of large megathrust earthquakes (e.g., Burgmann et al., 2005; Suwa et al., 2006; Chlieh et al., 2007). In these models, regions of little resolved interseismic creep are mechanically coupled.

Existing dynamic post-seismic creep models tend to ignore accelerations, and are therefore quasi-static in nature (e.g., Hearn et al., 2002; Johnson et al., 2006; Perfettini and Avouac, 2007). Most of these models:

(a) Do not attempt to describe the approximately steady interseismic deformation observed before earthquakes.
(b) Consider non-linear fault rheologies, and thus depend strongly on initial conditions. Since prior knowledge of initial stresses is difficult to obtain, researchers typically used simple, *ad-hoc*, spring-slider model based arguments to determine them.
(c) Some of these models constrain creep along sections of the fault: e.g., directivity constraints (that allow creep only where stresses are positive), and thermal constraints (that allow creep only below the brittle-ductile transition).

Here, we develop a quasi-static, dyamically self-consistent fault creep model for the entire interseismic period, that has a constant mean stress (once spun up) prior to an earthquake, independent of the initial conditions, and that does not impose any constraints on where creep can occur on the fault - except for coseismic rupture asperities, which are assumed to be locked post-rupture.

III. Methodology

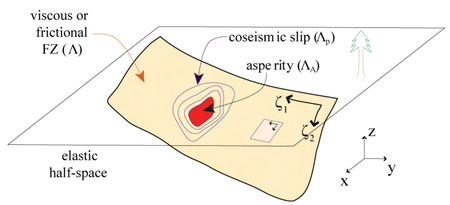


Figure III.1. Scnematic of the fault model used in this work

$$\tau_i(\varsigma,t) = \int_{\Lambda}\left[s_j(\xi,t) - tV_j\right]K_{ij}(\varsigma;\xi)\,d\xi + \sum_p \int_{\Lambda p} S_{jp}K_{ij}(\varsigma;\xi)\,d\xi \qquad (1)$$

$$f = f_0 + a\ln\left(\frac{v_i}{V_0}\right) + b\ln\left(\frac{V_0\theta}{L}\right), \text{ with } \frac{d\theta}{dt} = \frac{V_0\theta}{L}, \text{ where } v_i = \left(\frac{ds_i}{dt}\right) \qquad (2)$$

$$\frac{ds_i(\varsigma,t)}{dt} = \mathrm{sgn}\{\tau_i(\varsigma,t)\}V_i\exp\left\{\frac{|\tau_i(\varsigma,t)| - \sigma_{E_i}(\varsigma)f_0}{(a-b)\sigma_{E_i}(\varsigma)}\right\} \qquad (3)$$

$$= 2V_i\exp\{-\rho_h(\varsigma)\}\sinh\left\{\frac{\tau_i(\varsigma,t)}{\alpha_h(\varsigma)}\right\}$$

Technical details and assumptions:

(a) Models the complete interseismic period: transient postseismic and steady interseismic creep

(b) Includes fault loading due to steady tectonic loading as well as repeated ruptures on the fault. So, stress-state on the fault is as result of cumulative past activity on the fault.

(c) Simulates multiple-earthquake cycles starting from an arbitrary (zero) initial stress, until the pattern of stress variation during the interseismic period becomes cycle invariant (i.e., model is spun up). This leads to internally consistent initial conditions before an earthquake on the mature fault surface.

(d) Ties known rupture histories to interseismic and postseismic creep, thus allowing us to constrain fault rheologies from geodetic observations.

(e) Does not consider off-fault rheology

(f) Does not solve for any earthquake process related phenomena like nucleation, seismic wave propagation, etc. Therefore, radiation damping is not included.

Demonstration of the interseismic "stress-shadow" effect:

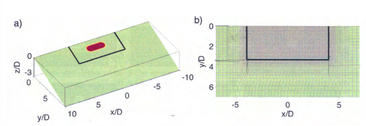


Figure III.2. Subduction Megathrust Rectangular Mesh for toy models (right) using rate-state rheology

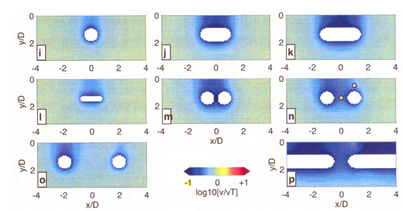
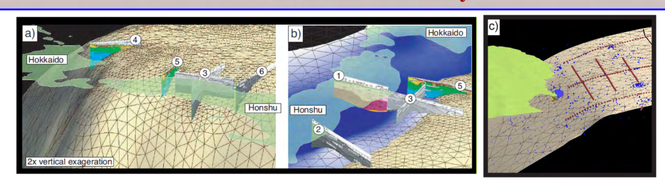


Figure III.3. Interseismic (t' ~ 1.0) creep is negligible in the regions that experienced co- and post-seismic slip.

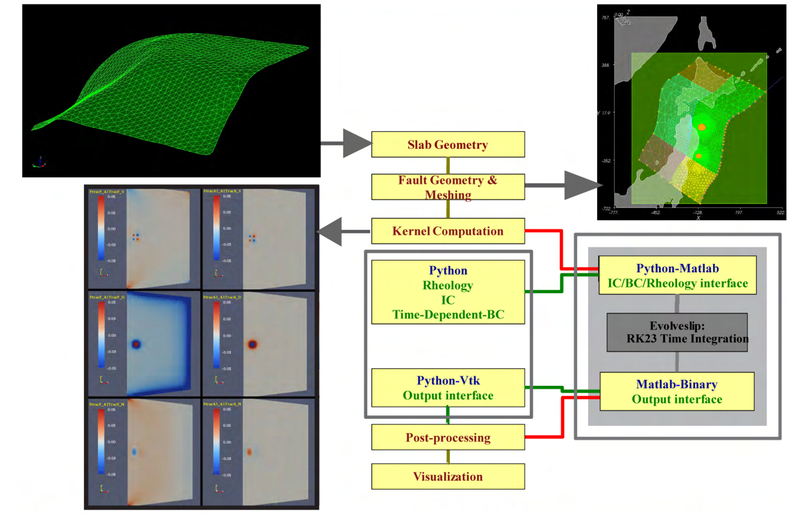
Regions of the megathrust experiencing rapid post-seismic creep experience interseismic creep rates that are well below the plate-loading rate. Such regions are experiencing a "stress-shadow" effect late in the seismic cycle. As a result, a larger region of fault appears to be geodetically coupled, compared to the original asperities that ruputred.

IV. Slab Geometry



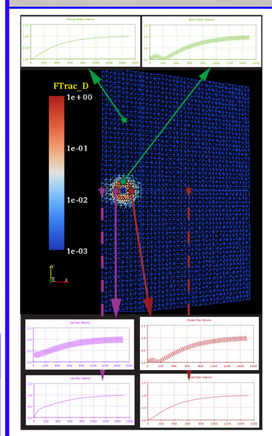
Models of the slab surface (a) and the Japan Moho (b); for reference, a few of the seismic lines used as constraints are shown: 1, Iwasaki et al., 2001; 2, Miura et al., 2003; 3, Ito et al., 2004; 4, Nakanishi et al., 2004; 5, Takahashi et al., 2004; 6, Miura et al., 2005. (c) The focal mechanism and fault plane (red) are for a characteristic small earthquake sequence off Sanriku (northeastern Honshu, Fig. II.1b) from Matsuzawa et al., 2002.

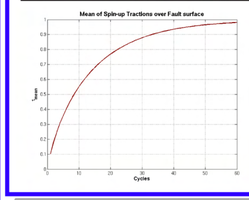
V. Work-flow

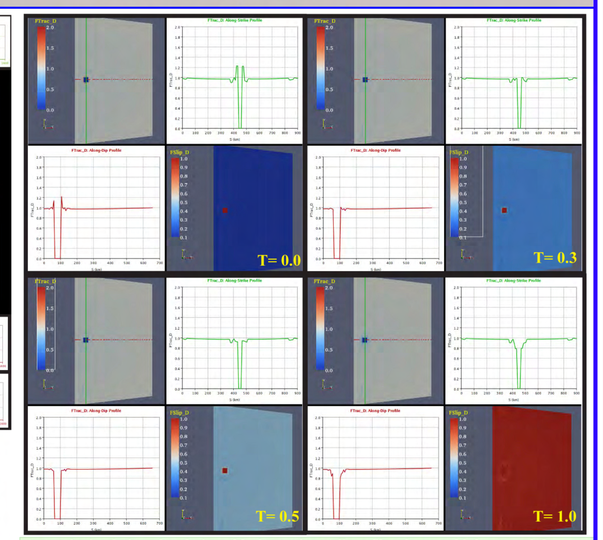


Sample model run work flow: Imported megathrust interface geometry (facets in upper left figure) is first 'chopped' into a surface bounded by orthogonal edges, and then meshed an unstructured grid of triangles, using Sandia National Lab's CUBIT gemetry/meshing tool. Mesh parameters like nodes, elements, centroids, areas, aspect ratios, strike and dip are then extracted for each patch to be input to the the solver. The solver output is visualized in VTK format.

VI. Preliminary Results







A sample simulation of evolution of fault tractions (all profiles above and left; upper-left panels above) and cumulative slip after spin-up (lower-right panels above), for a linear-viscous fault rheology. Also shown is the mean fault traction as the model spins-up. An ordered, good-quality mesh is needed to match the spin-up rates observed for rectangular meshes (e.g, like the ones depicted in Figures III.2 & 3).

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