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Tsunamigenic earthquake simulations using experimentally derived friction laws

S. Murphy [a,b,*], G. Di Toro [c,d], F. Romano [a], A. Scala [a], S. Lorito [a], E. Spagnuolo [a], S. Aretusini [c], G. Festa [e], A. Piatanesi [a], S. Nielsen [f]

[a] *Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy*
[b] *Ifremer, Plouzané, France*
[c] *University of Manchester, Manchester, United Kingdom*
[d] *Università degli Studi di Padova, Padua, Italy*
[e] *Università di Napoli Federico II, Naples, Italy*
[f] *Durham University, Durham, United Kingdom*

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ABSTRACT

Seismological, tsunami and geodetic observations have shown that subduction zones are complex systems where the properties of earthquake rupture vary with depth as a result of different pre-stress and frictional conditions. A wealth of earthquakes of different sizes and different source features (e.g. rupture duration) can be generated in subduction zones, including tsunami earthquakes, some of which can produce extreme tsunamigenic events. Here, we offer a geological perspective principally accounting for depth-dependent frictional conditions, while adopting a simplified distribution of on-fault tectonic pre-stress.

We combine a lithology-controlled, depth-dependent experimental friction law with 2D elastodynamic rupture simulations for a Tohoku-like subduction zone cross-section. Subduction zone fault rocks are dominantly incohesive and clay-rich near the surface, transitioning to cohesive and more crystalline at depth. By randomly shifting along fault dip the location of the high shear stress regions ("asperities"), moderate to great thrust earthquakes and tsunami earthquakes are produced that are quite consistent with seismological, geodetic, and tsunami observations. As an effect of depth-dependent friction in our model, slip is confined to the high stress asperity at depth; near the surface rupture is impeded by the rock-clay transition constraining slip to the clay-rich layer. However, when the high stress asperity is located in the clay-to-crystalline rock transition, great thrust earthquakes can be generated similar to the M_w 9 Tohoku (2011) earthquake.

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1. Introduction

Seismological, geodetic, and tsunami observations have shown that subduction zones are complex systems where the properties of earthquake rupture vary with depth (Lay et al., 2012). For example, earthquake duration normalised for event size has been observed to decrease with depth; this recurrent feature has been attributed to depth varying shear modulus and/or stress drop for individual earthquakes (Bilek and Lay, 1999; Bilek et al., 2016; Geist and Bilek, 2001). Depth variation in subduction ruptures is, for example, evident when comparing the different historical earthquakes that occurred off the Pacific coast of Tohoku region in Japan (Fig. 1). A number of major (M_w 7–7.9) thrust earthquakes mostly slipped within a depth range of 10–40 km. These events involved individual patches of concentrated slip implying the breaking of at least one prominent, high stress asperity (Shao et al., 2011; Yamanaka and Kikuchi, 2004). Conversely, the 1896 Meiji event (M 8.2–8.4), likely involved slip primarily at the base of the shallow accretionary wedge or beneath it. This earthquake produced a disproportionately large tsunami relative to its moment magnitude, possibly making it a potential 'tsunami earthquake' (Kanamori, 1972). The great M_w 9.0 2011 Tohoku earthquake nucleated at ∼20–25 km depth, and produced slip at traditionally expected depths while also realising a substantial amount of slip all the way to the trench (i.e., at less than 10 km depth) (Chu et al., 2011; Ide et al., 2011; Romano et al., 2014).

Numerical models of the dynamic rupture process have successfully described either individual types of earthquakes, for example

* Corresponding author.
E-mail address: shane.murphy@ifremer.fr (S. Murphy).

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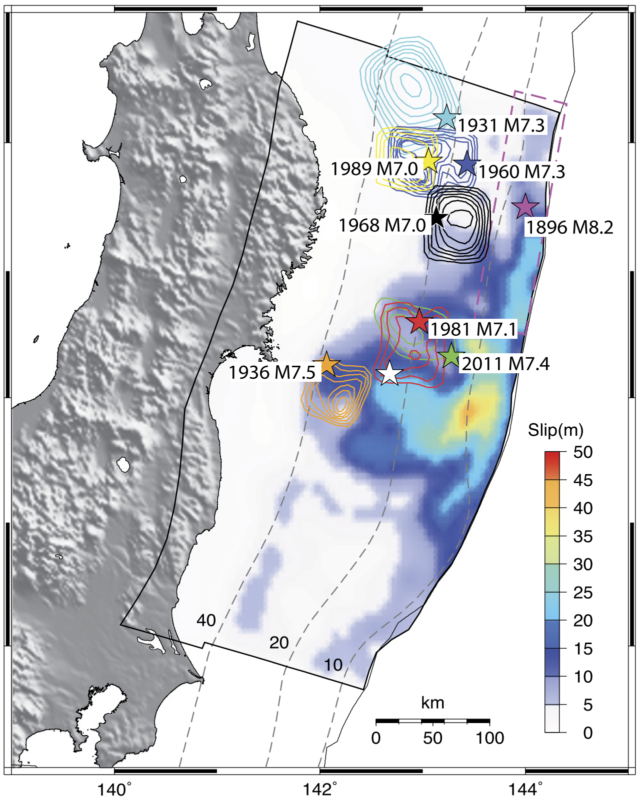

Fig. 1. Earthquake history off the Pacific coast of Tohoku region and model setup. Coloured contours represent slip distributions at 0.5 m interval for a number of historical thrust earthquakes (Shao et al., 2011; Yamanaka and Kikuchi, 2004); The magenta dashed box represents the location for the 1896 Meiji tsunami earthquakes (M 8.2–8.4). The colour slip distribution is the M_W 9 Tohoku earthquake (Romano et al., 2014), the red star is its epicentre. Dashed grey line is depth at 10, 20 and 40 km. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

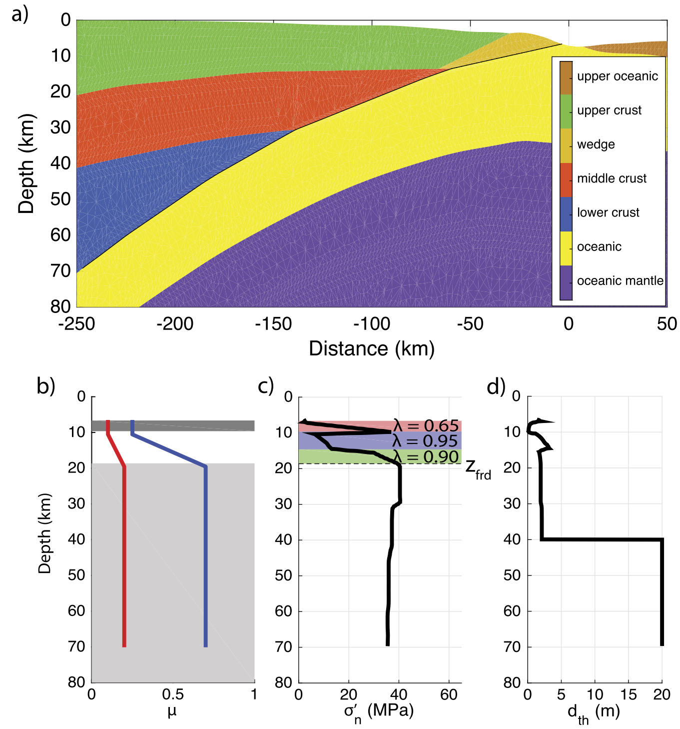

Fig. 2. Numerical model set up. a) Structural model used in the numerical simulations, black line denotes the subduction interface. b) Variation of frictional coefficients with depth: the dark and light grey boxes denote the clay-rich and crystalline rock frictional coefficients; the white is the transition between the two materials. Solid blue and red lines are the static and dynamic coseismic coefficients of friction respectively. c) The variation of the effective normal stress with depth, coloured boxes denote different pore fluid to overburden stress ratio, λ. The dashed black line denotes the fluid retention depth. d) Variance of d_{th} with depth which is a function of effective normal stress and frictional material type (i.e., rock or clay-rich). (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

the Tohoku event (Kozdon and Dunham, 2013; Noda and Lapusta, 2013), or both thrust and tsunami earthquakes in the same model (Mitsui and Yagi, 2013). Numerical models coupled with the rate-and-state friction law have been used to reproduce full seismic cycles for subduction environments. However, this comes at the expense of either failing to account for geometry/free surface effects and inhomogeneity in the material surrounding the fault (Cubas et al., 2015; Noda and Lapusta, 2013), or by simplifying wave propagation to static stress changes on the fault plane (Shibazaki et al., 2011). Fully dynamic simulations including a free surface and variable geometry have tended to focus on specific rupture features of the Tohoku earthquake such as the slip in the trench or long period guided wave propagation in the ocean (Hirono et al., 2016; Huang et al., 2013; Kozdon and Dunham, 2014). Depth dependent changes in frictional parameters have been tested using rate-and-state models for the 2011 Tohoku (Kozdon and Dunham, 2013). However, to our knowledge, no numerical model has been able to reproduce a range of different observed earthquakes types (e.g. Fig. 1) while at the same time accounting for the fault geometry and complex structure as proposed here.

The focus of this study is to provide a simple yet geologically consistent model that reconciles the different observed earthquake types with fault properties from independent theoretical and laboratory studies. We focus our investigation on the aspect of rupture dynamics due to depth-dependent frictional conditions focusing on a specific time window of the seismic cycle including the sub-seismic frictional properties of the fault materials (den Hartog et al., 2012). Hence, the friction law parameters were chosen based on available geological and geophysical constraints. On the other hand, investigating inter-seismic and nucleation processes is beyond the scope of this study. As a consequence, the set up for the numerical model was simplified, particularly as far as the initial stress distribution is concerned. While the initial stress is heterogeneous, being the derivative of a composite slip model (Murphy et al., 2016), it is highly localized. Moreover, since a 2D model is used, we do not address the influence of lateral variations on rupture features.

2. Numerical model

We modelled the earthquake rupture dynamics (Festa and Vilotte, 2006) on a 2D cross-section through a Tohoku-like fault (Figs. 2a–d). Dynamic rupture is simulated using a 2D non-smooth spectral element method (Festa and Vilotte, 2005). The curved fault geometry is based on Slab 1.0 (Hayes et al., 2012) which has been slightly modified so that the subduction interface extends to the surface. The media is heterogeneous with the layers and their elastic properties (described in Fig. 2 and Table S1 in Supplementary Material) based on a seismic survey in the zone of the 2011 Tohoku earthquake (Miura et al., 2005).

2.1. Laboratory derived thermal weakening friction law

A thermal slip weakening empirical friction law was used in all simulations which is particularly suitable for representing dynamic weakening observed in a regime of slip velocities that rapidly accelerate to seismic slip rates. There are a number of other empirical friction laws (e.g., linear slip weakening (Ida, 1972); rate-and-

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