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Review Article

Invited review paper: Fault creep caused by subduction of rough seafloor relief

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ABSTRACT

Among the wide range of thermal, petrologic, hydrological, and structural factors that potentially affect subduction earthquakes, the roughness of the subducting seafloor is among the most important. By reviewing seismic and geodetic studies of megathrust locking/creeping state, we find that creeping is the predominant mode of subduction in areas of extremely rugged subducting seafloor such as the Kyushu margin, Manila Trench, northern Hikurangi, and southeastern Costa Rica. In Java and Mariana, megathrust creeping state is not yet constrained by geodetic observations, but the very rugged subducting seafloor and lack of large earthquakes also suggest aseismic creep. Large topographic features on otherwise relatively smooth subducting seafloor such as the Nazca Ridge off Peru, the Investigator Fracture Zone off Sumatra, and the Joban seamount chain in southern Japan Trench also cause creep and often stop the propagation of large ruptures. Similar to all other known giant earthquakes, the Tohoku earthquake of March 2011 occurred in an area of relatively smooth subducting seafloor. The Tohoku event also offers an example of subducting seamounts stopping rupture propagation. Very rugged subducting seafloor not only retards the process of shear localization, but also gives rise to heterogeneous stresses. In this situation, the fault zone creeps because of distributed deformation of fractured rocks, and the creep may take place as transient events of various spatial and temporal scales accompanied with small and medium-size earthquakes. This process cannot be described as stable or unstable friction along a single contact surface. The association of large earthquakes with relatively smooth subducting seafloor and creep with very rugged subducting seafloor calls for further investigation. Seafloor near-trench geodetic monitoring, high-resolution imaging of subduction fault structure, studies of exhumed ancient subduction zones, and laboratory studies of low-temperature creep will greatly improve our understanding of the seismogenic and creep processes and their hazard implications.

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1. Introduction

Understanding how the roughness of subducting seafloor affects subduction earthquakes is important for assessing seismic and tsunami hazards, but it is also a subject of debate. Interests in this subject have been renewed by the two most recent giant earthquakes ($M_w = 9$ or greater). The $M_w = 9.2$ Sumatra earthquake of 2004 put in doubt some of the widely held views about what controls the size of subduction earthquakes (Stein and Okal, 2007). It is thus relevant to ask whether the potential of any subduction zone to produce giant earthquakes is limited only by its length (McCaffrey, 2008). This translates to the question: Can some physical processes, particularly the subduction of topographical features, persistently limit earthquake size? After the $M_w = 9$ Tohoku earthquake of 2011, ideas were proposed to explain its long lapse time from its predecessor (~1100 years) and its large coseismic slip (~50 m or more) and tsunami. One idea is that a subducting seamount or some other geometrical anomaly strongly locked the megathrust for a long time and then produced unusually high coseismic stress drop (Duan, 2012; Kumagai et al., 2012; Zhao et al., 2011). This reopens an old question: Do subducting topographic anomalies generally cause strong locking and generate large earthquakes?

Global or regional syntheses generally argue for a negative correlation between very large earthquakes ($M_w > 8$) and subducting seafloor with large topographic reliefs (Kelleher and McCann, 1976; Kopp, 2013; Loveless et al., 2010; Morgan et al., 2008; Sparkes et al., 2010) or, equivalently, a positive correlation between large events and subducting seafloor smoothed by a large amount of sediments (Heuret et al., 2012; Ruff, 1989; Scholl et al., 2011). Case studies of individual earthquakes yield mixed results (Bilek, 2007). An $M_w = 7.8$ earthquake in 1994 in the Java subduction zone was thought to be caused by a subducting seamount (Abercrombie et al., 2001), but recent seismic imaging found no evidence for a subducting seamount in the rupture area (Shulgin et al., 2011). A seismically imaged subducting seamount at the Nankai subduction zone is reported to be a slip barrier that caused the rupture in an $M_w \approx 8.2$ earthquake in 1946 to halt before propagating farther along strike to generate a large tsunami (Cummins et al., 2002; Kodaira et al., 2000). A fracture zone in the subducting plate is reported to have stalled the rupture of the 2001 $M_w = 8.4$ earthquake off Peru then allowed it to continue its propagation along strike (Robinson et al., 2006). A subducting aseismic ridge caused a slip minimum in the 2007 $M_w = 8.1$ Solomon earthquake but allowed large slip to both sides (Chen et al., 2009; Furlong et al., 2009). In general, subduction earthquakes that are thought to be linked to subducting seamounts tend to be relatively small in size (Bilek et al., 2003) and/or feature rather complex rupture processes (Das and Watts, 2009) that often imply the involvement of multiple faults in different orientations (Wang and Bilek, 2011).

Discussions on this subject are normally focused on how geometrical irregularities influence coseismic rupture, commonly in terms of seismic "asperities" or "barriers." The location of the geometrical feature relative to the rupture is usually poorly defined. The conjugate question of how these irregularities influence interseismic locking has been addressed only on a few occasions. Mochizuki et al. (2008) studied earthquake activity over an 80-yr period around a well imaged subducting seamount near the southern end of Japan Trench and concluded that the seamount had been creeping aseismically while causing earthquakes in its neighbourhood, including a repeating sequence of M ~ 7 events slightly farther landward. Singh et al. (2011) described seismic imaging of a seamount to 30–40 km depths in a seismically quiet area of the Sumatra subduction zone and proposed that the seamount is subducting seismically. Wang and Bilek (2011) reasoned that subducting seamounts create favourable structural and stress environments for aseismic creep and small earthquakes.

This review article attempts to summarise the state of knowledge of this subject, addressing both observational and theoretical aspects. We do not attempt to cover the much broader subject of what controls subduction earthquake processes. Even for a very smooth fault, the slip and seismogenic behaviour must be influenced by a range of geological and geophysical factors such as the type of fault wall rocks, the amount and type of subducted sediments, temperature and pressure-controlled rheology, and fluid pressure in the fault zone. But here we focus only on the effects of geometrical irregularities of the fault zone due to uneven subducting seafloor. We describe seafloor of large topographic relief as being rugged or rough, different from the scale invariant roughness described by fractals (Turcotte, 1992). The issue of scale invariance will be discussed in Section 3.1.

The article is structured as follows. Section 2 is focused on modern observations. We review observations from subduction zones with extremely rugged subducting seafloor. Where available, we pay special attention to geodetic observations made over the past two decades that constrain the locking or creeping state of the plate interface. A mostly creeping fault segment is unlikely to be a primary candidate for the location of a future great earthquake. We will show that, where large topographic reliefs are subducted, geodetic observations consistently suggest interface creep, usually accompanied with numerous small and some medium size ($M < 7.5$) earthquakes. Section 3 is focused on physical concepts. We provide a critique of various models seen in the literature pertaining to how subducting geometrical irregularities stop or facilitate large earthquakes, with references to relevant studies in continental settings. At the end of Section 3, we explore the geology and mechanics of fault zone creep caused by geometrical irregularities with reference to fault zone structures of exhumed ancient subduction zones. Before summarising our conclusions, we discuss in Section 4 the role of subducting seamounts in the Tohoku earthquake.

2. Fault behaviour observed at subduction zones of very rugged incoming seafloor

If subducting seamounts or similar geometrical irregularities generally cause large earthquakes, they should cause locking of the subduction fault most of the time. Conversely, if they act as rupture barriers in large earthquakes, they must creep during the time between large earthquakes to balance the slip budget of the subduction fault. Here we review geodetic and earthquake studies from a number of