Tectonophysics 670 (2016) 1–15

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Review Article

Teleseismic constraints on the geological environment of deep episodic slow earthquakes in subduction zone forearcs: A review

Pascal Audet [a,*], YoungHee Kim [b,*]

[a] Department of Earth and Environmental Sciences, University of Ottawa, Ottawa, Canada
[b] School of Earth and Environmental Sciences, Seoul National University, Republic of Korea

ARTICLE INFO

Article history:
Received 26 August 2015
Received in revised form 8 January 2016
Accepted 9 January 2016
Available online 18 January 2016

Keywords:
Subduction zone
Slow earthquakes
Geologic structure
Teleseismic scattering

ABSTRACT

More than a decade after the discovery of deep episodic slow slip and tremor, or slow earthquakes, at subduction zones, much research has been carried out to investigate the structural and seismic properties of the environment in which they occur. Slow earthquakes generally occur on the megathrust fault some distance downdip of the great earthquake seismogenic zone in the vicinity of the mantle wedge corner, where three major structural elements are in contact: the subducting oceanic crust, the overriding forearc crust and the continental mantle. In this region, thermo-petrological models predict significant fluid production from the dehydrating oceanic crust and mantle due to prograde metamorphic reactions, and their consumption by hydrating the mantle wedge. These fluids are expected to affect the dynamic stability of the megathrust fault and enable slow slip by increasing pore-fluid pressure and/or reducing friction in fault gouges. Resolving the fine-scale structure of the deep megathrust fault and the in situ distribution of fluids where slow earthquakes occur is challenging, and most advances have been made using teleseismic scattering techniques (e.g., receiver functions). In this paper we review the teleseismic structure of six well-studied subduction zones (three hot, i.e., Cascadia, southwest Japan, central Mexico, and three cool, i.e., Costa Rica, Alaska, and Hikurangi) that exhibit slow earthquake processes and discuss the evidence of structural and geological controls on the slow earthquake behavior. We conclude that changes in the mechanical properties of geological materials downdip of the seismogenic zone play a dominant role in controlling slow earthquake behavior, and that near-lithostatic pore-fluid pressures near the megathrust fault may be a necessary but insufficient condition for their occurrence.

Contents

* Corresponding authors.
E-mail addresses: pascal.audet@uottawa.ca (P. Audet), younghkim@snu.ac.kr (Y. Kim).

http://dx.doi.org/10.1016/j.tecto.2016.01.005

1. Introduction

Subduction zone great earthquakes (with moment magnitude $M_w > 8$) are generated by rupture of the megathrust fault within the so-called "seismogenic zone". There are many ways of determining the seismogenic zone based on a variety of indicators. In a static association with physical properties, the seismogenic zone is the portion of the fault that behaves in a brittle fashion. The depth to a specific geotherm commonly dictates the extent of the zone beyond which rocks deform by thermally activated creep processes (e.g., Handy et al., 2007). The strength of the brittle zone depends on the coefficient of friction on the fault and the pore-fluid pressure around the fault zone. Dynamically, the seismogenic zone is associated with the "locked" portion of the plate boundary fault as constrained by GPS and other geodetic data and coincides with the unstable slip region of fault rupture under rate and state friction (e.g., Lay et al., 2012). The extent of the seismogenic zone and the transition from unstable to stable slip depends on material properties and pore-fluid pressure around the fault surface (e.g., Scholz, 1998). Knowledge of the extent, geometry and material properties of the megathrust fault zone is therefore crucial to constrain the static and dynamic conditions under which large potentially damaging subduction zone earthquakes occur.

The megathrust fault remains largely inaccessible to direct sampling, except for exhumed ancient subduction thrust faults (e.g., Meneghini et al., 2010; Angiboust et al., 2015) and rare instances of direct drilling into the upper part of the subduction thrust (e.g., Chester et al., 2013). We therefore generally rely on indirect measurements to constrain its structure and physical properties via remote geophysical methods. Recent large-scale, high-density seismic array data have been very successfully in imaging the seismic structure of the subduction zone forearc, such as the megathrust fault zone, oceanic Moho, and upper plate Moho using receiver functions. Detailed images from three-dimensional regional seismic tomography and interface reflection structure models also provide additional constraints on subduction zone properties.

In recent years our view of the seismogenic zone has been improved by the discovery of widespread episodic slow slip events that occur downdip of the seismogenic zone. Slow slip events (sometimes referred to as slow earthquakes) had been recognized for some time in the literature using strainmeters (Linde et al., 1996) and seismometers (e.g., Kanamori and Stewart, 1979), although their importance and locations only became apparent when networks of GPS stations started recording and documenting their widespread occurrence. Associated with slow slip, a new source of seismic energy (called non-volcanic tremor) in the forearc was discovered by Obara (2002) off southwest Japan, which appeared as coherent noise propagating across arrays of seismograph stations. Rogers and Dragert (2003) then found similar signals in the forearc of the Cascadia subduction zone that occurred concurrently with slow slip events and both phenomena recurred episodically, which led to the term "Episodic Tremor and Slip", or ETS. Although initial studies focused on subduction zones where young and warm plates are being subducted beneath a continental margin, episodic slow slip and/or tremor events were later recognized in various other subduction zones, in the shallow part of the megathrust fault near the trench (Saffer and Wallace, 2015, and references therein) as well as in the deeper parts of strike-slip faults (e.g., Nadeau and Dolenc, 2005). In this paper we refer to episodic slow fault rupture events (with either or both documented slow slip and tremor) as slow earthquakes, and focus on the main deep subduction zone slow earthquakes, i.e. those that happen at depths of 30 to 45 km usually along a large extent of the subduction zone.

These slow earthquakes display important characteristics that provide a deeper understanding of fault zone properties and dynamics. Slow slip events and tremor can be correlated both temporally and spatially (e.g., Cascadia and Japan, Bartlow et al., 2011; Hirose and Obara, 2010), or temporally only (e.g., Hikurangi, Yabe et al., 2014). It is possible to have observed slow slip without detectable tremor, and perhaps observed tremor without detectable slow slip (however, see Frank et al., 2015). Both deep slow slip and tremor generally occur near but downdip of the brittle–ductile transition, approximately coinciding with the transition from unstable to stable sliding in a region of conditional stability (e.g., Scholz, 1998; Fig. 1), although there may be a gap between the slow earthquake source region and the seismogenic zone in some cases (Hyndman et al., 2015). Their occurrence may be induced by fluid flow and fluid processes at the plate interface and within the overlying plate (Rubinstein et al., 2010, and references therein). Low frequency earthquakes (LFEs) have also been observed in coincidence with the slow slip and tremor in subduction zones, with focal mechanism and location consistent with interplate slip (Shelly et al., 2006, 2007). Recent seismic and numerical modeling results point to the contribution of elevated fluid pressure near the plate interface (Kodaira et al., 2004; Liu and Rice, 2007; Audet et al., 2009; Song et al., 2009). These findings are consistent with thermo-petrological models that predict significant fluid production in the vicinity of the slow earthquake source region from dehydration of the subducting oceanic crust (Hyndman and Peacock, 2003). Nevertheless, the variety of thermal and petrologic conditions across different subduction zones precludes a simple relation between slow earthquakes and the thermal state or dehydration stages in the subducting plate in which they occur (Peacock, 2009).

Several reviews on the observations of slow earthquakes have been published recently (Beroza and Ide, 2011; Gomberg et al., 2010; Rubinstein et al., 2010; Schwartz and Rokowski, 2007). In this review we focus on the structural and geological environment in which slow earthquakes occur as inferred primarily from teleseismic studies. In particular we examine structural properties of the slow earthquake source region at six well-studied subduction zones: Cascadia, Nankai, Mexico, Costa Rica, Alaska, and Hikurangi (Fig. 2). The first three are considered as "hot" subduction zones, i.e., for which the seismogenic zone is thermally controlled downdip before the mantle wedge corner, and the other three are cooler. We first define the forearc structural elements and describe their seismic properties based on thermo-petrological models of metamorphism. We then focus on subduction zone structure inferred from teleseismic scattering techniques and high-resolution tomographic studies for the six subduction zones. Lastly we discuss the controls that structure may have on slow earthquake behavior.

2. Seismic structure of the subduction zone forearc

Slow earthquakes in subduction zones generally occur at and near the interface between the subducting slab and the overlying crust and mantle wedge (Fig. 1). The slab-mantle interface downdip of the forearc mantle corner is composed of some combination of heterogeneously deformed oceanic crust and sedimentary cover juxtaposed with hydrated and metasomatized materials. Recent receiver function studies of the slab-mantle interface have identified zones of low seismic velocity and high P-to-S velocity ratio (Vp/Vs) at or near the top of the subducting lithosphere. Abers (2005) reported a 2–8 km thick, low-velocity channel at the top of the downgoing plate at various subduction regions, that has up to 14% slower P-wave velocity (Vp) at depths less than 150 km. These low-velocity features also extend updip where the slab is juxtaposed to continental crust and have been interpreted as extensively hydrated assemblages in the subducting lithosphere (Abers, 2005; Bostock, 2013). Such hydrated materials can promote aseismic behavior at depths greater than the forearc mantle corner (Peacock and Hyndman, 1999).

There are two sources of fluids in subduction forearcs: evolved pore waters as the pore structure collapses and metamorphic dehydration reactions with increasing temperature and pressure, the latter likely being more important at the depths of slow earthquakes (e.g., Peacock et al., 2011). The thermal structure of the subducting slab is therefore the main control on the production of metamorphic fluids. Fig. 3