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Thermal–petrological controls on the location of earthquakes within subducting plates

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A B S T R A C T

We find that in young and warm subducting plates, earthquakes occur just below the Moho. In older plates, earthquakes occur throughout the subducting oceanic crust, as well as the subducting mantle. We document this behavior in several subduction zones where there are independent constraints on earthquake locations and slab structure, specifically for northern and southern Japan, Alaska, and Cascadia. The differences in earthquake depth relative to subducting crust may reflect large differences in temperature and thus locations of major dehydration reactions. In colder slabs, the crust passes through blueschist-facies dehydration reactions, while in Cascadia and Nankai the major dehydration reactions in crust may be due to zoisite- and amphibole-breakdown or associated melting. The cold paths allow more mineral-bound H_2O to be retained within the crust at shallow depths, eventually released upon dehydration over shorter time intervals than warm paths. The cold path dehydration reactions also result in net positive volume changes of solid+fluid, with solid volume decreasing less than the volume of H_2O produced. On hot paths the net volume changes are negative, with solid volumes decreasing more than the volume of H_2O produced. The difference in behavior could drive a net increase in pore pressure upon dehydration for the cold but not the hot crustal paths. The difference in rate of release in H_2O, and difference in sign of net system volume change may promote seismogenesis in cold subduction zones but inhibit it in the crust of warm slabs. Within the mantle of the downgoing plate earthquakes mostly occur where serpentine is stable or breaks down, in both settings.

1. Introduction

While the largest earthquakes in subduction zones lie on interplate thrust faults, seismicity continues much deeper within the downgoing slab, well past the apparent downdip limit of stick-slip behavior on the thrust zone. These deeper earthquakes seem to occur at conditions at which "normal" frictional conditions do not operate, leading to decades of speculation about their origins (e.g., Wadati, 1928; Raleigh and Paterson, 1965; Frohlich, 1989; Green and Houston, 1995; Kirby et al., 1996; Jung et al., 2004). As they descend subducting plates undergo a series of dehydration reactions, releasing fluids and increasing density of the remaining solid (e.g., Schmidt and Poli, 1998; van Keken et al., 2011) over depth ranges similar to those where many earthquakes occur. This has led many to argue that the dehydration process somehow facilitates earthquakes (Hacker et al., 2003b). Other possibilities, such as thermally modulated ductile instabilities in certain sets of conditions have also been proposed (Ogawa, 1987; Kelemen and Hirth, 2007). Differentiating between them may rely upon a better understanding of the physical conditions and systematics of these earthquakes in situ.

As imaging and hypocentral determination have become more accurate, it is becoming possible to tell where earthquakes lie relative to subducting crust at depths less than 200–300 km (e.g., Abers et al., 2006; Kita et al., 2006). Several recent advances in imaging methods and instrumentation have greatly increased the precision of both hypocenters and determination of the internal structure of slabs, such as through high-resolution tomography and migration of receiver functions. These advances are particularly successful in regions that have seen the deployment of dense temporary arrays of broadband seismographs or are characterized by high-quality dense long-term monitoring (e.g., in Japan and North America) (Fig. 1). With a small number of such studies now available, it is now possible to evaluate systematics of subduction zone behavior at the scale of subducting crust.

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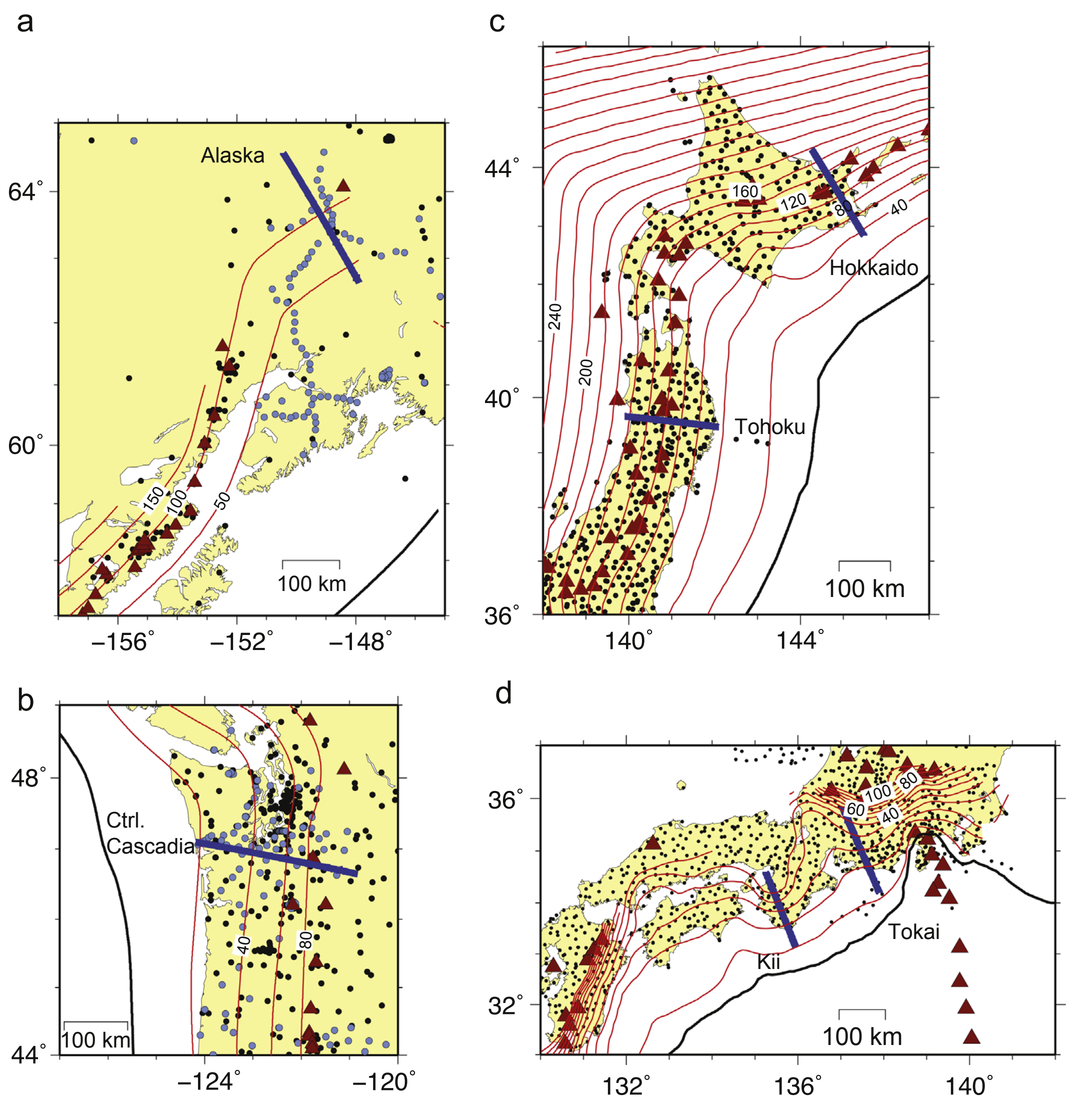

Fig. 1. Maps of study areas, showing location of cross sections analyzed (blue bars), trench (black line), contours to Wadati–Benioff Zone (red lines, depths in km labeled), and active volcanoes (red triangles). Black dots show permanent seismic stations, blue dots show temporary arrays used in this study. Volcanoes from Syracuse and Abers (2006) and updates. (a) Alaska, image transect following Abers et al. (2006); (b) Washington Cascades, image transect following Abers et al. (2009); (c) North Japan, transects following Kita et al. (2006, 2010b) with slab surface from Zhao et al. (1997) and Kita et al. (2010b); and (d) Southern Japan/Nankai Trough, transects following Hirose et al. (2008). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The importance of high-resolution imaging is that it provides information on the location of both the plate interface and internal interfaces—particularly the Moho of the subducting oceanic plate—independent of the subduction geometry inferred from seismicity. These images now allow us to answer in a systematic way the question “Do earthquakes occur within subducting crust or mantle?” We find that the answer depends on the thermal state of the slab; for many slabs the upper-plane seismicity takes place within the subducting crust, but for the hottest slabs all seismicity lies just below the Moho. (In northern Japan a double seismic zone is observed, but in this study examines just the upper plane of intraslab earthquakes where differences between behavior of subducted crust and mantle can be most easily compared.)

In most subduction zones earthquakes can occur within subducting mantle, and mantle dehydration reaction boundaries are largely isothermal, so it is difficult to tell fluid release or thermal weakening are more important in these earthquakes. However, within the subducting crust we observe that earthquakes occur in cold slabs but not in warm ones, even though crust passes through the same temperature range in both. Hence, the behavior of earthquakes within the crust constrains the mechanisms by which earthquakes can be generated. The sign of volume change during metamorphic dehydration appears to drive this behavior; hot crust dehydrates through different mineral systems than cold crust, resulting in reactions that inhibit rather than promote excess fluid pressure. Thus, dehydration processes seem to play an important role in generating intermediate-depth earthquakes.

2. Observations of seismicity in well-characterized subduction zones

2.1. Alaska

The Pacific plate subducts beneath Alaska at 55 mm/yr (DeMets et al., 1994) within 15° of normal to the strike of the imaged slab. The age of the lithosphere at the trench is roughly 38 Ma (Atwater, 1989). In the easternmost section of the Aleutian trench normal Pacific oceanic crust does not subduct, but instead the 50–55 Ma Yakutat terrane has entered the trench and is subducting to a depth of at least 130 km (e.g., Bruns, 1983; Fuis et al., 2008; Ferris et al., 2003). Seismic velocities of the Yakutat terrane indicate that it consists of