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Episodic deformation and inferred slow slip at the Nankai subduction zone during the first decade of CORK borehole pressure and VLFE monitoring

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ABSTRACT

With new data recovered in December 2011 and November 2012 from two Ocean Drilling Program (ODP) CORK (circulation obviation retrofit kit) borehole observatories in the toe of the Nankai subduction zone accretionary prism (Hole 808I) and in the subducting Philippine Sea plate (Hole 1173B) off Southwestern Japan, records of formation fluid pressure now span over 10 yr. Over nearly this same period of time the Japanese terrestrial HiNet array has enabled detection of small earthquakes across the breadth of the accretionary prism. The records include several formation fluid pressure anomalies and concurrent local very-low-frequency earthquake (VLFE) swarms. In the subducting plate, pressure anomalies are most commonly slow negative steps that are inferred to reflect dilatational strain associated with slow slip on the subduction thrust fault in the areas of VLFE activity. In three instances, concurrent positive impulsive anomalies are observed in the prism; these are inferred to reflect contraction when slip reaches the location of Hole 808I. The spatial distribution of VLFEs suggests that slow slip may occur in patches that cumulatively span the seaward half of the subduction prism. Two anomalies occurred at times of the largest earthquakes in the region, the September 2004 Mw 7.7 off-Kii earthquake 220 km to the northeast, and the March 2011 Mw 9.0 Tohoku earthquake roughly 900 km to the northeast. In the subducting plate, the observed changes in pressure are abrupt and consistent in sign with the expected coseismic strain (contractional and dilatational, respectively). In the case of the Tohoku earthquake, the co-seismic pressure decrease was followed 12 days later by an additional but slow decrease, and by an impulsive but complex and long-lived increase in the accretionary prism Hole 808I. In this instance, co-seismic cross-strike stress may have triggered post-seismic slip and the deformation seen in the plate and prism. Given the great distance from the Tohoku epicenter and small change in stress estimated at the Nankai observatory sites (ca. 7 kPa shear stress), triggering of local slip would require the outer subduction thrust and overlying prism in this region to be very fragile. To what degree this state might vary with time is not known, but tracking episodic slip in the seaward part of this and other subduction zones using formation-fluid-pressure and VLFE monitoring may provide valuable clues about the evolution of subduction faults through their thrust earthquake cycles.

1. Background

ODP Holes 808I and 1173B were drilled off Cape Muroto, Southwestern Japan, and instrumented in 2001 with the primary goal of determining fluid pressures and pressure gradients driving pore fluids from the Nankai subduction zone accretionary prism (Mikada et al., 2002). Hole 808I penetrates the toe of the accretionary prism down to the level of the decollement; Hole 1173B, located 13 km seaward, penetrates the sediments and just into the top of the igneous oceanic crust of the subducting Philippine Sea plate (Fig. 1). The holes were completed with permeable screens wrapped around the outside of 10 3/4 in. i.d. solid steel casing to provide hydraulic access to the formation at multiple depths (Fig. 2). Hydrologic isolation of the screens and good contact with the local formation are provided by collapse of the formation around the casing, and at some levels by inflatable packers (Mikada et al., 2002). Formation fluid pressure is transmitted from each of the screens to sensors at the seafloor via thick-walled hydraulic tubing strapped to the outside of the casing. At Hole 1173B, the interior of the casing was sealed at a depth of

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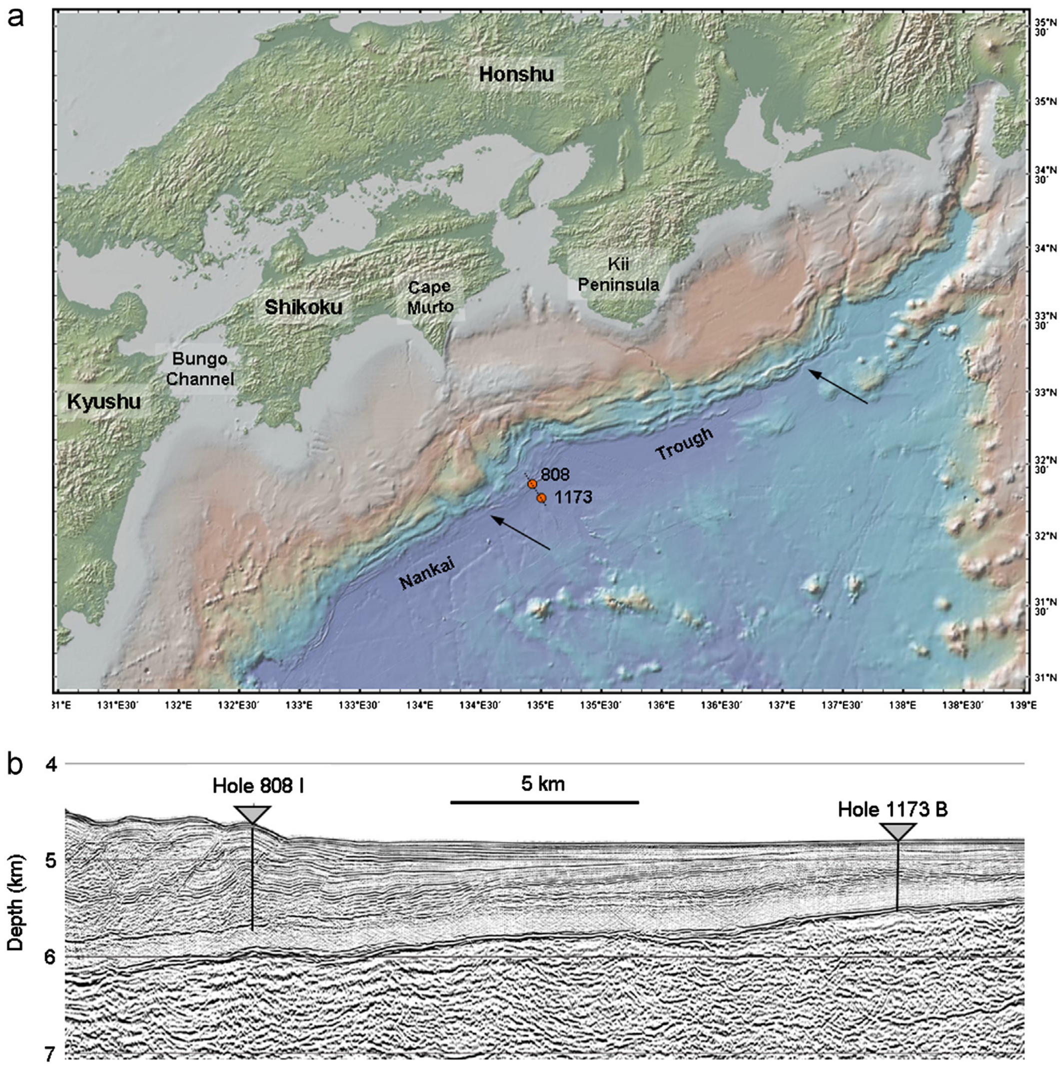

Fig. 1. Physiographic map (http://www.geomapapp.org) (a) and seismic reflection section (from Mikada et al., 2002) (b) of the Nankai Trough and adjacent subduction zone accretionary prism off southwestern Japan, showing the location of ODP CORK observatory Sites 808 and 1173. Direction of convergence of the Philippine Sea plate is shown with arrows. Location of the seismic section crossing the sites is indicated in (a).

approximately 633 m below seafloor (mbsf) with a mechanically set bridge plug. The interior of Hole 808I was not plugged until 2009, when a hydroscopic swelling plug was installed at the top of casing with the remotely operated vehicle (ROV) Kaiko 7 k. This was left to weep water through a ½ in. valve while swelling took place. The valve was closed at the time of the next site visit in December 2011. Bridge-plug seals were to have been set at the bottom of each hole at the time of drilling to allow installation of other sensors, but this was precluded by operational difficulties (see Mikada et al., 2002 for details). The first year of monitoring was ineffectual as a consequence of wellhead valves having been inadvertently rotated to an open position during installation operations, so reliable formation pressure data did not begin to be collected until August 2002.

The initial few years of monitoring revealed that despite this subduction zone being in an inter-seismic period—the last thrust earthquakes in the region having occurred in 1944 and 1946 (Fig. 3a)—discrete strain events involving the seaward part of the subduction thrust do occur. The first event was witnessed in the borehole data in 2003 and was associated with a very low frequency earthquake (VLFE) swarm within the outer accretionary prism a few tens of km landward of the borehole observatories (Davis et al., 2006) (Figs. 3b, 4 and 5a–c). Source characteristics determined for VLFEs like these show them to be located at or near the plate interface and possibly within the prism, to have dominantly low-angle thrust mechanisms (indicating cross-margin contraction of the prism and probably local slip on the plate interface), and to reflect very low stress drops (Ito and Obara, 2006a; Obara and Ito, 2005; Sugioka et al., 2012). The spatial and temporal relationships between the VLFEs and the pressure transients of this event, along with the signs of the transients (step-wise reductions in pressure in the incoming plate and positive impulsive transients in the prism; Fig. 6a) led to two important inferences. These were that slow slip on the shallow part of the subduction thrust may have been responsible for the VLFEs, and that slip propagated 40–60 km updip, reaching the prism toe 10 days after the initiation of the VLFE swarm to generate positive pressure pulses within the toe and dilatation of the incoming plate. This slip event appears to have been spontaneous.

A second event occurred in 2004, in this case triggered by a major shallow earthquake sequence within the subducting oceanic plate off Kii Peninsula 220 km to the northeast of the CORK observatory sites (Davis et al., 2009; Obara and Ito, 2005; Figs. 3b, 5 and 6b). Co-seismic and post-seismic strain generated by fault slip in the epicentral area appears to have dominated the pressure changes seen in the Philippine Sea plate Hole 1173B. Positive pressure steps were resolved at the times of the two largest earthquakes (Mw 7.2 and 7.5; Fig. 6b). These were nominally instantaneous (within the precision allowed by the 10 min sampling interval), much