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Tracing geologically constrained fluid flow pathways using a combination of heat flow measurements, pore water chemistry, and acoustic imaging near the deformation front of the Nankai Trough off the Muroto Peninsula, Japan

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ABSTRACT

Visual and acoustic surveys, heat flow measurements, and the analysis of pore water chemistry near the deformation front of the Nankai Trough accretionary prism off the Muroto Peninsula, Japan, show that fluid discharge is constrained by geological structures such as landslides. High heat-flow anomalies (up to 260 mW m^{-2}) exist near the base of a ca. 1.5 km ridge–trough structure, where the exit point of the secondary frontal thrust is thought to occur, but no other anomalies were detected. In contrast, on a 50-m-wide flat area on the steep slope inside the slope-scale landslide structure, where geological strata are exposed, high heat-flow anomalies of around 190 mW m^{-2} exist, accompanied by biological activity and methane-rich pore water. A sub-bottom profiler recorded strata cutting through the seafloor, which also supports the existence of a landslide. Based on these results, we propose a qualitative picture of fluid flow that may explain the observed heat-flow anomalies. Upward fluid flow through the frontal thrust, fluid flow cutting through geological strata, is inhibited near the foot of the slope, while fluid discharge occurs where the landslide exposes new surfaces as a result of geologically constrained fluid flow along strata.

1. Introduction

The discharge of pore water from accretionary prisms is an important element of the seismogenic activity associated with subduction zones, because the seismogenic zone is connected hydrologically with the forearc region through its seaward-extending décollement (e.g., Moore and Vrolijk, 1992; Saffer and Tobin, 2011). Fluid discharge rate (Brown et al., 2005) and pore water pressure (Davis et al., 2006, 2009, 2013) have been observed to change concurrently with large earthquakes and slow-slip events. Conversely, earthquakes induce landslides (e.g., Hampton and Locat, 1996) to affect the pathway of pore fluid flow. The degree of drainage not only influences the activity of seismic faults, but also affects the surface morphology of accretionary prisms (Saffer and Bekins, 2002, 2006).

Fluid discharge has previously been monitored using various methods including direct measurements of effluent fluid velocity (Linke et al., 1994; Tryon et al., 2001), proxies such as heat flow (Foucher et al., 1990; Henry et al., 1992; Zwart et al., 1996), reduced and low-chlorinity fluids (Toki et al., 2004), and heterogeneously distributed biological communities such as clams (e.g., *Calyptogena*) and tubeworms (e.g., *Lamellibrachia*) (Ashi, 1997; Bohrmann et al., 2002; Henry et al., 1992, 2002; Moore et al., 1990b; Olu et al., 1996, 1997). These anomalies usually coincide with each other (Foucher et al., 1990; Henry et al., 1992): anomalies of high heat flow and pore water chemistry are found where biological activity occurs, but no such anomalies are detected where biological activity is absent. This coupling is expected because fluid flow from below carries heat and reduced chemical species that are utilized by biological communities (Paull et al., 1984; Suess et al., 1985).

Fluid discharge is often controlled by geological structures such as landslides, faults, layered geological sequences, and talus deposits.

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Landslides are common near the deformation front of accretionary prisms including the Nankai Trough (Henry et al., 2002; Kawamura et al., 2009), the Cascadia subduction zone (McAdoo et al., 2000), and the Middle America Trench (Harders et al., 2011). Landslides that expose layered geological sequences are thought to have been formed associated with great earthquakes or elevated pore pressure (e.g., Hampton and Locat, 1996). At the Nankai Trough off Tokai, Henry et al. (2002) observed a correlation between fluid discharge and high-permeability geological structures (e.g., exposures of faults, and sandy layers). At the Nankai Trough off Kumano, Ashi (1997) reported that fluid discharge tends to occur slightly above the footwall area of fault scarps, where the surface exposure of the fault is predicted by seismic imaging but is covered by talus deposits. Ashi (1997) argued that fluid discharge in the middle of the slope is due to its high permeability relative to footwall areas. However, biological activity is often used as an indicator of fluid discharge (e.g., Olu et al., 1997), and the relationship between fluid discharge and geological structures has received relatively little attention. Combining measurements of heat flow and pore water chemistry, with visual and acoustic surveys at sub-kilometer scales, may help to improve our understanding of this interaction between geology and fluid flow.

This paper considers the influence of geological structures on fluid flow near the secondary frontal thrust of the Nankai Trough off the Muroto Peninsula, Japan, where anomalies of heat flow, pore water chemistry, and biological activity occur, but not always in the same locations. Our finding emphasizes that it is fundamental to conduct a suite of measurements simultaneously in order to figure out sub-seafloor fluid flow and its relation to geological structures (e.g., Ashi, 1997; Bohrmann et al., 2002; Henry et al., 2002; Moore et al., 1990a) in accretionary prisms. Monitoring fluid discharge in detail is essential to obtain better understanding of the activity of the seismogenic zone of accretionary prisms, because fluid discharge is related to earthquakes through many ways. The remainder of this paper is organized as follows. Section 2 summarizes the geological setting and the results of previous heat-flow surveys in the study area. Section 3 describes the observation methods, and Section 4 presents the results of visual and acoustic surveys, heat flow measurements, and analyses of pore water chemistry. Based on these observations, Section 5 proposes a qualitative model of geologically constrained fluid flow that may explain the observed features, and examine the effects of topography, sedimentation/erosion, and fluid flow on the heat flow to validate the model. Section 6 discusses the relationship between fluid discharge and the occurrence of thermal/geochemical anomalies to better understand the model results applied to the observations, and finally, Section 7 contains the conclusions.

2. Geological setting and previous heat-flow surveys

At the Nankai Trough, southern Japan, the Philippine Sea Plate (15–25 Ma) is subducting northwestward beneath the Japan Arc at a rate of ca. 5 cm yr^{-1} (Fig. 1; Seno et al., 1993). To the west of the trough, off the Muroto Peninsula, a fossil spreading-axis that is part of the Philippine Sea Plate (approximately 15 Ma in age) is subducting beneath Japan (Okino et al., 1994).

An accretionary prism, 1 km thick with an average seaward slope of 2°, has formed near the deformation front of the Muroto region (Moore et al., 2001). The deformation front is defined as the seaward end of the slope, or the seaward end of the deformed sub-seafloor geological layers and thrust faults detected by seismic studies. The décollement, a sub-horizontal slip plane of the major fault, is located at about 945 m bsf (below the seafloor) and is 30 m thick. Ocean Drilling Program (ODP) borehole 808 (Shipboard Scientific Party, 1991) is located between the exits of the primary and secondary frontal thrusts, penetrating the frontal thrust at about 400 m bsf. Here, the primary and secondary frontal thrusts are defined as the most seaward, and second most seaward, respectively, sequential thrusts detected by seismic studies; it is possible that these thrusts cut the seafloor.

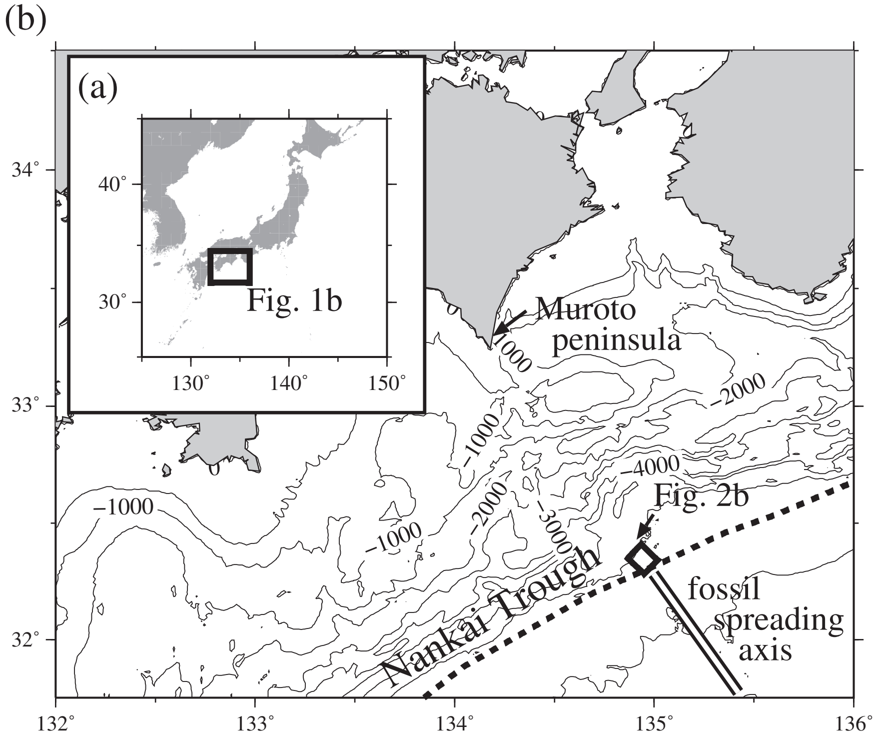

Fig. 1. Map of (a) Japan and (b) the deformation front of the Nankai Trough off the Muroto Peninsula. The box in (a) corresponds to the area of (b), and the box in (b) corresponds to the area of Fig. 2b.