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Difference in acoustic properties at seismogenic fault along a subduction interface: Application to estimation of effective pressure and fluid pressure ratio

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ABSTRACT

Fluid pressure along subduction plate boundaries plays a role in seismogenesis and tsunami genesis because it is strongly related to the physical properties of faults. In this study, we conducted P-wave velocity (Vp) and S-wave velocity (Vs) measurements for the hanging wall and footwall of a fossil subduction interface with pseudotachylyte located at the northern edge of the Mugi mélange in the Cretaceous Shimanto Belt, Shikoku, southwest Japan. This area corresponds to the depth of the shallow seismogenic zone in the transition zone between the inner and outer wedges. By combining the acoustic properties with parameters obtained from Amplitude Variation with Offset (AVO) analysis on the Nankai seismic profile, we estimated the fluid pressure at the seismogenic fault.

The Mugi mélanges are composed of shale matrices and are juxtaposed with the coherent unit of the Hiwasa formation in the north, which is composed mainly of sandstone. We collected 5 sandstone samples from the hanging wall (Hiwasa formation) and 4 mudstone samples from the footwall (Mugi mélange). We conducted velocity measurements while controlling both the fluid pressure and confining pressure by using two pumps. The effective pressure in each measurement ranged from 5 to 65 MPa with intervals of 5 MPa.

The Vp and Vs of sandstone increase exponentially with effective pressure from ~4500 to ~5000 m/s and ~2500 to ~3000 m/s, respectively. The Vp and Vs of the mudstone also increased exponentially from ~4100 to ~4500 m/s and ~1900 to ~2200 m/s, respectively.

We used AVO parameters along the décollement based upon a seismic profile of the Nankai trough, which is off Muroto 40–45 km landward from the trench axis, corresponding to approximately 66 MPa of effective pressure under a hydrostatic condition. By combining the velocities obtained from this study and the AVO parameters derived from the Muroto seismic data, we estimate the mean effective pressures for the hanging wall and the footwall as approximately 10–20 MPa and 8–10 MPa, respectively. The normalized fluid pressure ratios for the hanging wall and the footwall correspond to approximately 0.82–0.91 and 0.91–0.93, respectively. This high fluid pressure indicates a very low effective friction coefficient along the décollement in the transition zone, possibly causing a rupture to propagate to the shallower outer wedge and thus generating a large tsunami.

1. Introduction

Fluid pressure in subduction zones plays a significant role in our understanding of the transformation of mass and heat, wedge geometry, coupling of plate interface, and seismogenic behavior. In particular, fluid pressure has the effect of weakening the strength of the plate interface; this is strongly related to fault behavior such as rupture propagation, slip localization, and the mechanism of slip (e.g., Scholz, 1998). Because of its essential role, many studies have been conducted to estimate fluid pressure or fluid pressure ratios along subduction interfaces (e.g., Saffer, 2003; Saffer and Bekins, 1998; Tobin and Saffer, 2009; Tobin et al., 1994; Tsuji et al., 2008). They have proposed very high fluid pressure ratio and low effective stress along décollement. These estimations, however, have had a limited focus on the shallower portion of the décollement down the beginning of the seismogenic zone, because they mainly address physical properties based upon samples from ocean drilling projects that drill into shallow accretionary wedges which are ~1000 m thick. The estimation of fluid pressure in a deeper subduction interface within a so-called seismogenic zone is rare; however, it is important to understand the role of fluid pressure along subduction plate interfaces in seismogenic zones. Fluid pressure at shallower portion of seismogenic zone along subduction plate interface is possibly one of the keys to understand the processes in seismic-rupture propagation from seismogenic zone to shallower aseismic zone as observed in Tohoku earthquake (Ide et al., 2011; Kimura et al., 2012). The examination of fluid pressure at deeper décollement can be connected with the studies estimating high fluid pressure for shallower décollement. In this study, we present estimations of fluid pressure and fluid pressure ratios at the seismogenic depth along a

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subduction zone, using the elastic properties of an on-land accretionary complex combined with reflection coefficients obtained from multichannel seismic reflection data.

Geological studies of on-land accretionary complexes have revealed various forms of deformation such as tectonic mélange formation (Cowan, 1985; Hashimoto and Kimura, 1999; Hashimoto et al., 2003; Kimura and Mukai, 1991; Onishi and Kimura, 1995), brittle reactivation of mélange foliations (Shibata and Hashimoto, 2005), shear veins (Hashimoto et al., 2002; Hashimoto et al., 2012; Shibata and Hashimoto, 2005), an underplating fault (Ikesawa et al., 2003; Ujiie et al., 2007b), a seismogenic fault at the northern edge of the mélange zones (Hashimoto et al., 2012; Ikesawa et al., 2003; Kitamura et al., 2005; Ujiie et al., 2007a, 2007b), and out-of-sequence thrusts (Kondo et al., 2005; Mukoyoshi et al., 2006; Ohmori et al., 1997; Okamoto et al, 2006). Here, we focus upon a seismogenic fault at the northern boundary of a mélange zone. Localized faults with pseudotachylyte or partially melted materials were found at the boundary of the Okitsu mélange, Mugi mélange, and Yokonami mélange in the Cretaceous Shimanto Belt, southwest Japan (Hashimoto et al., 2012; Ikesawa et al., 2003; Kitamura et al., 2005; Ujiie et al., 2007a), which are boundaries between the northern coherent unit composed of sandstone in the hanging wall and the mélange zone mainly composed of foliated shale in the footwall. In addition, paleothermal structures across the boundary are not cut into by the fault zones, suggesting that the boundaries were formed along a décollement.

We measured the Vp and Vs of samples from the hanging wall and footwall of the seismogenic boundary fault at controlled effective pressures. By comparing the amplitude variations with the offset (AVO) parameters from seismic reflectors in the Nankai Trough with those of elastic velocities from the Shimanto Belt, we estimated the fluid pressure and fluid pressure ratio along the décollement at a seismogenic depth.

2. Geological setting

The study area is in a hanging wall and footwall at the northern boundary of the Mugi mélange, in the Cretaceous Shimanto Belt, southwest Japan (Fig. 1). The Shimanto Belt is an on-land accretionary complex that is exposed parallel to the Nankai Trough, from the Kanto Region to Okinawa Islands (Fig. 1). The Shimanto Belt in Shikoku Island is the most studied on-land accretionary complex because of its readily available lithologies, age, paleothermal structures and deformation structures. The Shimanto Belt is divided in two on the basis of age,

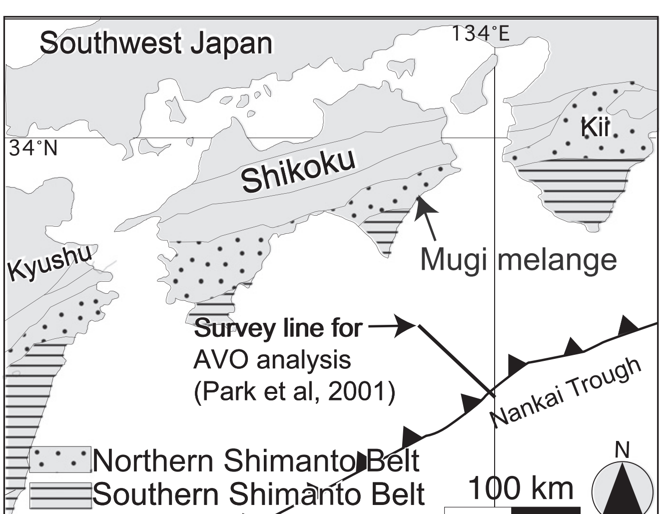

Fig. 1. Distribution of Shimanto Belt in Southwest Japan. The location of the Mugi mélange is also shown.

forming the Cretaceous Shimanto Belt in the north and the Paleogene Shimanto Belt in the south. The Shimanto Belt is further divided into two units on the basis of lithologies. One is a mélange unit with asymmetric blocks composed of sandstone, basalt, and chert surrounded by a foliated shale matrix, and the other is a coherent unit composed of sandstone and mudstone with weaker deformations (Taira et al., 1988).

The Mugi mélange is composed of tectonic mélanges, mainly with sandstone blocks and shale matrices, and small amounts of basalt, chert, tuff, and red shale. The oceanic materials represent the ocean floor stratigraphy. The continuous features of the ocean floor stratigraphy show a map-scale duplex structure, indicating that the Mugi mélange was formed by underplating (Shibata et al., 2008). The Mugi mélange is Santonian to Campanian in age, as concluded on the basis of its radiolarian age (Hollis and Kimura, 2001). The Hiwasa formation is a coherent unit that is located at a structurally higher position on the Mugi mélange. Its lithologies are composed mainly of sandstone and mudstone. The radiolarian age of the Hiwasa formation is in the Campanian to Maastrichtian age range (Hollis and Kimura, 2001). The paleo-temperature, as derived from its vitrinite reflectance, indicates a value of approximately 175–200 °C in this area (Ohmori et al, 1997). Fluid inclusion analysis conducted in the Mugi mélange consistently showed a temperature range of approximately 130–245 °C and pressure in the range of 90–150 MPa (Matsumura et al., 2003). The geothermal gradient from the temperature–pressure condition is approximately 55–65 °C/km, which is a relatively higher value than the general geothermal gradient, possibly because of the subduction of the young plate. This higher geothermal gradient can be an analog of the modern setting of the Nankai Trough, with its young slab subduction.

The northern boundary of the Mugi mélange we focused on in this study is the boundary to the Hiwasa formation, which is a coherent unit in the hanging wall. Its lithologies are bounded by very thick sandstone in the hanging wall, and the mélanges are mainly composed of a shale matrix, with minor sandstone blocks in the footwall (Mugi mélange). Localized faults with pseudotachylyte have been observed in the boundary (Kitamura et al., 2005; Ujiie et al., 2007a), and the fault does not cut into the paleothermal structure (Ohmori et al., 1997), suggesting that the fault was a seismogenic fault along a décollement as will be described in detail later.

The study area ranges from the boundary fault to approximately 100 m northward in the Hiwasa formation in the hanging wall, to approximately 200 m southward in the Mugi mélange in the footwall (Fig. 2). We collected 5 sandstone samples from the hanging wall and 4 shale samples from the footwall (Fig. 2). To avoid weathering, we collected the samples during low tide, as they are under seawater during high tide.

3. Setting of the boundary fault

The boundary fault that is focused on in this study is located at the northern edge of a tectonic mélange zone that cuts into the tectonic mélange. The tectonic mélange is considered to be formed by shear along the décollement (e.g., Cowan, 1985; Kimura and Mukai, 1991; Onishi and Kimura, 1995). In addition, the boundary fault does not cut into the paleo-maximum thermal structures (Ohmori et al., 1997). An out-of-sequence thrust (OST) cuts into the paleo-maximum thermal structures, indicating that the formation of the OST took place after overprinting of the paleo-maximum thermal structures (e.g., Ohmori et al., 1997). Taking these events into account, the boundary fault is interpreted as having been formed along the décollement after the mélange formation, and prior to the formation of OSTs. The paleo-maximum temperature, as derived from vitrinite reflectance, indicates a value of approximately 175–200 °C (Ohmori et al, 1997), and temperature–pressure conditions, as derived from fluid inclusion analysis, consistently showed values in the range of approximately 130–245 °C and 90–150 MPa (Matsumura et al., 2003) as described earlier. On average, the temperature and pressure conditions for the boundary fault are