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Co-seismic frictional melting along an out-of-sequence thrust in the Shimanto accretionary complex. Implications on the tsunamigenic potential of splay faults in modern subduction zones

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Abstract

Out-of-sequence thrusts (OST) play an important role in the thickening of accretionary prisms, formation of forearc basins, and tsunami generation in subduction zones. By detailed investigations of geological and paleogeothermal structures, an ancient seismogenic OST is identified in the Shimanto accretionary complex, southwest Japan. This OST consists of a mappable en echelon fault system developed at a late stage of the accretionary process. The estimated accumulated displacement of 2.5–8.5 km and formation depth of 2.5–5.5 km, based on a thermal analysis, indicates much higher fault activities sense of slip with a sinistral slip, and the large displacement was distributed among multiple small faults each with a small offset. Most of the faults in the en echelon fault system recorded repeated brittle failure, and one fault preserves pseudotachylyte, a fault rock indicative of seismic faulting. This is the first report of pseudotachylyte along an OST in an accretionary prism. Repeated fracturing in the same narrow shear zones (each only a few millimeters thick) suggests the OSTs perform as major shear localized zone in the accretionary prism. Shallow estimated formation depth and consequent low normal stress also support the hypothesis by a weak coupling along this fault zone. These findings are in accord with a thrust activity in the shallow portion of the accretionary prism being associated with rupture propagation from the deep seismogenic region. This OST showed high activity and repeated faulting in the shallow portion of the accretionary prism, comparable to that of the submarine tsunamigenic OST in the present Nankai trough.

Keywords: out-of-sequence thrust; Shimanto accretionary complex; paleogeothermal structure; vitrinite reflectance; fault rocks; pseudotachylyte

1. Introduction

Although quantification of the properties of seismogenic fault zones is crucial for elucidating the mechanisms and processes of earthquakes, such properties are still poorly understood. Because it is difficult to recover rock samples from trench-type seismogenic zones, the detailed nature and structure are not well understood, compared with onland counterparts.

Recent studies have shown that the Shimanto accretionary complex of southwest Japan, which is part of the onshore extension of the present Nankai Trough subduction zone, experienced a maximum

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temperature in the range of 150–350 °C (e.g., [1–4]), similar to temperatures suggested in the present seismogenic zones [5,6]. Ikesawa et al. [7] found pseudotachylyte, which is a typical evidence for seismic slip in a fault zone, in the Okitsu Mélange of the Cretaceous Shimanto accretionary complex. They concluded that the fault zone was a flat-lying plate-boundary decollement that did not crosscut the previous stratigraphic sequence. Another major fault type that develops in accretionary prisms is the out-of-sequence thrust (OST). An OST is characterized by late faulting subparallel to the preexisting stratigraphic structure that thickens the accretionary prism [4,8–11]. In some subduction zones, the growth of the outer ridge of the accretionary prism caused by the progressive displacement along an OST leads to development of a forearc basin. Tilted forearc-basin-fill sediments are found just above the OST in the Nankai accretionary prism [12]. Moreover, if it reaches the seafloor, an OST is expected to contribute to tsunami generation because sudden displacement along the shallow portion of the OST will change significantly the seafloor topography. Park et al. [12] imaged a splay-faulted OST off Kumano Basin where a large tsunami was generated by the 1944 Tonankai earthquake. The fault slip distribution model determined by tsunami waveform inversion for the 1944 Tonankai earthquake shows that the tip of the slip area coincides with the distribution of the OST off Kumano basin [13].

It is expected that a fault rock and fluid behavior during seismic slip affect dynamic friction. Many mechanical lubrication models have been proposed such as: acoustic fluidization [14], elastohydrodynamics [15], thermal pressurization [16–19] and frictional melt models (e.g., [20,21]). Frictional behavior in the fluid-bearing fault is one of noticeable object [22–24], and the fault rock analysis in the accretionary sediment will contribute to the understanding of this subject.

In this paper, we clarify the tectonic setting of an exhumed OST in the Shimanto accretionary complex and its relationship with the submarine OST in the Nankai subduction zone. Analysis of the fault rock of the shallow portion of the OST provides clues for understanding fault propagation there and the mechanism of tsunami generation.

2. Geological setting

The accretionary complex of southwest Japan is divided into three units: the Jurassic Chichibu, the Cretaceous Shimanto, and the Tertiary Shimanto complexes. The boundary between the Chichibu and Cretaceous Shimanto complexes is the Butsuzo Tectonic Line (BTL). The Cretaceous Shimanto accretionary complex on Shikoku Island, furthermore, can be subdivided into two groups: the Lower Cretaceous Shinjyogawa Group and the Upper Cretaceous Taisho Group [25] (Fig. 1). These groups are characterized by a fold and thrust belt with southward vergence. The Taisho Group is composed of four representative types of facies: slope basin, forearc basin, trench-fill, and mélange facies, with trench-fill sediments being dominant. The sedimentary succession of trench-fill, forearc basin, and slope facies compose a relatively coherent sedimentary sequence, with only locally tight fold structures. In contrast, the mélange facies have suffered much greater deformation, and include 'exotic' oceanic blocks. From northern older to southern younger rocks, the Taisho Group is composed of the Yokonami Mélange, the Shimotsui Formation, the Kure Mélange, the Nonokawa Formation, the Okitsu Mélange, and the Nakamura and Sada formations [26]. The Yokonami, Kure, and Okitsu mélanges are interleaved within the trench-fill sediments (Fig. 1). These mélange units are significantly more deformed than the surrounding units, and they incorporate exotic oceanic blocks such as basaltic blocks [25]. These mélange and trench-fill sediments are bounded by generally EW-trending thrust faults [26].

A NW–SE en echelon fault system cuts across the Kure Mélange and Nonokawa Formation with large cumulative displacement. This en echelon fault system may have developed after emplacement of the Kure Mélange and Nonokawa Formation.

3. Paleogeothermal analysis

3.1. Previous report

A regional thermal structure analysis of southwestern Shikoku based on the vitrinite maximum reflectance (R_{max}) indicated that R_{max} increases gradually from the BTL to the Kure Mélange, from 1.1–1.2% to 2.2%, drops suddenly to 1.2% immediately south of the Kure Mélange, and then gradually increases again southward to 2.0% [3] (Fig. 2). A similar trend of a gradual increase and then a sudden drop, repeated at 20- to 30-km intervals, independent of the facies, ages and geologic structure has been found elsewhere in the Shimanto complex (e.g., eastern Shikoku [1,2,4] and northeastern Kyushu [11]). This independent thermal structure has been explained by the formation of the thermal structure after the emplacement of the rock and a sharp