Journal of Structural Geology 29 (2007) 599–613

JOURNAL OF STRUCTURAL GEOLOGY

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Pseudotachylytes in an ancient accretionary complex and implications for melt lubrication during subduction zone earthquakes

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Received 2 June 2006; received in revised form 30 October 2006; accepted 30 October 2006

Abstract

Pseudotachylyte-bearing fault zones, found in the Shimanto accretionary complex, southwest Japan, developed during subduction or underplating at seismogenic depths. The pseudotachylytes occur in narrow dark veins less than a few millimeters thick that are sharply bounded by foliated cataclasites that originated from a mélange. The microstructures of pseudotachylytes are represented by a fragment-laden, glass-supported texture resulting from the rapid cooling of the frictional melt. Transmission electron microscopy reveals the presence of glass in which euhedral microcrystals of mullite are locally developed. The compositions of the pseudotachylyte matrix and the characteristics of the unmelted grains and microlites in the matrix suggest that frictional melting occurred in an illite-rich slip zone with a minimum melting temperature of 1100 °C. The viscosities of the frictional melt were calculated from the pseudotachylyte matrix composition as well as from the volume fraction and aspect ratio of the unmelted grains. The viscosities at 1100 °C range from 85 to 290 Pa s, and the corresponding shear resistance along a 1-mm-thick melt layer at a slip rate of 1 m/s was 0.1–0.3 MPa. The formation of a melt layer in an illite-rich slip zone can possibly induce large stress drops, increase the slip rate and enhance rupture propagation, which together could affect the earthquake magnitude in a subduction zone.

Keywords: Pseudotachylyte; Frictional melting; Dynamic weakening; Accretionary complex; Subduction zone

1. Introduction

Approximately 85% of the seismic moment release occurs at subduction zones (Scholz, 2002). Previous studies have revealed that temperature limits of ∼100–150 °C and ∼350–450 °C coincide with the updip and downdip limits, respectively, of the seismogenic zone in subduction zones (Hyndman et al., 1997; Oleskevich et al., 1999). The updip limit of the seismogenic zone appears to be controlled by diagenetic to low-grade metamorphic processes along subduction thrusts (Moore and Saffer, 2001), whereas the downdip limit may correlate with the onset of plastic deformation (Hyndman et al., 1997). For accretionary margins such as Nankai and Cascadia, the seismogenic zone is located mainly beneath the accretionary prism. In contrast to the shallow subduction thrusts where the Ocean Drilling Program has drilled boreholes (Ujiie et al., 2003), subduction thrusts at seismogenic depths are not yet accessible for study; hence, the mechanisms and dynamic processes of seismic slip in subduction zones are not yet well understood.

An accretionary complex consists mainly of offscraped and underplated rocks (Moore, 1989). Some underplated rocks in ancient accretionary complexes may record deformation related to paleo-subduction thrusts (Fisher and Byrne, 1987; Ujiie, 2002). Thermal and metamorphic analyses suggest that some underplated rocks were subducted in the thermal regime of the seismogenic zone (Vrolijk et al., 1988; Ohmori et al., 1997), so that on-land analogs of subduction thrusts at seismogenic depths may be exposed in underplated rocks of ancient accretionary complexes.

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0191-8141/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsg.2006.10.012

Recently, pseudotachylytes (i.e., solidified frictional melts produced during seismic slip) have been discovered in the Shimanto accretionary complex in southwest Japan (Ikesawa et al., 2003) and the Kodiak accretionary complex in Alaska (Rowe et al., 2005). They are considered to have developed in underplated rocks at seismogenic depths and thus may help our understanding of the dynamics of earthquake faulting in subduction zones. Descriptions of pseudotachylytes in accretionary complexes are as yet severely limited: there is little information on their microstructures, compositions, and melting temperatures. At present, it is uncertain how the frictional melting of subducted material affects seismic slip. The high viscosity of a frictional melt may restrain seismic slip (Scholz, 1980), alternatively, the generation of a low-viscosity melt from subducted material may cause an increase in the slip rate and control the efficiency with which stored strain energy is released, thus, increasing the earthquake magnitude in subduction zones. In contrast to pseudotachylytes in other geological settings, such as continental plutonic and metamorphic rocks that indicate fault weakening by friction-induced melts occurs during earthquakes (Spray, 1993; Di Toro et al., 2006), the effects of frictional melting on a seismic slip in a subduction zone remain poorly understood, reflecting the paucity of research on pseudotachylyte generation in subducted material.

In this study, we analyzed pseudotachylytes from the Shimanto accretionary complex of eastern and western Shikoku, southwest Japan (Fig. 1). We first describe the characteristics of the fault rocks and the microstructures and compositions of the pseudotachylytes, and then we calculate the viscosities and cooling times of the frictional melts. Based on these descriptions and calculations, we discuss the role of frictional melting on seismic slip in the paleo-subduction zone. Our results may be applicable to fault zones in other sediment-rich subduction zones, where the subducted material is similar to the material in the coseismic slip zones of the Shimanto accretionary complex.

2. Paleotectonic settings of pseudotachylyte-bearing fault zones

The Shimanto accretionary complex is exposed along the Pacific side of southwest Japan and is divided into Cretaceous and Tertiary units (Fig. 1a). It consists mainly of offscraped coherent turbidites and underplated tectonic mélange, and it represents an ancient analog of the Nankai accretionary margin where earthquakes larger than magnitude (M) 8 are generated repeatedly (Ando, 1975; Taira et al., 1988). Pseudotachylyte-bearing fault zones occur in the Late Cretaceous Shimanto accretionary complex of eastern (Mugi area) and western (Okitsu area) Shikoku.

The paleotectonic settings of the pseudotachylyte-bearing fault zones have been examined by Ikesawa et al. (2003) and Kitamura et al. (2005) and are briefly summarized here. In both the Mugi and Okitsu areas, the pseudotachylyte-bearing fault zones separate offscraped coherent turbidites above from the mélanges below (Fig. 1b and c). The mélanges consist of a sheared black shale matrix with blocks of pillow and massive basalt, hemipelagic red shale, and sandstone. They display the tectonic disruption of ocean floor stratigraphies caused by layer-parallel shear and vertical loading during subduction. These disrupted stratigraphies are imbricated at least five times in the mélanges, delineating a duplex structure (Fig. 1b and c). The possible tectonic settings of these pseudotachylyte-bearing fault zones in the Shimanto accretionary complex are (1) plate boundary subduction thrusts, (2) roof thrusts of duplex structures, (3) out-of-sequence thrusts, and (4) intracrustal faults. The first and second are associated with the processes of subduction and underplating, respectively. In contrast, the third and fourth are related to later exhumation processes.

The foliation of the mélanges and the shear surfaces of the pseudotachylyte-bearing fault zones generally strike east–northeast and dip steeply northward, showing that these fault zones are subparallel to the mélange fabric formed during subduction. This is expected in the subhorizontal subduction thrust and flat parts of the hinterland-dipping duplex structure (i.e., floor and roof thrusts) because the mélange fabric formed during subduction is generally subhorizontal (Fisher and Byrne, 1987; Ujiie, 2002). In contrast, out-of-sequence thrusts and intracrustal faults crosscut the mélange fabric at various angles. The kinematics of the pseudotachylyte-bearing fault zones indicate a southward-directed, sinistral reverse shear sense (Fig. 1b and c), which is consistent with the shear directions of both the mélanges and the underplating-related thrusts, and with the relative plate motion during the Late Cretaceous (Onishi and Kimura, 1995; Kitamura et al., 2005). The thermal structure commonly shows a sharp discontinuity across the out-of-sequence thrusts and the intracrustal faults with a large displacement, resulting in a thermal inversion across the faults (e.g., Sakaguchi, 1996; Ohmori et al., 1997). However, the maximum paleotemperatures determined by vitrinite reflectance indicate that there was no distinct thermal inversion across the pseudotachylyte-bearing fault zones (Ikesawa et al., 2003; Kitamura et al., 2005). Considering the thermal structures in subduction zones (e.g., Underwood et al., 1993), the isotherm is nearly parallel to both the subduction thrust and roof thrust of the hinterland-dipping duplex for at least several kilometers without distinct thermal inversion across these thrust faults. Therefore, the pseudotachylyte-bearing fault zones are interpreted to represent subduction thrusts or the roof thrusts of the duplex structures rather than out-of-sequence thrusts and intracrustal faults (Fig. 2).

The maximum paleotemperatures of the host rocks were in the range of 170–190 °C and 230–270 °C in the Mugi and Okitsu areas, respectively. If we adopt a paleogeothermal gradient of 50 °C/km, as recorded in the Late Cretaceous Shimanto accretionary complex (Sakaguchi, 1996), the corresponding depths are 3.2–4 km and 4–6 km in the Mugi and Okitsu areas, respectively. Thus, we can infer that the pseudotachylyte-bearing fault zones occurred at seismogenic depths in a subduction zone (Marone and Scholz, 1988).