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Fluid overpressure along an Oligocene out-of-sequence thrust in the Shimanto Belt, SW Japan

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ABSTRACT

Out-of-sequence thrusts (OSTs) exposed in ancient accretionary prisms are considered as fossil analogs of present-day megasplay faults in subduction margins and can provide direct information about the conditions of deformation during thrust activity. In modern as well as in ancient accretionary prisms, first-order megasplay faults or OSTs truncate or merge with faults of lesser importance called second-order OSTs. Structural analysis of the Makinokuchi fault, a branch of an Oligocene to lower Miocene second-order OST in the Tertiary Shimanto Belt of central Kyushu, SW Japan, brings information about the conditions of deformation at the time of thrusting. The studied exposure shows that the fault footwall and, to a much lesser extent, the fault hanging-wall, consist of quartz-cemented syntectonic dilatant hydraulic breccias testifying to pore fluid pressures larger than the least principal stress component. The footwall sandstones are crossed by several centimeters thick quartz veins that merge with the footwall breccias. The continuity between the veins and the breccias suggest that the veins acted as conduits which likely collected fluids from the footwall side sandstones upward and toward the fault. Fluid inclusions indicate that the quartz cementing the breccias and that filling the feeder veins crystallized from similar fluids and under similar pressure and temperature conditions (245–285 °C and 5–8 km depth). These similarities suggest that the fluids responsible for syn-tectonic hydraulic brecciation were collected from the footwall through the conduits. The fluid inclusion trapping temperatures are close to the temperatures expected to be reached along the seismogenic zone. Our analysis shows that fluid overpressures can play a key role in the growth and activity of second-order OSTs in accretionary prisms and suggests that fluids collected along second-order OSTs or splay faults may flow upward along first-order OSTs or megasplay faults.

1. Introduction

Megasplay faults crossing accretionary prisms (Moore et al., 1991; Park et al., 2000, 2002; Collot et al., 2008; Hsu et al., 2013) are suspected to propagate seismic ruptures from the plate interface upward and could therefore be responsible for strong motions in coastal areas and for the triggering of major tsunamis. Recent examples of such possible trajectories include the 1944 Tonankai earthquake (Tanioka and Satake, 2001), the 1946 Nankaido earthquake (Cummins and Kaneda, 2000; Cummins et al., 2001; Park et al., 2000, 2002), the 1964 Alaska earthquake (Plafker, 1972), the 2004 Sumatra earthquake (Waldhauser et al., 2012) or the 2010 Maule earthquake (Melnick et al., 2012).

In addition to their possible role in conveying large interplate ruptures upwards, megasplay faults seem to be the site of very low frequency (VLF) earthquakes and, as such, may mechanically interact with the deep parts of the plate interfaces by releasing a part of the strain. This has been recognized in the Nankai accretionary prism (Ito and Obara, 2006a; Obana and Kodaira, 2009). The Nankai VLF earthquakes nucleating in the vicinity of the emerging megasplay fault recognized there are characterized by very low stress drops, suggesting a weakening of the faults by fluids (Ito and Obara, 2006b).

The shallow parts of megasplay faults can be explored by drilling. For example, drilling during IODP NanTroSEIZE Project (expeditions 314, 315 and 316 and ensuing expeditions) crossed the shallow part of the SW Japan Nankai accretionary prism main megasplay fault and succeeded in obtaining fluid and rock samples (Kimura et al., 2007; Kimura et al., 2008; Strasser et al., 2009; Kinoshita et al., 2009; Sakaguchi et al., 2011; Yamaguchi et al., 2011). However, the deeper parts of megasplay faults, which are the targets of future IODP drilling, are less easy to reach and coring of long sections will probably be challenging.

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Onshore out-of-sequence thrusts (OSTs) exposed in emerged accretionary prisms are regarded as ancient equivalents of offshore active megasplay faults. As such, they have received much attention (Ohmori et al., 1997; Kimura, 1998; Ikesawa et al., 2003; Kondo et al., 2005; Mukoyoshi et al., 2006, 2009; Hara and Kimura, 2008; Rowe et al., 2009). Typically, these OSTs are characterized by lateral extensions of several tens of kilometers, total displacements estimated between 1 and about 10 km, damage zone thicknesses of the order of several tens or hundreds of meters. Moreover, the studied OSTs are thought to have been active at large depths (estimated between 1 km and 10 km) and for significant periods (a few million years). The study of such OSTs can provide complementary information to the offshore equivalents and guidance for future drilling and sampling strategies.

In addition to regional-scale 'first-order' OSTs, other OSTs have also been reported from the Shimanto accretionary prism (Kimura, 1998). These 'second-order' OSTs are truncated by their first-order equivalents, and their surface extensions, offsets and damage thicknesses are less important than those characterizing the first-order OSTs. Despite their lesser importance, the second-order OSTs deserve to be studied. They probably play a role in the hydrological behavior of the whole prism by connecting first-order OSTs between them or by allowing fluid expulsion from the deep parts of the prism (Moore, 1989; Moore and Vrolijk, 1992).

This paper presents the results of a microstructural analysis carried out along a branch of a second-order OST exposed in the Shimanto accretionary prism of SW Japan. Abundant siliceous breccias and fluid paleo-channels in the fault footwall are described and analyzed. A special attention is carried on polyphase breccia cement formation. In particular, fluid inclusions in breccia cements also provide constraints on the pressure and temperature (P–T) conditions of the fluids trapped in the various syn-tectonic cements. The results of these structural and micro-thermometry analyses are integrated in a hydro-mechanical model of the activity of the OST.

2. The Makinokuchi branch of the Nakanomata OST

2.1. Geological setting of the Nakanomata thrust

The Nakanomata out-of-sequence thrust can be followed over about 60 km across Eocene–Oligocene units of the Hyuga Group of the Shimanto Belt in central Kyushu (Fig. 1; Imai et al., 1979, 1982; Kimura et al., 1991; Kimura, 1998; Hara and Kimura, 2008; Hara et al., 2009a,b). It is located between three major, first-order OSTs, the Nobeoka Tectonic Line (NTL) and the Oyabu thrust to the north, and the Ogawa thrust to the south. The geometrical relationships between the Nakanomata OST and the three surrounding first-order OSTs are unknown. On the cross-section of Fig. 2, the Nakanomata OST is considered as truncated by the Ogawa thrust. Total displacement along the Nakanomata OST is about 5 km (Kimura et al., 1991; Kimura, 1998), but significantly decreases in the study area where it is less than 1 km (Hara et al., 2009a).

In the study area, the Nakanomata OST consists of several branches (Hara et al., 2009a). One of these branches, the Makinokuchi branch, is exposed in the bed of the Hitotsuse river, at the Makinokuchi locality (Fig. 2). For a distance of about 50 m, a complete section across the fault can be examined and sampled.

2.2. The Makinokuchi fault zone

The Makinokuchi branch of the Nakanomata OST consists of a planar to slightly undulating, polished and locally striated fault surface separating folded sandstone/siltstone alternations in the hanging-wall from massive sandstones in the footwall. The fault surface, which can be followed along the entire exposure, is interpreted as the most recent slip surface. It has a mean attitude of N70°E-15°NW. Weakly marked striations trend N165°E to N173°E. Folds in the hanging-wall sandstone and siltstone beds are asymmetric and have axes trending N92°E ± 10° and plunging westward of 45° ± 10°. Fold asymmetry is in agreement with a reverse (top-to-the-south) motion along the fault. A 0.5–2 cm thick, indurated, siliceous layer is preserved beneath the fault surface. As detailed below, this layer consists of a siliceous ultracataclasite which is regarded as the most deformed zone (core zone) of the Makinokuchi fault. The footwall consists of a massive sandstone which, with increasing fracturing and brecciation, progressively evolves from a weakly fractured sandstone at a distance of about 4–5 m from the fault to a strongly brecciated and silicified sandstone immediately beneath the ultracataclasite layer (Fig. 3a and b). The hanging-wall sandstone/siltstone beds are only moderately fractured and silicified, with the exception of more important fractured and brecciated sandstones close to the fault, over a thickness of about 50 cm (Fig. 3a and b). The contrast in intensity and thickness of brecciation and silicification between the hanging-wall and the footwall is a key feature of the studied exposure and will be described in the following.

3. Detailed structure of the Makinokuchi fault zone

3.1. Protoliths

3.1.1. Footwall protolith

The footwall protolith is a coarse-grained massive and fractured sandstone. The sandstone is a quartz greywacke (Hara et al., 2009b) consisting of monocrystalline or polycrystalline quartz grains, alkali and plagioclase feldspars, lithic fragments, illite (coating some grains), and minor opaque minerals. The alkaline feldspars are altered and invaded by sericite. The average size of individual grains ranges from 200 to 800 μm. The porosity of the sandstone was not measured. However, porosities between 6% and 12% were obtained in similar coarse-grained sandstones sampled in the footwall of the Nakanomata thrust about 5 km east of the Makinokuchi exposure (Boutareaud, 2007). Thin section counting suggests that the porosity of the intact sandstone at Makinokuchi is about 10%. Diffusive mass transfer (DMT) processes are indicated by stylolitic surfaces and dissolution at grain contacts. The contact between the intact or fractured protolith and the damage zone breccias is progressive and cannot be accurately located.

3.1.2. Hanging-wall protolith

The hanging-wall consists of alternating beds of sandstone and siltstone. The sandstone is a quartz greywacke, but is finer than the footwall sandstone. The average size of individual grains ranges from 30 to 300 μm. The siltstone consists of grains of quartz, plagioclase feldspars, opaque minerals and dominantly phyllosilicates. The average size of individual grains is less than 30 μm. Like in the footwall sandstone, stylolithes and dissolution at grain contacts testify to DMT processes. Here also, the porosity of the sandstone or the siltsone were not measured. However, porosities between 1.5% and 4% were obtained in fine-grained sandstones sampled in the hanging-wall of the Nakanomata thrust about 5 km east of the Makinokuchi exposure (Boutareaud, 2007). Thin section counting suggests that the porosity of the intact hanging-wall sandstone is less porous than the footwall one due to the large amount of clay and the small size of the grains.

3.2. Footwall breccias

Footwall breccias can be divided into three types which are, with decreasing distance to the fault plane, A-, B- and C-type breccias.