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The role of bedding in the evolution of meso- and microstructural fabrics in fault zones

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ABSTRACT

To investigate the role of bedding in the evolution of meso- and microstructural fabrics in fault zones, detailed microscopic, mineralogical, and geochemical analyses were conducted on bedding-oblique and bedding-parallel faults that cut a folded Neogene siliceous mudstone that contains opal-CT, smectite, and illite. An analysis of asymmetric structures in the fault gouges indicates that the secondary fractures associated with each fault exhibit contrasting characteristics: those of the bedding-oblique fault are R_1 shears, whereas those of the bedding-parallel fault are reactivated S foliation. The bedding-oblique fault shows the pervasive development of S foliation, lacks opal-CT, and has low SiO_2/TiO_2 ratios only in gouge, whereas the bedding-parallel fault exhibits these characteristics in both gouge and wall rocks. The development of S foliation and the lack of silica can result from local ductile deformation involving the sliding of phyllosilicates, coupled with pressure solution of opal-CT. Although such deformation can occur in gouge, the above results indicate that it may occur preferentially along bedding planes, preceding the formation of a gouge/slip surface. Thus, in sedimentary rocks that contain phyllosilicates and soluble minerals, bedding can influence the rheological evolution of meso- and microstructural fabrics in fault zones.

1. Introduction

Meso- and microstructural fabrics along slip surfaces and in clayey gouge have been well documented in previous studies (e.g., Rutter et al., 1986; Chester and Logan, 1987; Petit, 1987; Doblas et al., 1997; Doblas, 1998). In brittle rocks, R and/or T surfaces develop along slip surfaces as secondary fractures oriented oblique to the slip surfaces (Fig. 1a, b; Petit, 1987; Doblas et al., 1997). Conversely, in clayey gouge, S foliation develops instead of R or T surfaces (Fig. 1c, d; Rutter et al., 1986; Chester and Logan, 1987), as is the case in mylonite (Berthé et al., 1979; Lin and Williams, 1992). Although S foliation is defined by the preferred alignment of minerals such as phyllosilicates, it may be highlighted by macroscopic cleavage or desiccation cracks (Lin and Williams, 1992; Casciello et al., 2011).

Previous studies have investigated the mechanical effect of bedding on faulting in laboratory experiments (e.g., Gomez-Rivas and Griera, 2012; Ikari et al., 2015), but the role of bedding in the development of fault-related meso- and microstructural fabrics remains uncertain. Two types of faults are recognized in a folded and fractured Neogene siliceous mudstone (Wakkanai Formation: Fig. 2) in the Horonobe area, Hokkaido, Japan: bedding-oblique faults and bedding-parallel faults (Fig. 3a). The bedding-oblique faults are predominantly strike-slip faults, and the morphology of secondary fractures (slickensteps) associated with these faults is consistent with the brittle shear deformation shown in Fig. 1a (Ishii and Fukushima, 2006; Ishii et al., 2010). In contrast, the bedding-parallel faults are reverse faults that formed by flexural slip folding in a transpressional/compressional tectonic setting (Ishii et al., 2006; Ishii and Fukushima, 2006), and the morphology of the secondary fractures (Fig. 3b) is consistent with the ductile shear deformation shown in Fig. 1c. However, the reason for this difference in secondary fracture morphology between bedding-oblique and bedding-parallel faults cannot be explained by any existing model. The fault morphologies and structural relationships may indicate that bedding plays an important role in the evolution of meso- and microstructural fabrics in fault zones.

To elucidate the role of bedding in the evolution of meso- and microstructural fabrics in fault zones, detailed microscopic observations and bulk mineralogical and geochemical analyses were conducted on rock samples that contain the bedding-oblique and

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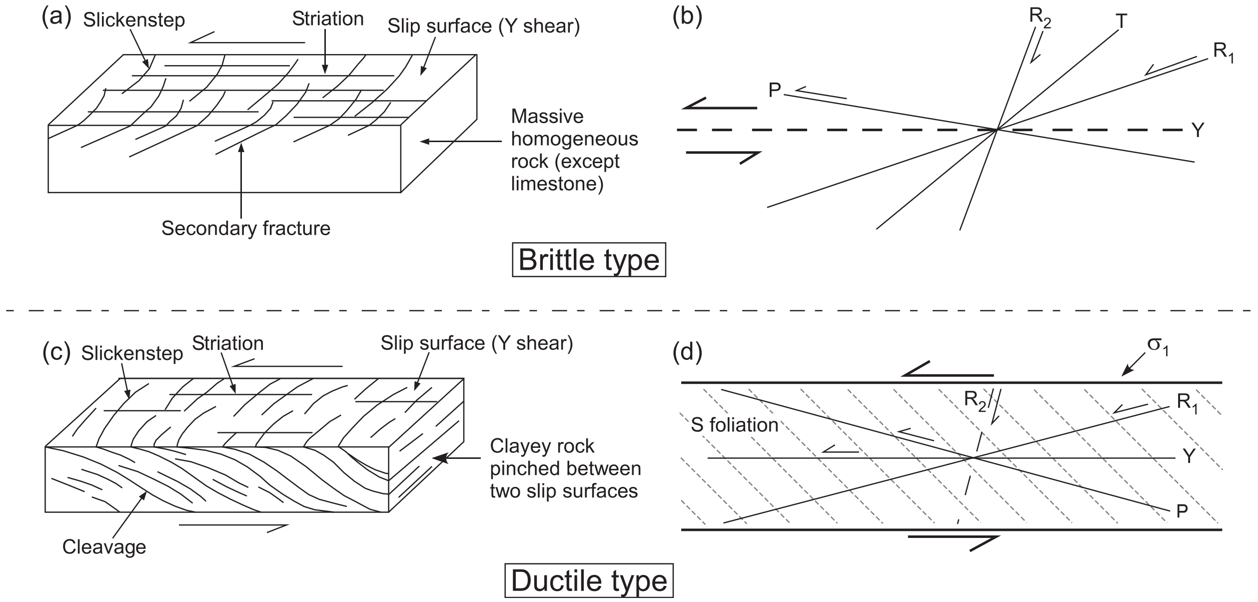

Fig. 1. Schematic model showing the terminology and features of secondary fractures related to (a, b) brittle shear deformation and (c, d) ductile shear deformation. Modified from Petit (1987), Logan et al. (1992), and Casciello et al. (2011).

bedding-parallel faults described above. These analyses are also important for improving our understanding of the relationship between the morphology of secondary fractures and the displacement sense of slip surfaces, which is helpful in analyses of paleostresses (Yamaji et al., 2005; Federico et al., 2010; Tonai et al., 2011) and in determining whether faults are of tectonic or nontectonic origin (Anders et al., 2013; Wakizaka, 2015; Yamane et al., 2015).

2. Geological setting

The Horonobe area, located on the eastern margin of a Neogene–Quaternary sedimentary basin on the western side of northern Hokkaido, Japan, is in an active Quaternary foreland fold-and-thrust belt located near the boundary between the Okhotsk and Amurian plates (Fig. 3). From stratigraphically lowest to highest, the basin fill consists of the Masuporo, Wakkanai, Koetoi, Yuchi, and Sarabetsu formations (Fig. 4; the Masuporo Formation is not shown in these figures).

The Wakkanai Formation, a Neogene siliceous mudstone, is poorly exposed in the Horonobe area. The mudstone consists mainly of a single massive homogeneous lithofacies (Mitsui and Taguchi, 1977; Iijima and Tada, 1981), although weakly developed bedding planes are recognized in electrical micro-imaging (EMI) borehole logs (Ishii et al., 2006). As for the mineral composition, the mudstone consists of 40–50 wt% silica (mainly opal-cristobalite/tridymite: opal-CT), 19–33 wt% clay minerals (10–18 wt% smectite and 7–13 wt% illite), 9–13 wt% quartz, 7–13 wt% feldspar, 0–2 wt.% pyrite, and 0–1 wt.% carbonate (Mazurek and Eggenberger, 2005; Hiraga and Ishii, 2008). The effective porosity is 30%–50% (Sanada et al., 2009). The mudstone formed by the induration of diatomaceous sediments during progressive burial diagenesis of silica minerals, involving the dissolution of opal-A and the precipitation of opal-CT within pore spaces (Ishii et al., 2011b). Early diagenetic pyrite (spherical, framboidal, and cubic) is disseminated throughout the matrix (Kemp et al., 2002; Iwatsuki et al., 2009).

Burial and subsidence of the Wakkanai, Koetoi, and Yuchi formations occurred during the Neogene–Quaternary. The siliceous mudstone was buried to a maximum depth of more than 1 km (Ishii et al., 2008; Kai and Maekawa, 2009). Subsequently, uplift and denudation began at about 1 Ma, with deposition of the Sarabetsu Formation. Prior to 1 Ma, the strata were affected by flexural folding that began at 2.2–1.0 Ma in response to regional E–W shortening, which was related to the eastward migration of the Amurian plate (Ishii et al., 2008; Ishii, 2012). Anticlines (e.g., F_1, F_2, and F_3 in Fig. 3) developed at this time, with fold axes trending NW–SE to NNW–SSE and plunging gently to the northwest or southeast. The Omagri Fault (Fig. 3) also formed during this period (Ishii and Fukushima, 2006) through sinistral transpressional deformation (Ishii et al., 2006).

In the folded siliceous mudstone, bedding-oblique and bedding-parallel faults occur in outcrop and in drillcores, as described above (Ishii and Fukushima, 2006; Ishii et al., 2010). The faults exhibit slickensides, slickenlines, slickensteps (secondary fractures), contain fault rocks, and are commonly accompanied by brittle damage-zone fractures (i.e., tensile and/or hybrid fractures) (Ishii, 2015, 2016). The growth histories of the faults can be summarized as follows (Ishii et al., 2011a; Ishii, 2012): (1) bedding-oblique faults first nucleated as strike-slip faults, just before the initiation of folding, in response to regional E–W shortening; (2) bedding-parallel faults formed during the folding, while movement on the bedding-oblique faults was suppressed, probably due to stress relief afforded by the development of bedding-parallel faults; and (3) the bedding-oblique faults were reactivated subsequent to folding.

3. Methods

To avoid the complexities of overprinting by both tectonic and nontectonic deformation, a bedding-oblique fault and a bedding-parallel fault were selected from deep drillcores for analysis. Because the displacement sense must be determined conclusively, faults were selected with slip surfaces marked by clayey gouge, in which the S foliation is apparent. The selected faults include a bedding-oblique fault at a depth of 518.3 m in vertical borehole PB-V01 (sample PB-V01_518.3 m) and a bedding-parallel fault at a depth of 434.6 m in vertical borehole HDB-10 (sample HDB-10_434.6 m). In the case of a fault that has experienced multiple