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Frictional properties of saponite-rich gouge from a serpentinite-bearing fault zone along the Gokasho-Arashima Tectonic Line, central Japan

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ABSTRACT

We studied a serpentinite-bearing fault zone in Gokasho-Arashima Tectonic Line, Mie Prefecture, central Japan, characterizing its internal structures, mineral assemblage, permeability, and frictional properties. The fault core situated between the serpentinite breccia and the adjacent sedimentary rocks is characterized by a zone locally altered to saponite. The clayey gouge layer separates fault rocks of serpentinite origin containing talc and tremolite from fault rocks of sedimentary origin containing chlorite but no quartz. The minerals that formed within the fault are the products of metasomatic reaction between the serpentinite and the siliceous rocks. Permeability measurements show that serpentinite breccia and fault gouge have permeability of 10^{-14}–10^{-17} m^2 and 10^{-15}–10^{-18} m^2, respectively, at 5–120 MPa confining pressure. Frictional coefficient of the saponite-rich clayey fault gouge ranged between 0.20 and 0.35 under room-dry condition, but was reduced to 0.06–0.12 when saturated with water. The velocity dependence of friction was strongly positive, mostly ranging between 0.005 and 0.006 in terms of $a-b$ values. The governing friction law is not constrained yet, but we find that the saponite-rich gouge possesses an evolutional behavior in the opposite direction to that suggested by the rate and state friction law, in addition to its direct velocity dependence.

1. Introduction

Serpentinites frequently occur along major faults and plate boundaries and its rheological behavior is believed to play a major role in tectonics and seismicity. For instance, weak serpentinite shells are thought to accommodate the diapiric motion of mantle materials which exposes mantle peridotites along mountain belts (Hess, 1955). Guillot et al. (2000) suggested that serpentinized mantle wedges at subduction zones facilitate the exhumation of eclogitized oceanic crusts by acting as lubricants. Early measurements of serpentinite rock strengths (Raleigh and Paterson, 1965) observed embrittlement and significant reduction of strength at elevated temperatures due to enhanced pore pressure by dehydration, and suggested that serpentinites and other hydrated phases could extend brittle faulting to greater depths in subduction zones. Recent high-pressure high-temperature laboratory experiments (Hilairet et al., 2007) also showed that serpentinites would accommodate ductile deformation at upper mantle conditions, and its deformation could occur at strain rates comparable to post-seismic deformation and slow earthquakes.

The presence of serpentinites along certain subduction zones and the creeping section of the San Andreas fault have also stimulated the investigation of its relation to the seismicity/aseismicity of these plate boundaries. Discoveries of serpentinite seamounts in the Izu-Bonin and Marina forearcs (Fryer et al., 1990; Fujioka et al., 1995) and the seismic structure indicative of hydrated mantle wedges and serpentine diapirs in these trenchs (Takahashi et al., 1998; Kamimura et al., 2000) suggested that the serpentinites are responsible for the absence of large subduction earthquakes in this region (Hyndman and Peacock, 2003). Serpentinite is commonly found along faults of the San Andreas system in central and northern California that are characterized by creep (e.g., Allen, 1968; Hanna et al., 1972; Irwin and Barnes, 1975; Moore and Rymer, 2007). Laboratory experiments investigating the frictional properties of serpentine minerals (Reinen et al., 1994; Moore et al., 1996, 1997; Morrow et al., 2000) revealed that serpentine minerals are weaker than typical crustal materials.

Recently, attention has been directed to the mineral species produced by the metasomatic reaction between serpentinites

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juxtaposed against crustal rocks. Reactions are facilitated by silica-rich hydrothermal fluids, typically producing mineral assemblages containing talc, actinolite/tremolite, chlorite, and carbonates (Phillips and Hess, 1936; Curtis and Brown, 1969; Koons, 1981; Sanford, 1982; Mori et al., 2007; Viti and Collettini, 2009; Soda and Takagi, 2010; Moore and Rymer, 2010). If fault slip occurs along margins of serpentinites, mechanical properties of these metasomatic products would ultimately control the mechanical behavior of serpentinite-bearing faults and diapirs. In fact, Lockner et al. (2011) argue that saponite, a Mg-rich smectite clay formed by reaction of serpentinite with quartzo-feldspathic rocks, rather than serpentine species can explain the low frictional strength of the San Andreas fault suggested by the lack of a heat-flow anomaly (Brune et al., 1969; Lachenbruch and Sass, 1980) and the orientation of maximum horizontal stress (Zoback et al., 1987), at least at 2.7 km depth in the central creeping section.

These studies therefore highlight the importance of understanding not only the serpentinite itself, but also the structure/composition of the entire fault zone to understand the mechanical significance of serpentinites in various tectonic settings. This study reports the internal structure of a serpentinite-bearing fault along the Gokasho-Arashima Tectonic Line, Mie prefecture, Japan and results from laboratory measurements on the fault zone permeability and the frictional/rheological properties of the fault gouge. We find that the fault core is composed of saponite-rich gouges which exhibit extremely low frictional coefficient and prominently velocity-strengthening properties.

2. Geological setting

The Gokasho-Arashima tectonic line (referred as G-A Line hereafter) is a major serpentinite-bearing fault structure that cuts through the Chichibu Belt of Shima Peninsula, longitudinally but slightly obliquely, in the NE–SW direction. The Chichibu Belt in this area lies between the Mikabu tectonic line and the Butsuzo tectonic line, which separate the Chichibu Belt from the Sambagawa Belt on the northern side and from the Shimanto Belt on the southern side, respectively, as commonly seen in southwest Japan (Fig. 1a). The Chichibu Belt mainly consists of accretionary complexes and fore-arc basin deposits from the Jurassic to early Cretaceous period. Branching faults exist to the southeast of the main trace of the G-A Line, which dissects the Chichibu Belt into alternating units or lens-like blocks (Fig. 1b). The geology of the area around the G-A Line has been studied in detail by Yamagiwa (1957), Saka et al. (1979, 1988) and Katoh et al. (1992). Due to the presence of granitic rocks, metamorphic rocks, and felsic tuff characteristic of the Kurosegawa Tectonic Zone (Ichikawa et al., 1956) on Shikoku Island, the G-A Line is interpreted to be a serpentine mélange that serves as the eastward extension of the Kurosegawa Tectonic Zone (Hamada, 1963; Saka et al., 1988; Yoshikura and Terashima, 1984). The precise tectonic history of the Kurosegawa Tectonic Zone is still under debate, but Kato and Saka (2003) suggested that the Kurosegawa Tectonic Zone was once a dextral strike-slip transform fault that was active between 120 and 100 Ma in response to the subduction of the oceanic ridge between the “Izanagi” plate and “Kula” plate.

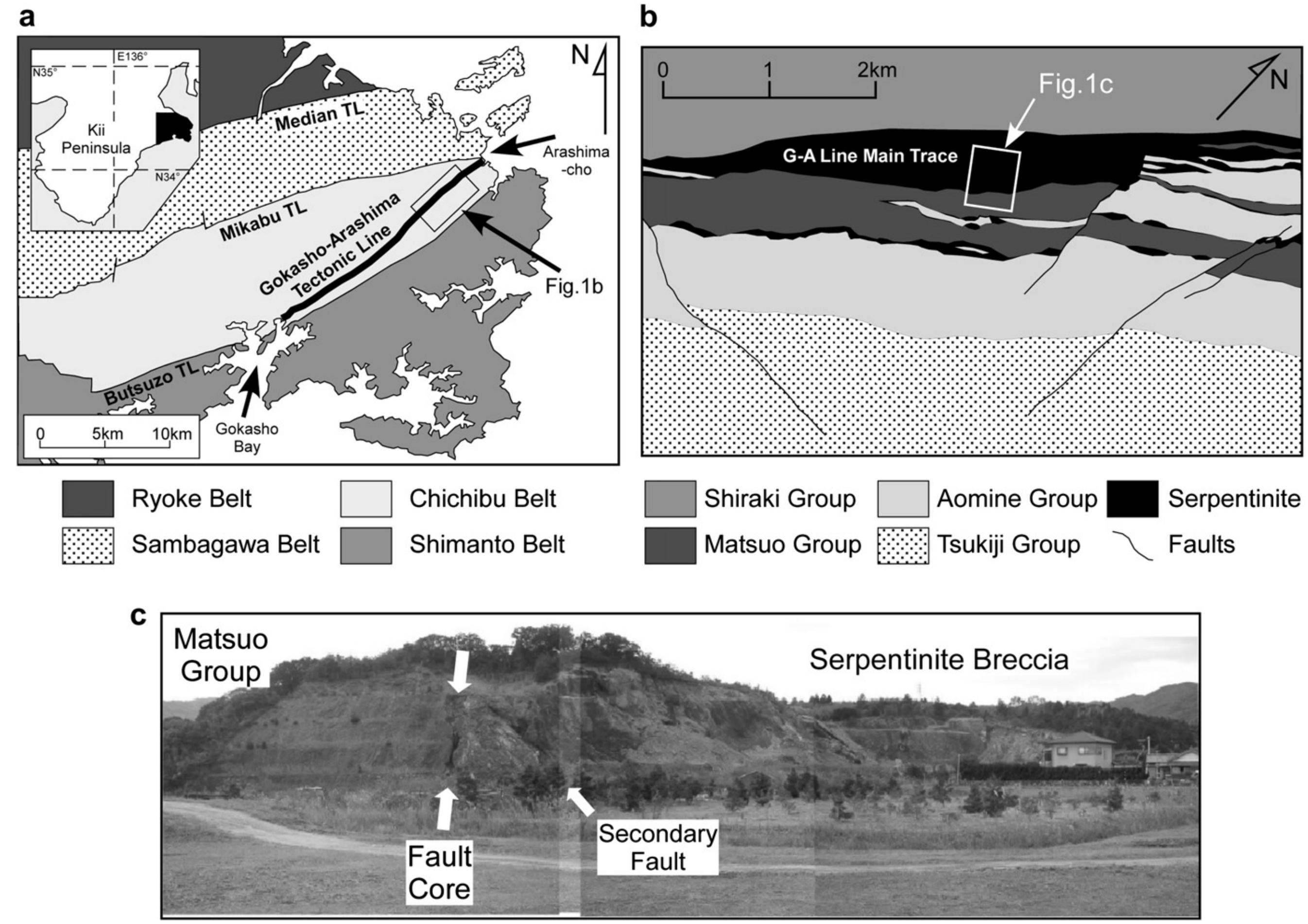

Fig. 1. (a) Geological map of Shima Peninsula reproduced from Saka et al. (1979). (b) Local geological map around the studied outcrop modified from Saka et al. (1988). (c) Photograph of the studied outcrop near Matsuo station. The entire photograph shows the outcrop that spans about 250 m horizontally and there is a house towards the right as a scale.