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Determination of slip sense along a fault in an unlithified sediment

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Abstract

It is usually difficult to measure slip sense along a fault in unlithified sediments due to the lack of mesoscopic indicators such as slickenlines. In this paper, scanning electron microscope (SEM) images of fault surfaces in mudstone at the sandstone–mudstone contacts are used for measuring the microscopic slickenlines formed by the scratching of sand grains. The lineations are subparallel to the presumed slip direction deduced from a conjugate fault set. Therefore, even in the case of no mesoscopic slickenlines, a microscopic scratching by a sand grain on the fault surface where sandstone and mudstone are juxtaposed by the fault is useful as an indicator of slip sense along a fault in sediments lithified subsequent to faulting.

1. Introduction

Determination of slip direction and sense of displacement is important for fault kinematics and dynamics. Slip direction on a fault or in a fault zone is commonly deduced from cataclastic lineations (Tanaka, 1992) or slickenlines (Uemura, 1977; Means, 1987; Petit, 1987). However, it is usually difficult to recognize slip direction and sense along a fault in unlithified sediments or sedimentary rocks due to the scarce presence of such indicators. Since the inversion method of determining a stress tensor from fault-slip data was established by Carey and Brunier (1974), many structural geologists have applied the method (e.g. Delvaux et al., 1995; Hirono, 1998). In shallow levels of accretionary prisms or sedimentary basins, the fault-slip senses are commonly unknown. I describe below microscopic slickenlines as a slip-sense indicator on a fault surface. In this case, faulting occurred in unlithified sediments, and both fault and sediment were subsequently lithified.

2. Description of sample

The examined sediment samples were obtained from alternating beds of very fine- to fine-grained sandstone, mudstone and tuff in the Kiyosumi Formation of the Miura Group, exposed on Cape Tendo along the eastern coast of the Boso Peninsula, Japan (Fig. 1). This formation is thought to be a slope deposit (turbidite) of Early Pliocene age (Eto et al., 1987). The sandstone is a fine-grained tuffaceous wacke, with a porosity of approximately 30%. The mudstone is composed mainly of silt-sized quartz, augite, plagioclase and clay minerals.

Two faults, considered to be a conjugate set, show vertical separations of 30–50 cm (Fig. 1). The fault zones are less than 1 mm thick at the mudstone–mudstone and mudstone–sandstone contacts, while those at the sandstone–sandstone contact are about 10 mm in thickness. Slickenside and slickenside striations (slickenlines) are not visible with the naked eye. Com-

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posite planar fabrics such as Riedel shear surfaces are not observed within the fault zones. Because the faulting is associated with dewatering and deformation of unlithified sediments (e.g. dish structures), the faulting occurred in unlithified sediments and subsequently both the fault zone and host sediment were lithified. Such a fault is often observed in cores from accretionary prisms (e.g. Lundberg and Moore, 1986).

Three oriented fault samples were collected from the contacts between the sandstone and sandstone ('ss' in Fig. 1), sandstone and mudstone ('ms' in Fig. 1) and mudstone and mudstone ('mm' in Fig. 1) using a drill

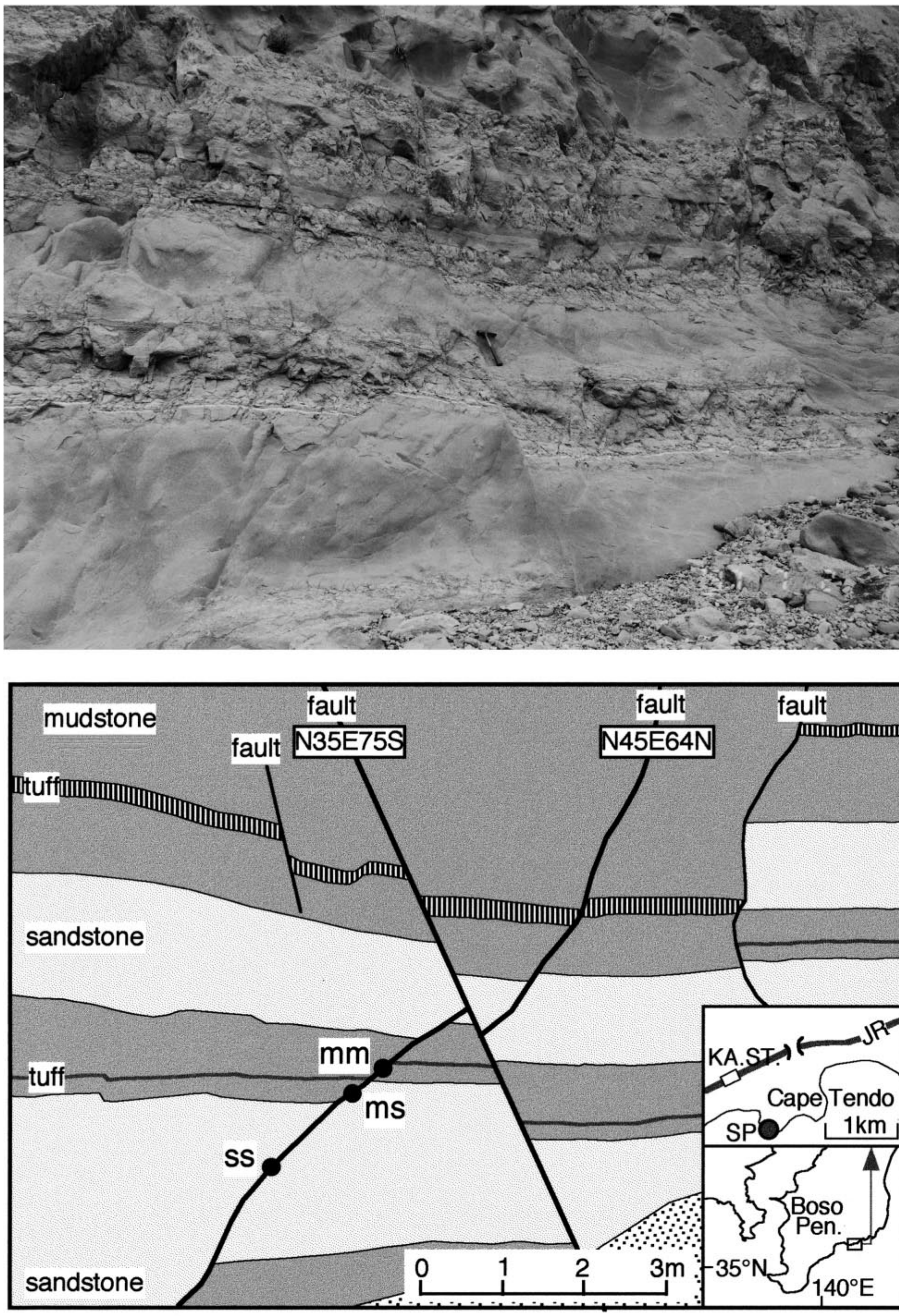

Fig. 1. Photograph and sketch of outcrop with sample points shown. Location map provided in lower right corner; SP: sample point; KA.ST.: Kazusaokistu Station (JR Sotobo line). Outcrop includes alternating beds of very fine- to fine-grained sandstone, mudstone and tuff in the Kiyosumi Formation of the Miura Group, Boso Peninsula, Japan. Two faults of a conjugate set are shown. mm: Mudstone–mudstone contact in a fault; ms: mudstone–sandstone contact in a fault; ss: sandstone–sandstone contact of a fault.

core. Each sample obtained is described in detail below.

3. Lineations of fault surface at sandstone–mudstone contact

The fault surface at the sandstone–mudstone contact ('ms' in Fig. 1) was exposed carefully with tweezers. Scanning electron microscope photographs of the mudstone-side fault surface are shown in Fig. 2(a, b). The lineations from top left to bottom right (Fig. 2a) are prominently developed on the surface. The lineations are well oriented, as shown in the rose diagram in Fig. 2(c). They are restricted to the upper-left area of very fine sand-sized grains (Fig. 2b), and are not developed on the lower-right area, suggesting that the lineations were formed by ploughing of sand grains from upper left to lower right. The orientation of the lineations is reasonably consistent with the direction of the maximum compressive axis deduced from the conjugate fault set (Fig. 3) using Anderson's theory (Anderson, 1951), so that it is concluded that the lineations record the slip direction, during faulting. The restricted existence of the lineations to the upper left of sand grains suggests that the sandstone slipped from upper left to lower right and the mudstone slipped in the opposite direction.

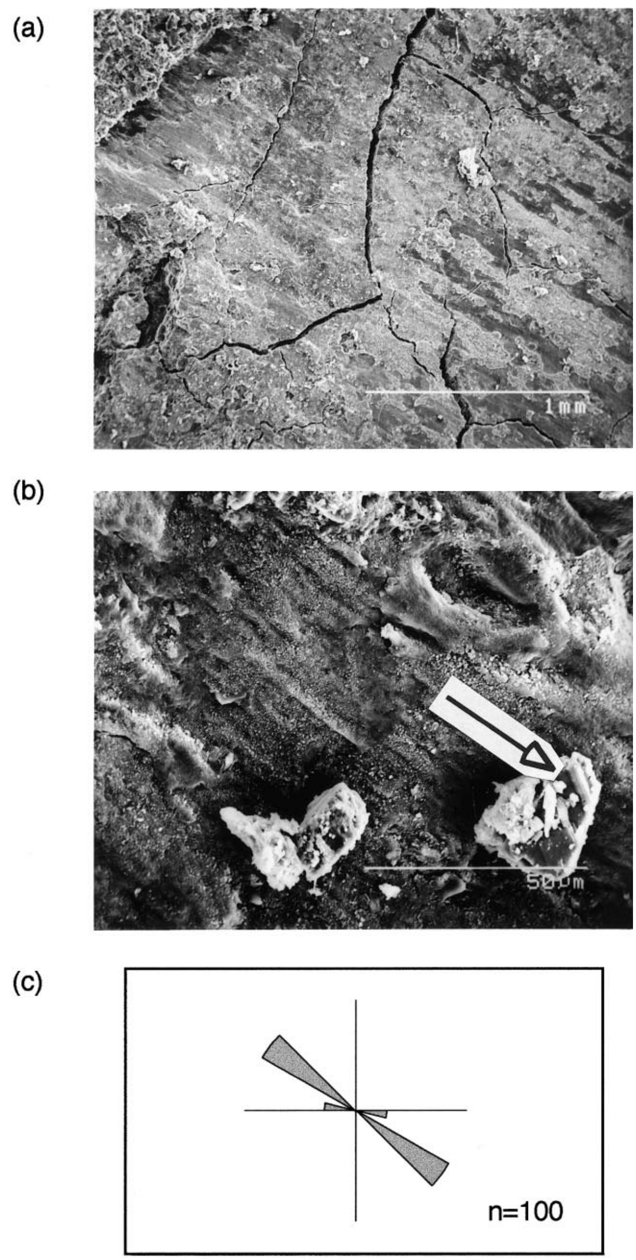

Fig. 2. Lineations on healed fault surface at the sandstone–mudstone contact point ('ms' in Fig. 1). (a) A scanning electron microscope photograph showing the mudstone-side fault surface at 'ms'. (b) Detailed scanning electron microscope photograph. Two sand grains whose size is about 10–25 μm are recognized in the lower-right area. An arrow indicates the slip direction of the sand grains. (c) Rose diagram of the lineations. Number of measurements (n) is 100.

4. Microstructures at sandstone–sandstone and mudstone–mudstone contacts

Mesoscopically, a fault at the sandstone–sandstone contact shows slight opaque coloration. The fault surface cannot be separated due to its hardness. Therefore, it is difficult to observe the fault surface under the naked eye or SEM. An optical microscope photograph at the sandstone–sandstone contact is shown in Fig. 4. The plane of the photograph includes the direction of the maximum compressive axis. The grain size within the fault zone is reduced relative to the surrounding rock. Boundaries of the zone are not distinct with gradational margins. The relatively larger sand

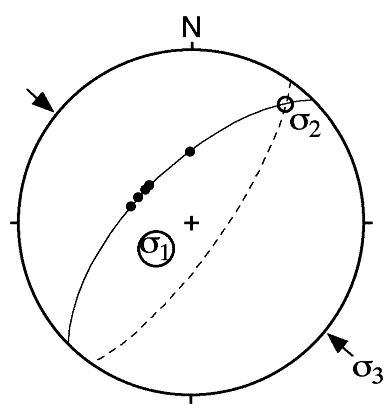

Fig. 3. Lineation and paleo-stress field using a conjugate fault set. Lower hemisphere stereographic projection illustrates the fault plane solutions. Five typical lineations on the fault surface, detected under the SEM, are projected as dots. σ_1, σ_2 and σ_3 indicate inferred maximum, intermediate and minimum compressive stress axes, respectively.

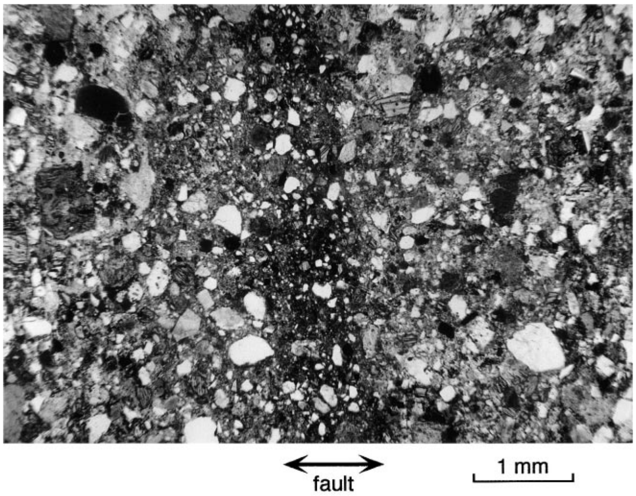

Fig. 4. An optical microscope photograph showing fault zone at sandstone–sandstone contact (ss in Fig. 1). Open nicols.

grains show weak dimensional preferred orientations parallel to the direction of the maximum compressive axis.

Scanning electron microscope photograph of a fault surface at the mudstone–mudstone contact (Fig. 5) shows well-developed preferred orientations of clay minerals. These planar minerals array parallel to the fault plane. These fabrics might be referred to as micro-scale slickensides or fault gouges. Lineations are also observed with the uneven surface.

Although the origin of the lineations is not yet understood, it might be asperity ploughing or debris streaking, defined by Means (1987). The lineations are parallel to the direction of the maximum compressive axis.

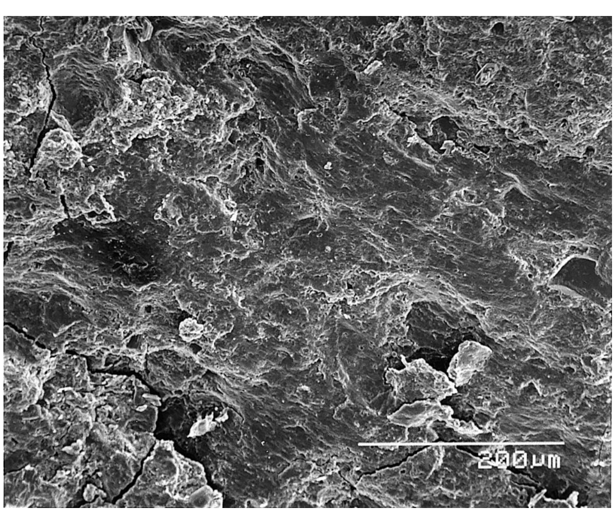

Fig. 5. A scanning electron microscope photograph showing fault surface at mudstone–mudstone contact (mm in Fig. 1).

5. Criteria for slip sense of a fault in an unlithified sediment

The lineations are developed on the mudstone-side fault surface at the 'ms' contact in the unlithified sediments. They are formed by scratching of the mudstone-side fault surface by sand grains (Fig. 6), similar to a tool mark (Hancock, 1985), a striation by a ploughing element (Petit, 1987) and a groove and scratch resulting from asperity ploughing (Means, 1987). The lack of mesoscopic slickensides on a fault in unlithified sediments is generally ascribed to low friction along the shear zone under wet, low confining pressure and low strain rate conditions (Lundberg and Moore, 1986; Maltman, 1994). However, the friction between sandstone and mudstone may be large enough

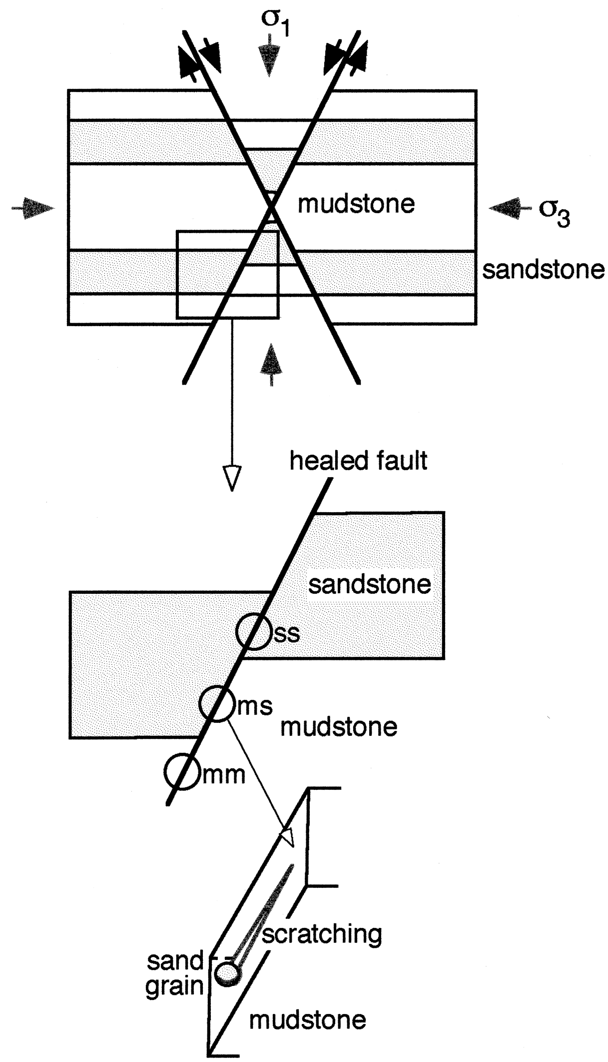

Fig. 6. Criteria for slip direction of a fault in unlithified sedimentary rocks. At the sandstone–mudstone contact (ms), the slickenline resulting from scratching by sand grains indicates slip direction and sense.

Table 1
Indicators of slip direction and sense of a fault in unlithified sediments[a]

Contact	DPO	Slickenline	Slip direction	Slip sense
SS	recognised	–	provable	–
MS	–	recognised (scratches)	provable	provable
MM	recognised	recognised	provable	–

[a] DPO: dimensional preferred orientation of grains.

to make scratching by sand grains. Therefore, microscopic slickenlines due to scratching by sand grains where the fault juxtaposes sandstone and mudstone contact ('ms' in Fig. 6) is useful as an indicator for slip sense along a healed fault in unlithified sediments. On the other hand, dimensional preferred orientations of grains, consistent with the direction of the maximum compressive axis, are observed at the sandstone–mudstone and mudstone–mudstone contacts. Lineations are microscopically observed on the fault surface at the mudstone–mudstone contact. These fabrics could indicate the slip direction, but not the sense (Table 1). The scratching by sand grains is the only indicator for slip sense of a fault in unlithified sediments.

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