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Reactivation of map-scale faults in response to changes in crustal stress: Examples from Boso Peninsula, Japan

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ABSTRACT

We have investigated the reactivation of Quaternary faults near the trench-trench-trench type triple junction off Boso Peninsula, central Japan. On the Pacific side of the Boso Peninsula (PSBP region), map-scale NNE–SSW-trending faults developed during ~1.2–0.7 Ma, although these faults are inactive at present. We observed multiple and overlapped slickenlines on parts of map-scale fault planes in the PSBP region. These slickenlines can be classified into two different directions, which we consider to be the reactivation of the map-scale faults in response to a change in crustal stress after ~1 Ma. Based on angular misfits between the predicted and observed slip directions, we successfully compared the older and younger slip directions to dip-slip normal faulting and oblique sinistral normal faulting, respectively. The reactivation of the map-scale faults in response to a relatively short (10^5 yrs) stress change has been verified based on the direct evidences on the map-scale fault planes.

1. Introduction

Understanding the pattern and evolution of crustal stress in subduction zones is important for the reconstruction of geodynamic processes. It is well known that one of the dominant controls on crustal deformation is tectonic stress. The first-order tectonic stress has been thought to have the principal orientations directly linked to relative plate motion directions (Zoback, 1992). The agreement between the geodetically detected instantaneous plate motion and long-term one determined from marine magnetic anomalies as old as ~10^6 yrs (e.g., Argus and Gordon, 1990) suggests that the first-order tectonic stress has been associated with the plate motion for as long as ~10^6 yrs. Such long-term deformation in subduction zones is thought to be associated with fault activity (e.g., Mazzotti et al., 2001). Hence, the long-term evolution of crustal deformation should be evaluated through the fault activities in the context of the long-term (~10^6 yrs) stress field. It is widely accepted that during fault movement, the slip vector is parallel to the resolved shear stress on the fault (Fig. 1; Wallace–Bott hypothesis: Wallace, 1951; Bott, 1959). Consequently, a sense of the fault slip can be changed by variations in the stress field over timescales of 10^6 yrs. As a result, it is possible to observe overprinting of slickenlines with different slip directions on the same fault plane (e.g., Nemcok and Lisle, 1995).

We have investigated a reactivation of the map-scale faults in response to the crustal stress changes in the forearc region of the Japan island arc during the Quaternary. Where different sets of slickenlines can be found on a fault plane, the slip directions can be used to identify the paleo-stress field and how it has evolved or changed through time (e.g., Otsubo et al., 2009). According to the Wallace–Bott hypothesis, the direction of fault movements should have also changed in response to these stress changes on timescales of 10^5 yrs. We therefore hypothesize that fault plane preserves even stress change in such short time scale.

In the Pacific side of the Boso Peninsula in central Japan (Fig. 2; PSBP region), Pleistocene forearc basin deposits (Kazusa Group) are cut by many map-scale NNE–SSW-trending faults with a normal faulting sense (The Minor Fault Research Group, 1973, Figs. 2 and 3). Previous studies showed that the stresses in the PSBP region changed a number of times during the Quaternary (Angelier and Huchon, 1987; Kinugasa et al., 1969; Mino and Yamaji, 1999; Yamaji, 2000). These changes of stress state must be influenced on the crustal deformation such as faulting during Quaternary. We examined our hypothesis that the evidence for changing stress might be preserved on the map-scale NNE–SSW-trending faults in the PSBP region.

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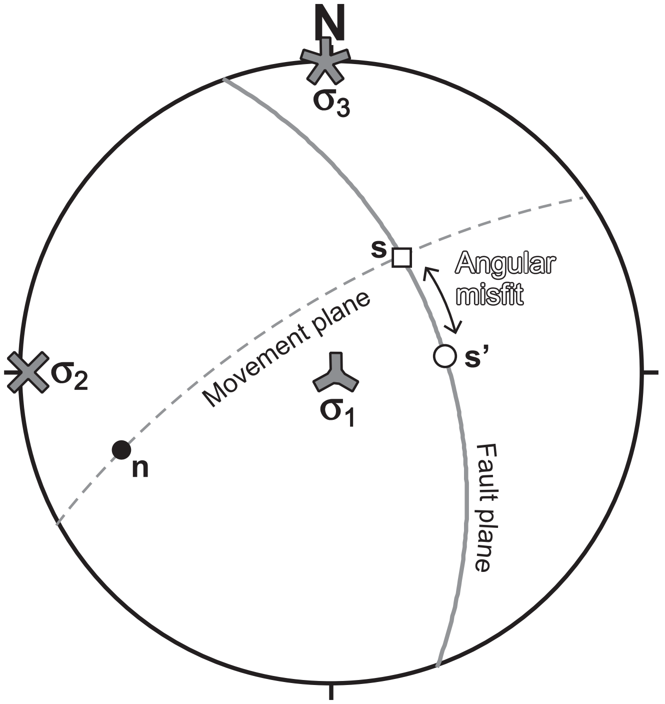

Fig. 1. Schematic drawing to explain the Wallace-Bott hypothesis (Wallace, 1951; Bott, 1959). The slip vector (s), or maximum resolved shear stress on a fault plane (gray) resulting from an applied stress system ($\sigma_1>\sigma_2>\sigma_3$) can be plotted on a lower hemisphere stereographic projection. In this case, the assumed stress ratio is $\Phi = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3) = 0.5$. The vector normal to the fault plane (n) and the slip vector define a movement plane (dashed gray line). Angular misfits are the angles between the slip direction (s) predicted from the stress and observed slip direction (s').

Our results identified changing fault slip directions related to crustal stress variations at timescales of 10^5 yrs after ~1 Ma in the PSBP region. In this paper, we firstly demonstrate that cross-cutting slickenlines preserved on map-scale fault planes in the PSBP region. Secondly, we compare the slip behavior of the map-scale fault based on geological observations with slip directions predicted from the crustal stresses during the past 10^6 yrs, by using the angular misfit technique. Finally, we discuss the implications of the fault reactivation for understanding crustal stress changes since ~1 Ma.

2. Geological setting

The PSBP region is located westward of a trench–trench–trench-type triple junction where the Philippine Sea Plate is subducting beneath the North American Plate, and the Pacific Plate is subducting beneath both the North American and Philippine Sea plates (Fig. 2; De Mets et al., 1990; Seno et al., 1993). The Kazusa Group is up to ~3000 m thick, but thins westward. In the study area, the Katsuura, Namihana, Ohara, Kiwada, Otadai, Umegase and the Kokumoto formations are exposed, in ascending order. The formations mainly comprise alternating beds of sandstone and mudstone. Sedimentological studies have shown that the strata are forearc basin fill sediments (Ito and Katsura, 1992). The downdip direction of the paleoslope in the Boso area has been estimated to be southeastward in the lower Kazusa Group, and northeastward in the middle and upper Kazusa Group, based on turbidite analyses (Hirayama and Nakajima, 1977; Tokuhashi, 1992). Benthic foraminiferal assemblages indicate that the formations were deposited up to 1500 m below sea level, but the formations gradually became shallower during deposition (Kitazato, 1997). The Kazusa Group is overlain by the Shimosa Group that was deposited in a non-marine or shallow marine setting (Tokuhashi and Kondo, 1989; Ito and Katsura, 1992; Okazaki and Masuda, 1992). Accordingly, the formations of the Kazusa Group have been uplifted and exhumed by more than a thousand meters during the last million years.

The depositional ages of the Kazusa Group on the Boso Peninsula are estimated based on sequence stratigraphy (Ito and Katsura, 1992), fission-track dating (Watanabe and Danhara, 1996), microbiostratigraphy (Oda, 1977; Sato and Takayama, 1988), magnetostratigraphy (Niitsuma, 1976; Okada and Niitsuma, 1989), tephrochronology (Satoguchi and Nagahashi, 2012; Suzuki et al., 2011) and oxygen isotope stratigraphy (Okada and Niitsuma, 1989; Pickering et al., 1999; Tsuji et al., 2005). Based on such chronostratigraphic studies, the depositional age of the basal part of the Kazusa Group on the eastern Boso Peninsula is estimated to be 2.3 Ma (Satoguchi, 2006) or 2.4 Ma (Ito and Katsura, 1992). The base of the Brunhes Epoch (0.77 Ma) was found in the middle part of the Kokumoto Formation (Okada and Niitsuma, 1989; Suganuma et al., 2015). Consequently, our fault data were obtained from rocks with ages of 0.7–2.4 Ma.

The Kazusa Group in the PSBP region is cut by many map-scale faults (Figs. 2 and 3). The Minor Fault Research Group (1973) observed many map-scale faults in the lower Kazusa Group in the PSBP region, and traced many marker beds and determined stratigraphic offsets on the N–S- to NNE–SSW-trending faults (Figs. 2 and 3). It was found that most of the fault blocks step down eastwards and that the total amount of subsidence of the marker beds is ca. 0.5 km along 10–20 km long, E–W transects (The Minor Fault Research Group, 1973).

The stress field in the PSBP region has changed a number of times during the Quaternary (Angelier and Huchon, 1987; Kinugasa et al., 1969; Tsukahara and Ikeda, 1987; Mino and Yamaji, 1999; Yamaji, 2000; Yukutake et al., 2015). Paleo-stresses are inferred from mesoscale faults (Mino and Yamaji, 1999; Yamaji, 2000). The middle part of the Kazusa Group (Otadai and Umegase formations) was deposited from 1.2 to 1.0 Ma, and has been affected by normal faulting with an approximately NW–SE-trending σ_3-axis (Yamaji, 2000). The upper part of the Kazusa Group (Kokumoto Formation) was deposited between 1.0 and 0.7 Ma, and has been affected by normal faulting with an approximately NE–SW-trending σ_3-axis (Yamaji, 2000). The orientation of the σ_3-axis changed from NW–SE to NE–SW at 1.0 Ma (Yamaji, 2000). The present-day stress is estimated from hydraulic fracturing and earthquake focal mechanisms (Tsukahara and Ikeda, 1987; Yukutake et al., 2015), and is of reverse faulting type with an approximately NW–SE-trending σ_1-axis and vertical σ_3-axis.

3. Measurement of slip directions on map-scale NNE–SSW-trending faults

We targeted 35 map-scale faults in the PSBP region for this study (Figs. 2c, 3, 4, and 5; Table 1). In this region, the NNE–SSW-striking faults were observed (Figs. 3–5). Most faults have the eastward dip. The slip directions were measured at these outcrops, based on the linear slickenlines (Fig. 4). Most of the faults are normal in character, and have experienced dip-slip movement. On three fault planes, we identified cross-cutting slickenlines. The slickenlines with a low rake angle cut those with a high rake angle on the same planes (Fig. 4). We refer to the slickenlines with high and low rake angles as slips A and B, respectively. The slickenlines with a high rake angle have SE and SSE directions, whereas the slickenlines with a low rake angle have NE and NNE directions. For example, in the outcrop “Ichinogo” (Figs. 2c and 4), the slickenlines have two different directions of S22°E and N09°E (Fig. 5). In the outcrop “Kaigake” (Fig. 2c), the slickenlines also have two different

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