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Landward migration of active folding based on topographic development of folds along the eastern margin of the Japan Sea, northeast Japan

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ABSTRACT

The eastern margin of the Japan Sea, northeast Japan, lies in a strongly compressional area, and contractional deformation in the region is ongoing. We reconstructed the temporal and spatial evolution of contractional deformation across the Tohoku district on the eastern margin of the Japan Sea, by using surface geologic and geomorphologic data. We measured the distance from the fold hinge to the topographic ridge line in antiforms, developed by surface uplift, associated with fold growth under the E–W to WNW–ESE compressional stress regime. The topographic development of fold structures, developed in the region since the Pliocene, is consistent with the activity of the folds. When the folding that generates the uplift becomes inactive, the topographic contrasts between hinge and ridge location can be remarkable. Spatial variations in this parameter are consistent with the systematic eastward migration of fold growth in the area. The documentation of fold-related topography thus provides important information for understanding the dynamics of folding along the eastern margin of the Japan Sea.

1. Introduction

The Quaternary tectonics of the Japan island arc are characterized by strong crustal deformation, whose mode and rate are quite different from those of the preceding late Pliocene. The Tohoku district, on the eastern margin of the Japan Sea, lies within a strongly compressive area (Fig. 1) that has been experiencing large, contractional, crustal deformations, since the late Pliocene (Sato and Amano, 1991; Sato, 1994). Fold-and-thrust structures (Sato, 1989) and fold–topographic structures with distributed reverse faults (Okamura et al., 1995; Okamura, 2002; Sato et al., 2002) have developed in response to this contractional deformation. Geodetic surveys in the Tohoku district have detected zones with a high rate of horizontal strain (Sagiya et al., 2000). Within these zones, a number of large, reverse-faulting earthquakes have occurred in the upper crust over the past 10 years (Fig. 1; e.g., Sibson, 2009). When the rates and kinematics of contemporary contractional deformation are similar to those of the long-term regime, the high-strain-rate zones observed at geological (10^{5-6} years) and geodetic (10^{0-2} years) scales should coincide. However, the high horizontal strain-rates recognized at geological and geodetic time-scales are spatially heterogeneous. Rates are consistent in the Niigata region, in the southwestern part of the Tohoku district, but not in the Akita region in the northwestern part of the district (Fig. 1). The accumulation and release of crustal strain in and along a subduction zone are important drivers of active onshore faulting (e.g., Farías et al., 2011). The difference in location between the geologic and geodetic horizontal high-strain-rate zones at the eastern margin of the Japan Sea indicates temporal variations in the continuity of strain accumulation and release. The evidence at time-scales that are intermediate between the geologic and geodetic time-scales is a key to understanding these variations in continuity. However, few data at such time-scales are available for the Tohoku district.

We focus here on the erosional and topographic evolution of fold structures developed since the late Pliocene in the Akita and Niigata regions. Topography has long been recognized as an expression of the interplay or coupling between surface processes and tectonic processes (for a brief review, see Merritts and Ellis, 1994). The advantages of topographic analysis are that the surface

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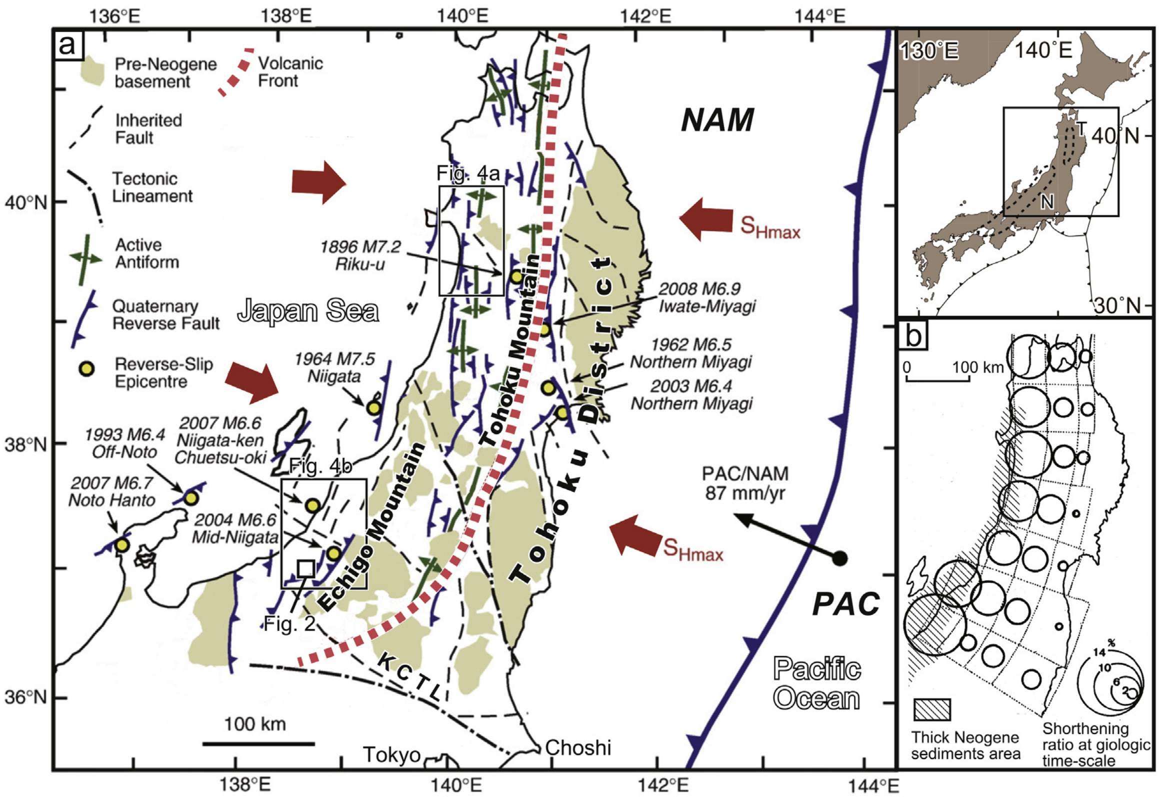

Fig. 1. Active tectonics of the eastern margin of the Japan Sea. (a) Seismo-tectonic sketch map showing the epicenters of recent reverse-fault ruptures in relation to basin-bounding faults, exposed areas of pre-Neogene basement, actively growing regional antiforms, Quaternary volcanoes, and the volcanic front (modified after Sato, 1994; Sibson, 2009). These features are shown in the context of the subduction plate boundary at the Japan trench and inferred trajectories of maximum horizontal stress (SHmax). N: Niigata-Kobe Tectonic Zone (Sagiya et al., 2000). T: Tohoku Mountain concentrated deformation zone (Hasegawa et al., 2005). NAM: North American Plate. PAC: Pacific Plate. KCTL: Kashiwazaki–Choshi (Chiba) Tectonic line (Yamashita, 1970). (b) Shortening ratios estimated from geological fold structures in each grid in the Tohoku district (modified after Sato, 1989). Shading indicates areas of thick Neogene sediments (Sato, 1994).

of the crust is easily observed, and topographic observations can be used to constrain parameters that are otherwise difficult to measure, especially when deformation is distributed (Kirby et al., 2003; Boulton and Whittaker, 2009; Barnes et al., 2011). Landforms develop and erosion occurs at an intermediate time-scale, between the geological and geodetic time-scales (e.g., Lavé and Avouac, 2000). Hills and mountains with elevations of less than 1000 m in the Tohoku district of Japan are antiforms (Fig. 2), and have developed by surface uplift associated with fold growth under an E–W to WNW–ESE compressional stress regime (e.g., Sato, 1989, 1994). We would expect to find spatial heterogeneity in the elevation of ridges and the distances between the topographic ridges and corresponding fold hinges if fold growth is spatially variable.

Based on the degree of fold activity, the balance between erosion and surface uplift controls the topographic development (Fig. 3; Ellis and Densmore, 2006). When tectonic displacement outpaces the rate of erosion, the topographic divide and fold hinge remain close (Fig. 3). Over time, when relief diminishes with respect to rock uplift, and the divide occupies an equilibrium

Fig. 2. Photograph (view to the east) showing the topography (antiforms) generated by folding since the late Pliocene in the southern part of Niigata region. The antiforms have elevations of ~100–700 m. The Echigo Mountains (Mesozoic basement) are more than 1500 m above sea level. PF: Fold structures (antiforms) since the late Pliocene. EM: Echigo Mountains.