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Paleomagnetic study of Plio-Pleistocene sediments in the concentrated deformation zone along the eastern margin of the Japan Sea

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ABSTRACT

Paleomagnetic results are presented for a concentrated deformation zone (CDZ) in a convergent plate boundary region along the eastern Eurasian margin. We sampled late Pliocene–early Pleistocene tuffs and clastic sediments of the Sasaoka Formation (~750 m thick) in northeastern Honshu, Japan, to test whether the late Pliocene–Quaternary crustal deformation within the CDZ along the eastern margin of the Japan Sea was accompanied by rotation about a vertical axis. Rock magnetic experiments suggest that the principal magnetic carrier is magnetite in the fine tuffs, and magnetic iron sulfide in the fine sandstones. Pre-folding characteristic remanent magnetization was confirmed using a positive bootstrap fold test. We obtained 21 acceptable site-mean characteristic directions that include our preliminary published results, and which cover an interval from ca. 2.7 to 1.7 Ma on the basis of magnetostratigraphic correlations. An updated age–depth model is given, and this allowed us to make numerical age estimates for key interbedded tuff beds (tephras). A positive fold test also suggests that the Gojome syncline began to develop after 1.7 Ma, which means the folding began long after the initiation of late Pliocene crustal shortening in northeastern Honshu. After 100% unfolding, the overall mean direction ($D = 359.7°$, $I = 54.9°$, $\alpha_{95} = 6.7°$) is indistinguishable from the geocentric axial dipole field direction, indicating that the Gojome syncline, the most prominent structural element in the study area, developed without vertical-axis rotation. A comparison of our results with Plio-Pleistocene directions reported from other areas reveals no paleomagnetically detectable rotation in or adjacent to the CDZ, except for local rotation near strike-slip faults in central Honshu.

1. Introduction

Among convergent plate boundary regions in eastern Eurasia, the main island of Japan (Honshu) is suitable for investigating the geometry, kinematics, and dynamics of crustal deformation in response to lateral compression. The Pacific plate is being subducted beneath northeastern Honshu as the result of a relatively high rate of convergence (~8 cm/y), and the resultant strong interplate coupling causes E–W compression in Honshu, as well as frequent large-magnitude earthquakes such as the 2011 Tohoku earthquake (e.g. Ozawa et al., 2011). In Honshu, this E–W compression has given rise to intense crustal shortening since the late Pliocene (Awata and Kakimi, 1985; Awata, 1988; Sato et al., 2004b), although in northeastern Honshu the onset of deformation is thought to have occurred at different times in the forearc and backarc regions (Awata, 1988; Sato and Amano, 1991). Along the eastern margin of the Japan Sea, there is a concentrated deformation zone (CDZ) that extends from central Honshu through northern Honshu to western Hokkaido (Fig. 1a). Large-magnitude earthquakes often occur in this zone (e.g. the 1964 Niigata, 1983 Japan Sea, 1993 southwest Hokkaido, 1995 Kobe, 2004 Chuetsu (mid-Niigata), and 2007 Chuetsu-oki earthquakes; e.g., Kato et al., 2009). Within the northern half of this CDZ (which corresponds to the deformation zone of the eastern margin of the Japan Sea proposed by Okamura, 2002), Pleistocene and older strata have been folded and faulted, as best represented by the Gojome syncline in the Gojome area, Akita Prefecture (Fig. 1a, b). Map-scale intense deformation of sedimentary and volcanic units has taken place in this northern half of the CDZ, where NNE–SSW-trending folds and reverse faults are pervasive, and where some oil and

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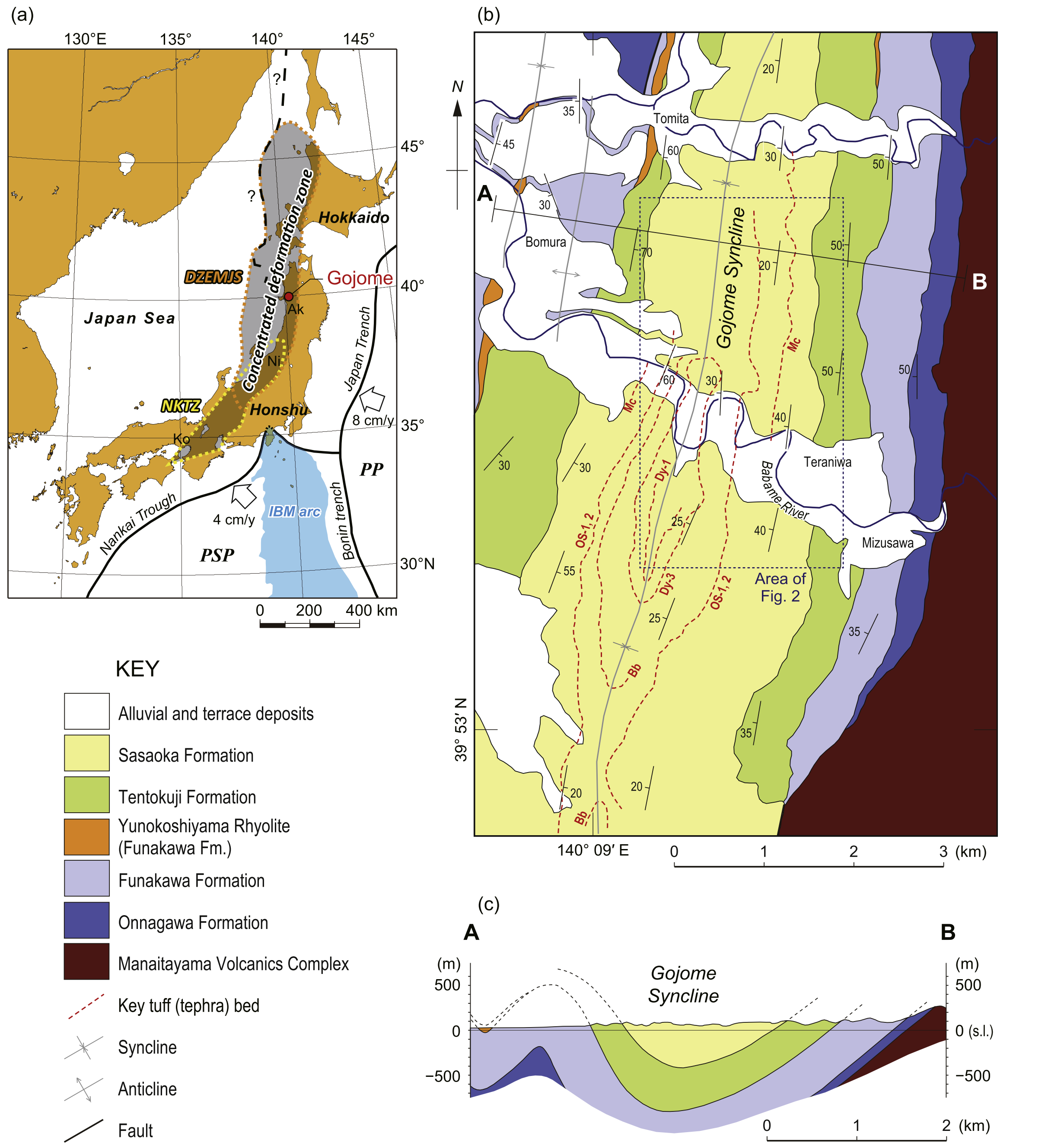

Fig. 1. (a) Location of the study area (Gojome) on a simplified tectonic map of Honshu and surrounding regions. DZEMJS = deformation zone of the eastern margin of the Japan Sea (Okamura, 2002); IBM arc = Izu–Bonin–Mariana arc; NKTZ = Niigata–Kobe tectonic zone (Sagiya et al., 2000); PP = Pacific plate; PSP = Philippine Sea plate. Ak = Akita; Ko = Kobe; Ni = Niigata. The concentrated deformation zone is the combined areas of the DZEMJS and NKTZ. (b) Geological map of the Gojome area, modified from Hase and Hirayama (1970) and Matsui (1981). The map shows the locations of prominent key tuff beds, as mapped by Matsui (1981). (c) East–west geological profile along the line A–B (position shown on b) after Hoshi et al. (2001). s.l. = present-day sea level.

natural gas reservoirs occur (Sugimura and Uyeda, 1973; Sato, 1989, 1994a; Chakhmakhchev et al., 1996; Sato et al., 2004a; Okamura et al., 2007). The northern half of the CDZ generally experienced extensional or transtensional tectonism during the major phase of opening of the Japan Sea in the early Miocene (Yamaji, 1990; Jolivet et al., 1991; Sato, 1994a). There exists geological and geophysical evidence for inversion tectonics, as many reverse faults were originally normal faults bordering extensional sedimentary basins in the early Miocene (Okamura et al., 1995; Sato et al., 2004a; Okada and Ikeda, 2012). In the southern half of the CDZ (which corresponds to the Niigata–Kobe tectonic zone proposed by Sagiya et al., 2000), geological manifestations of crustal shortening are not obvious when compared with the northern half. Nevertheless, geodetic observations (including Global Positioning System data) demonstrate a present-day high strain rate within the southern half (e.g. Mazzotti et al., 2000; Sagiya et al., 2000; Townend and Zoback, 2006). Two different interpretations have been proposed for the CDZ. One is that the CDZ is now part of an incipient convergent plate boundary between the Eurasian (or Amur) and North American (or Okhotsk) plates (Kobayashi, 1983; Nakamura, 1983; Heki and Miyazaki, 2001). The other is that the CDZ is not a plate boundary, but an intraplate zone of high strain rate (Iio et al., 2002).