Journal of Structural Geology 38 (2012) 39–50

Contents lists available at SciVerse ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

The occurrence of graphite-bearing fault rocks in the Atotsugawa fault system, Japan: Origins and implications for fault creep

Kiyokazu Oohashi [a,*,1], Takehiro Hirose [b], Kenta Kobayashi [c], Toshihiko Shimamoto [d]

[a] Department of Earth and Planetary Systems Science, Graduate School of Science, Hiroshima University, Higashi-Hiroshima 739-8526, Japan
[b] Kochi Institute for Core Sample Research, Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Kochi 783-8502, Japan
[c] Department of Geology, Faculty of Science, Niigata University, Niigata 950-2181, Japan
[d] State Key Laboratory of Earthquake Dynamics, Institute of Geology, China Earthquake Administration, P.O. Box 9803, Beijing 100029, China

ARTICLE INFO

Article history:
Received 11 April 2011
Received in revised form
28 October 2011
Accepted 30 October 2011
Available online 15 November 2011

Keywords:
Graphite
Pressure solution
Diffusive mass transfer
Graphite vein
Atotsugawa fault system
Fault creep

ABSTRACT

Graphite in fault zones has received little attention even though it is a well-known solid lubricant that could affect frictional properties of faults dramatically. This paper reports the presence of abundant graphite in fault zones of the Atotsugawa fault system, central Japan. Mesoscopic and microscopic observations of fault rocks revealed two processes of carbon enrichment in fault zones. One is a pressure solution process or diffusive mass transfer in general which removes water-soluble minerals such as quartz and carbonates from rocks, resulting in the enrichment of insoluble minerals including carbon. The other process is precipitation of graphite from a high-temperature carbon-rich fluid, forming graphite filling fractures within cataclasitic fault zones. The two processes have led to the concentration, up to 12 wt% of graphite, in the Atotsugawa fault zones, compared to 0 to 3 wt% of carbonaceous materials in the host rocks. This concentration is high enough for graphite to affect frictional properties at wide range of slip rates. The presence of graphite may provide an explanation for the low resistivity, the patterns of microearthquakes and fault creep along the western part of the Atotsugawa fault system. Graphite should receive more attention as a weakening and stabilizing agent of faults.

1. Introduction

The occurrence of graphite has been reported in a few fault zones, notably: the KTB borehole, Germany (Zulauf et al., 1990); the Err nappe detachment fault, Switzerland (Manatschal, 1999); and the Tanakura Tectonic Line, Japan (Awaji, 2006). However, its mechanical importance had received little attention until Oohashi and Kobayashi (2008) reported massive graphite in the Ushikubi fault zones (Fig. 1a) of the Atotsugawa fault system, Japan. These faults are composed typically of blackish ultracataclasite or fault gouge in the fault core and graphite is contained within the fine matrix of those fault rocks. Graphite in a fault core can have a dramatic effect on its frictional properties because it is a well-known solid lubricant (Savage, 1948; Oohashi et al., 2011a). However, the occurrence and genesis of graphite in fault zones have not been described and discussed in detail. Thus the first aim of this paper is to describe the natural occurrence and spatial distribution of graphite-bearing fault rocks along the Atotsugawa fault system. It represents a good case study for studying graphite-bearing fault zones, their mechanical properties and potential influence on fault behaviour because detailed geodetic, seismological and electromagnetic investigations have been performed already around the fault system (e.g., Goto et al., 2005; Nakajima et al., 2010; Ohzono et al., 2011).

Dark grey-black coloured, graphite-bearing fault zones reported from the Ushikubi fault, the Tanakura tectonic line and the Err nappe detachment fault are all developed within apparently graphite-free (or poor), pale-coloured leucocratic host rocks. The difference in graphite content between host rock and fault zone suggests that enrichment processes of graphite could act within the fault zones. Zulauf et al. (1999) found from the KTB borehole that carbon content increased by 80–140% in the shear zones compared to the wall rock gneisses. They proposed that the following chemical reaction operated along the lower crustal shear zone at relatively high temperatures (>400 °C; Luque et al., 2009):

$$CH_4 + CO_2 \rightarrow 2C + 2H_2O \quad (1)$$

Craw (2002) also suggested that graphite enrichment along the Hyde-Macraes shear zone in New Zealand can be attributed to the

* Corresponding author. Tel.: +81 43 290 2856; fax: +81 43 290 2859.
E-mail address: oohashik@earth.s.chiba-u.ac.jp (K. Oohashi).
[1] Present address: Department of Earth Sciences, Graduate School of Science, Chiba University, Chiba 263-8522, Japan.

0191-8141/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsg.2011.10.011

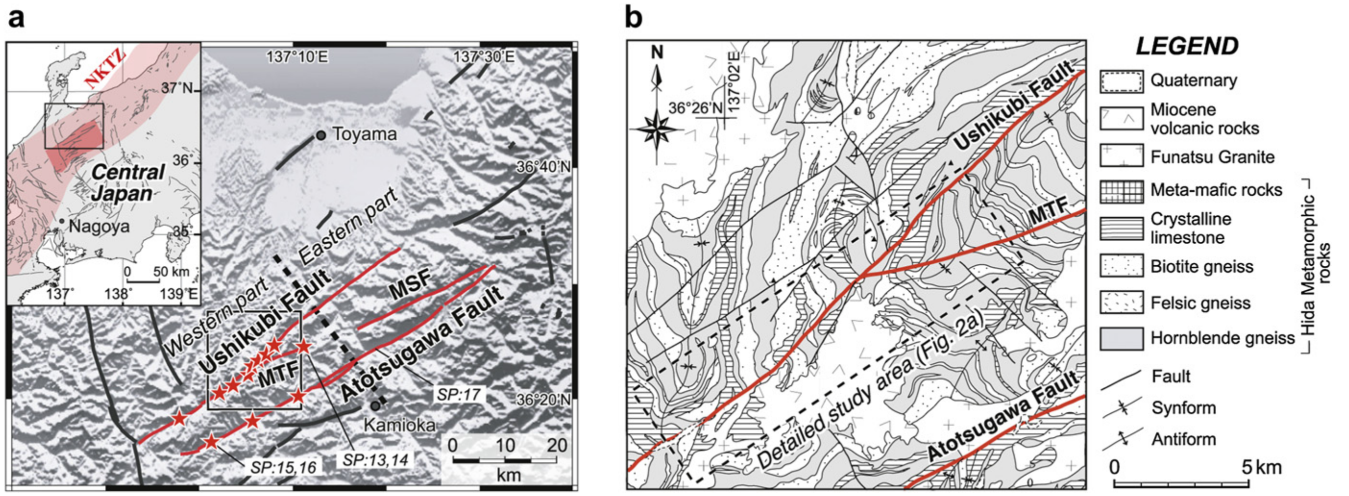

Fig. 1. (a) Topographic map of the study area and its location in central Japan (framed area in the inset diagram). The dark shadow area in the inset shows the high strain-rate zone in the Niigata-Kobe tectonic zone (NKTZ; light shadow). The map also shows traces of active faults after The Research Group for Active Faults of Japan (1991) and the locations of the outcrops of graphite-bearing fault zone are also shown by stars. Please see Fig. 2a for detailed locations of graphite-bearing fault rocks in framed area since they are too numerous to be shown in this figure. Locations of gouge specimens analyzed with X-ray powder diffraction are labelled in the figure (SP: sample number in Table 1). The topographic relief was created from a 50 m-DEM of the Geographical survey Institute of Japan. The framed area is shown in (b). MTF: Man-nami toge fault, MSF: Mozumi-Sukenobu fault (b) Geological map of the study area (modified after Sohma and Akiyama, 1984). The framed area with a dashed line is shown in the next figure. MTF: Man-nami toge fault.

hydrothermal deposition of graphite at a temperature higher than that for the brittle regime in continental crust (300–400 °C). However, microstructural evidence of graphite precipitation and enrichment process are still unclear particularly for upper crustal fault zones where country rock temperatures lie below 300 °C. Thus, the second aim of this paper is to identify graphite enrichment mechanisms using the Atotsugawa fault system as an example.

2. Outline of the Atotsugawa fault system

The Atotsugawa fault system in central Japan is composed mainly of four sub-parallel, right-lateral strike-slip faults referred to as the Atotsugawa, Mozumi-Sukenobu, Man-nami toge and Ushikubi faults (Fig. 1a). The strikes of the fault trace are approximately N60°E (Atotsugawa and Ushikubi faults) to N75°E (Man-nami toge and Mozumi-Sukenobu faults), with the dips consistently being almost vertical (90° ± 10°) near to the surface. The Atotsugawa fault is one of the most prominent active faults in Japan that caused the 1858 *M*7.0–7.1 Hietsu Earthquake (The Research Group of Active Faults in Japan, 1991). The Atotsugawa fault system has several specific characteristics based on seismological and geodetic observations: (1) it is located in the Niigata-Kobe Tectonic Zone (NKTZ) which is a high strain-rate belt identified from GPS observations (Sagiya et al., 2000); (2) swarms of microearthquake are aligned along the faults (Ito et al., 2007, Imanishi et al., 2011), unlike most active faults in Japan which do not show such associated microseismicity; and (3) fault creep may be taking place in the middle part of the Atotsugawa fault at a rate of about 2 mm/y (based on electronic distance meter (EDM) measurements, Tada, 1998) and in the middle to western part of the Atotsugawa and Ushikubi faults at a rate of 2–3 mm/y (GPS measurements, Ooi, 2003; Ohzono et al., 2011).

The Atotsugawa fault system cuts the Hida belt which is composed of the Paleozoic to early Mesozoic Hida metamorphic rocks, Upper Jurassic to Lower Cretaceous sedimentary rocks (Tetori group), intrusions of Cretaceous granitic rocks and Miocene volcanic rocks (Fig. 1b). The Hida metamorphic rocks consist of paragneisses, volcanic gneisses, crystalline limestone (marble) and older granitoids which underwent high-T-low-P metamorphism. Paragneisses such as biotite gneiss often contain small amount of graphite (less than a few %; Kano, 1980) as an accessory mineral. Crystalline limestone also contains limited amounts of graphite together with interbedded siliceous layers of quartz and feldspar. The Hida metamorphic belt around the Atotsugawa fault system is divided into two massifs in terms of petrological features (Sohma and Akiyama, 1984). One is predominantly biotite gneiss and is distributed in the western part of the Atotsugawa fault system (the western massif). The other is characterized by a dominance of graphite-free (or poor), volcanic-origin amphibole gneiss and lies in the eastern part (the eastern massif). The Tetori Group, that is composed mainly of sandstone, mudstone (shale) and conglomerate, is distributed only in the shallow crust (<2 km in depth) of the eastern part.

Some brittle fault rocks are preserved along the Atotsugawa fault (e.g., Niwa et al., 2008; Tanaka et al., 2007), but they are best exposed along the western part of the Ushikubi fault where it cuts the western massif of the Hida metamorphic belt. Oohashi and Kobayashi (2008) showed that the brittle shear zone here is 250–600 m wide consisting of parallel or sub-parallel, multiple fault zones and highly intersected subsidiary faults (gray line in Fig. 2a) linked to the Ushikubi master fault (dark line in Fig. 2a). Additionally, they also reported that the brittle shear zone along the Ushikubi fault has two different stages of deformation: earlier sinistral faulting of Late Cretaceous to Paleogene age that is recorded in the cataclasites; and later dextral faulting of Quaternary period recorded in later-formed cataclasites and fault gouges.

3. Occurrence of graphite-bearing fault zones

3.1. Distribution and structures of graphite-bearing fault zones

Fig. 2a shows the distribution of major and minor fault zones greater than 1 m wide along the Ushikubi fault. The strike of the major fault zone is ENE–WSW in the southwestern part of the study area (Mizunashi segment), changing to NNE–SSW in the central and northeastern parts (Harayama and Shirakimine segments). Subsidiary faults with NNE–SSW trends are developed in the Harayama and Shirakimine segments (shown grey lines in Fig. 2a) forming compressional jogs. Many small-scale faults, which