Chemical Geology 275 (2010) 176–185

Contents lists available at ScienceDirect

Chemical Geology

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

Timing of brittle deformation within the Nojima fault zone, Japan

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ARTICLE INFO

Article history:
Received 10 September 2009
Received in revised form 30 March 2010
Accepted 7 May 2010

Editor: B. Bourdon

Keywords:
Neotectonics
Brittle deformation
Clay gouge
Unspiked and conventional K–Ar dating
Nojima fault
Japan

ABSTRACT

K–Ar ages from clay fault gouges of outcrop and core samples (UG500 well) from the Nojima fault zone, Awaji Island, Japan are consistent internally with established field constraints, and with apatite and zircon fission track ages, demonstrating the suitability of this method for dating of brittle deformation. Six unspiked and thirty conventional K–Ar data of clay minerals separated from gouge zones were analysed. Characterized by protoliths of high-grade metamorphic and magmatic rocks, the samples from the Nojima fault zone offer the opportunity to distinct identify newly grown illite in the fault planes. All dated sample fractions were characterized by XRD, SEM and TEM. K–Ar ages of 29 separates have an age range from 63.4 ± 1.3 Ma (Early Palaeocene–Danian) to 42.2 ± 1.0 (Palaeogene–Middle Eocene–Lutetian). Some <0.1 and <0.4 μm fractions of samples in close proximity to a pseudotachylyte zone are thermally influenced and indicate loss of radiogenic Ar. The K–Ar data from illite support a model that the Nojima fault zone was initiated ~55 Ma ago based on ZFTA data. The data confirm elevated temperatures and a heterogeneous thermal history within the study area. The <2 μm ages of the outcropping samples document the age of gouge formation, whereas the <0.1 and <0.4 μm illite fractions suggest the influence of a secondary thermal heating event probably caused by circulation of hot fluids within the fault zone about 31–38 Ma ago and even a potential influence of Quaternary faulting. Ar diffusion models support elevated temperatures for outcrop samples collected near the Hirabayashi site. The thermal anomalies documented in the outcrop samples could not be observed in the UG500 core samples supporting further a heterogeneous thermal history model within the Nojima fault zone.

1. Introduction

Numerous studies have highlighted the potential for determining timing of near-surface deformation and brittle faulting using isotopic dating. The method has been applied in numerous studies using tools such as K–Ar, ^{40}Ar–^{39}Ar, Rb–Sr and Zircon Fission Track Analysis (ZFTA), see summary by Zwingmann and Manckeltow (2004) and Tagami and Murakami (2005). Displacement of fault planes can result in the development of fault gouges containing rock fragments and newly formed authigenic clay minerals such as illite that crystallized in the fault planes. Understanding these processes and the timing and extent of clay-rich fault gouge formation is important for: (1) regional correlation of shallow fault activity, which is of critical importance in neotectonic studies, (2) civil engineering and evaluation of earthquake hazards, (3) assessment of the suitability of sites for waste storage including nuclear waste, and (4) hydrocarbon exploration, as faults may act as either conduit zones or seals for fluids and/or hydrocarbons. Here, we attempt to determine the timing of authigenic illite formation within outcrop and drill core samples of the Nojima Fault zone on Awaji Island, Japan. The Nojima Fault is related to the Median Tectonic Line (MTL) in Japan (Oshiman et al., 2001). The fault zone was drilled in a scientific program (Ando, 2001). Some studies have dated illite to establish the timing of prograde incipient metamorphism in the MTL (Takagi and Shibata, 1992) but no illite dating was reported from the Nojima Fault zone at Awaji Island, Japan.

2. Location and sampling

The study area is located in the southern area of Inner Zone of Southwest Japan, with the southern tip of the island in contact with the MTL (Fig. 1). Comprehensive geological summaries of the study area can be found elsewhere (Oshiman et al., 2001). The Nojima fault zone was activated during the 1995 Kobe earthquake (Hyogoken–Nanbu earthquake). The thermochronological framework of the study area was investigated in detail by ZFTA (Murakami and Tagami, 2004; Tagami, 2005; Murakami et al., 2002; Tagami and Murakami, 2007). The basement is for the most part Cretaceous granodiorite,

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doi:10.1016/j.chemgeo.2010.05.006

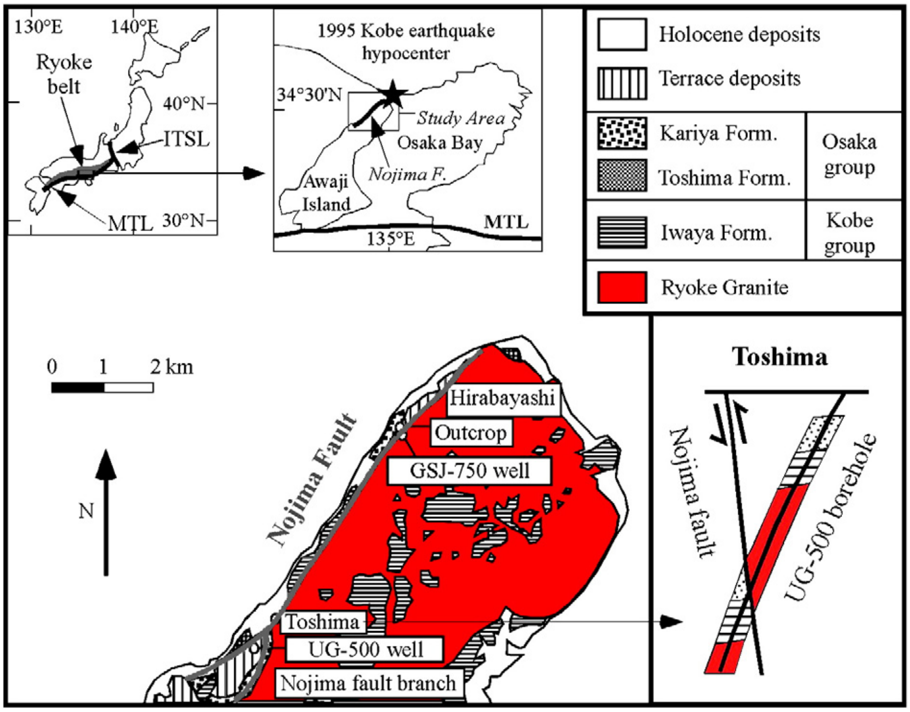

Fig. 1. Simplified map of the study area and UG 500 well, modified from Tagami (2005).

with hornblende and biotite K–Ar ages ranging from 88 ± 4 to 90 ± 5 Ma and 70 ± 4 to 88 ± 4 Ma, respectively (Takahashi, 1992). ZFT age analysis suggests that the Ryoke basement was initially cooled through the ZPAZ at 74 ± 3 Ma near the Nojima fault (e.g. Tagami and Murakami, 2007). In the northern part of the island, the Eocene–Oligocene Iwaya Formation partially overlies the basement (Mizuno et al., 1990). The Plio-Pleistocene Osaka Group is distributed along the northwest coast of the island. As a result of the 1995 Kobe earthquake, a surface rupture more than 10 km in length developed along the pre-existing NE–SW striking Nojima fault (Fig. 1). The maximum surface displacement was as 180 cm right lateral and 130 cm reverse components at Hirabayashi, located to the north of the fault. Here, the fault forms a geological boundary between the Osaka Group and Iwaya Formation to the west and the Cretaceous Ryoke Granitic rocks to the east.

Five surface samples of granitic cataclasite (Fig. 2) were collected in a river outcrop near a previously investigated trench (Murakami and Tagami, 2004). The Nojima fault samples (NFS) 4 and 5 are in close proximity to a pseudotachylyte. Six small core samples from Nojima University group 500 m (UG500) borehole were also investigated. A description of the UG500 well can be found elsewhere (Murata et al., 2001). Alteration was described in numerous studies identifying clay minerals such as smectite, illite and chlorite in various amounts (Fujimoto et al., 2001). Typical alteration minerals in the fault zone comprise smectite, illite–smectite mixed layers, montmorillonite, zeolites and carbonate minerals such as calcite, siderite and dolomite (Fujimoto et al., 2007). The mineral assemblages and textures are indicative of several episodes of hydrothermal activity in the fault zone.

3. Methods

Each surface sample consisted of ca. 200 g of gouge material collected from 30-to-40 cm depth. For the UG500 core samples ca. 20 to 50 g were collected. The surface and core samples were extensively washed with deionized water to remove soil or drilling fluid contamination (Schleicher et al., 2006). Larger pieces were first crushed into <10 mm chips, and then gently disaggregated by using a repetitive freezing and thawing technique to avoid artificial reduction of rock framework components and contamination of finer size fractions with relict K-bearing minerals such as K-feldspar or micas (Liewig et al., 1987). Two splits of sample NFS5 were collected at different depths in the outcrop to investigate influence of potential weathering and alteration of the surface samples. Grain size fractions of <2, 2–6 and 6–10 µm were separated in distilled water (Stoke's law). Fractions <0.1 and <0.4 µm were obtained using a high speed centrifuge.

The mineralogy of most size fractions was determined by X-ray diffraction (XRD). The identification and analysis of clay minerals X-ray diffraction has been summarised by Moore and Reynolds (1997). Diffractograms were obtained from air-dried slides, analysed with a Philips X'Pert X-ray diffractometer fitted Cu X-ray tube operated at 40 kV/40 mA and a graphite monochromator in the diffracted beam path to select CuKa radiation. Samples were scanned over the range 2 theta = 3–60° at 0.015° 2 theta/s. The CSIRO X-PLOT software was used for peak and mineral identification. Glycolated XRD analyses were carried out to investigate potential occurrence of expandable mixed layer smectite mineral content. Due to limited sample amount it was not possible to analyse illite polytypes by XRD.

Freshly broken surfaces of sample chips were carbon-coated and examined in secondary and backscattered electron mode using a Philips 300 SEM equipped with an energy dispersive system X-ray analyzer (EDS). A JEOL 2010 TEM (200KV) was used for detailed grain-by-grain morphological characterization of selected clay fractions and for control of grain-size distribution within the fractions. Samples were prepared by placing one drop of clay solution on a micro carbon grid film and drying under air. The composition of individual particles was investigated by an attached EDS system.

3.1. K–Ar age dating

Two different K–Ar methods were used to determine the ages of separated clay fractions. The conventional “spike” K–Ar dating technique was applied at CSIRO, Perth, which follows basic fundamental