Journal of Structural Geology 79 (2015) 75–79

Contents lists available at ScienceDirect

Journal of Structural Geology

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

Nanometre-scale faulting in quartz under an atomic force microscope

Yasutomo Omori*, Hideaki Ikei, Yasuo Kugimiya, Toshiaki Masuda

Institute of Geosciences, Shizuoka University, Ohya 836, Suruga-ku, Shizuoka 422-8529, Japan

A R T I C L E I N F O

Article history:
Received 11 December 2014
Received in revised form
10 July 2015
Accepted 19 July 2015
Available online 21 July 2015

Keywords:
Atomic force microscope
Indentation
Linear displacement–length scaling relationship
Nanometre-scale faulting
Quartz

A B S T R A C T

We conducted nano-indentation tests of quartz under a load of 294 mN at room temperature and ambient pressure. Using an atomic force microscope, we performed topographic mapping of the indented surface immediately after the nano-indentation test and again 46 h later. Differences in the contour patterns of the two surface topographies reveal that a new fault developed in the quartz specimen while it was secured on the specimen stage of the atomic force microscope between the two mapping times. The fault length is ~2 μm and the maximum displacement on the fault plane is ~20 nm. When combined with existing displacement–length data from natural faults, the data suggest that a linear displacement–length scaling relationship can be extrapolated to nanometre-scale faulting.

1. Introduction

Displacement–length scaling relationships for faults have been thoroughly analysed, and both the linear displacement–length scaling relationship (e.g., Muraoka and Kamata, 1983; Cowie and Scholz, 1992a,b; Gillespie et al., 1992; Clark and Cox, 1996; Schlische et al., 1996; Xu et al., 2006; Schultz et al., 2008; Torabi and Berg, 2011; and many references therein) and non-linear scaling relationship (e.g., Watterson, 1986; Walsh and Watterson, 1988; Marrett and Allmendinger, 1991; Gillespie et al., 1992) have been proposed. Schultz et al. (2008) reported that the linear scaling relationship has been well documented in previous studies of normal, strike-slip and thrust faults. The data sets for displacement and length that have been used to establish the displacement–length scaling relationship range from approximately 0.1 mm to 100 km and 1 cm to 1000 km, respectively. Here, we report displacement and length data from a much smaller (nanometre) scale fault that developed in a single crystal of quartz on the specimen stage of an atomic force microscope in the laboratory. The displacement–length data from the fault indicate that the linear scaling relationship appears to be applicable to nanometre-scale faulting.

2. Nano-indentation test

An idiomorphic quartz single crystal was cut perpendicular to the c-axis using a low-speed cutter to prepare a 2.5 mm wide and 2 mm thick specimen. The specimen was polished with diamond paste to obtain a flat surface. A nano-indentation test was then performed on the quartz specimen parallel to the c-axis using a depth-sensing nano-indentation tester (RIDER, Mitsutoyo-AKASHI Co., Japan) with a Vickers pyramidal diamond indenter at room temperature and ambient pressure (for details of the test procedure, see Masuda et al., 2000). The maximum load applied to the specimen was 294 mN. The loading rate, dwell time and unloading time were 2.6 mN/s, 0.5 s and 20 s, respectively.

3. Topographic mapping by atomic force microscope

We performed topographic mapping of an indentation on two separate occasions, and were able to discriminate two events (Event 1 and Event 2) that had occurred in the quartz specimen. Event 1 represents the indentation test, the products of which were visualised by the first topographic mapping, while Event 2, which occurred after the first topographic mapping, involved later changes in the Event-1 surface topography revealed by the second topographic mapping.

* Corresponding author.
E-mail address: f5844006@ipc.shizuoka.ac.jp (Y. Omori).

http://dx.doi.org/10.1016/j.jsg.2015.07.008
0191-8141/

3.1. First topographic mapping: Event 1

The indented surface was observed with an atomic force microscope (AFM; SPA300, Seiko SII Co., Japan), which has a precision of <1 nm. The room temperature was kept constant at 20 °C during observation. Fig. 1a shows the result of the first topographic mapping of the indentation site, which was performed immediately after the nano-indentation test. The pyramidal indentation is ~6 μm across and ~400 nm deep with slightly convex sides, and contour lines within the indentation are concentric and smooth. Bulges occur adjacent to each of the four sides of the indentation, and have heights of 50–60 nm from the flat surface of the quartz crystal.

Three lineaments are also observed, defined by a sharp deflection of contour lines, radiating from the indentation site (Fa, Fb and Fc in Fig. 1a). The bottom-right lineament (Fb) terminates at the corner of the indentation, whereas the other two lineaments (Fa and Fc) terminate on the side of the indentation. We regard these three lineaments as fault scarps. As the deflection of contour lines is not sharp along the fault scarps, it is difficult to determine the maximum vertical offset from the contour diagram. Fig. 2 shows profiles of the offset amount along the fault scarps. We obtained a maximum vertical offset (fault scarp) of ~5–7 nm and a fault length of ~1–2 μm for these faults. These data have a maximum measurement error of ±30%. The maximum offsets do not occur in the central parts of the faults. As the contour lines representing zero level on the surface are not disturbed, these faults appear to have a minor strike-slip component or none at all. Thus, we regard the offset data as approximate values of displacement along these faults (Fig. 3a).

A flat area occurs outside the top-left corner of the indentation where no fault is detected (Fig. 1a). This area is the site of a new fault (F2 in Fig. 1b) that formed during Event 2.

3.2. Second topographic mapping: Event 2

After the first topographic mapping (Fig. 1a), the specimen was left undisturbed on the specimen stage of the AFM. The specimen was continuously secured at a constant temperature of 20 °C with no artificial mechanical disturbances. We performed the second topographic mapping of the same indentation site 46 h later, and found that the topography differed from the first map (Fig. 1b). Thus, Event 2 represents the deformation that occurred in the period between the times of the first and second topographic mapping. We noticed four prominent differences in the second topographic map relative to the first: a newly developed fault (F2), which is the main topic of this paper; sharpening of the lineaments along the three pre-existing faults (Fa, Fb and Fc) with an increase in offset and length; shallowing of the indentation by ~5%, and

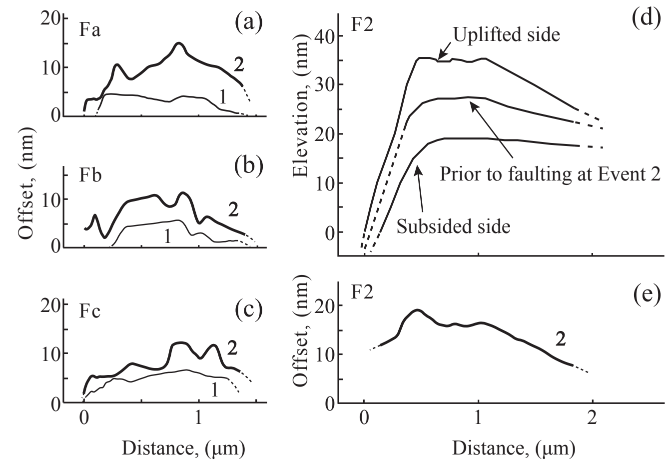

Fig. 2. Profiles of offset and elevation along the faults. The positions where the faults terminate are poorly defined. (a), (b) and (c) are profiles of the offset for the three faults (Fa, Fb, and Fc, respectively) at Event 1 (thin line) and Event 2 (thick line). (d) Change in elevation above the quartz surface along the F2 fault. (e) Offset along the F2 fault at Event 2. The offset reaches 20 nm, which is about two times larger than the offsets of Fa, Fb and Fc that occurred during Event 2.

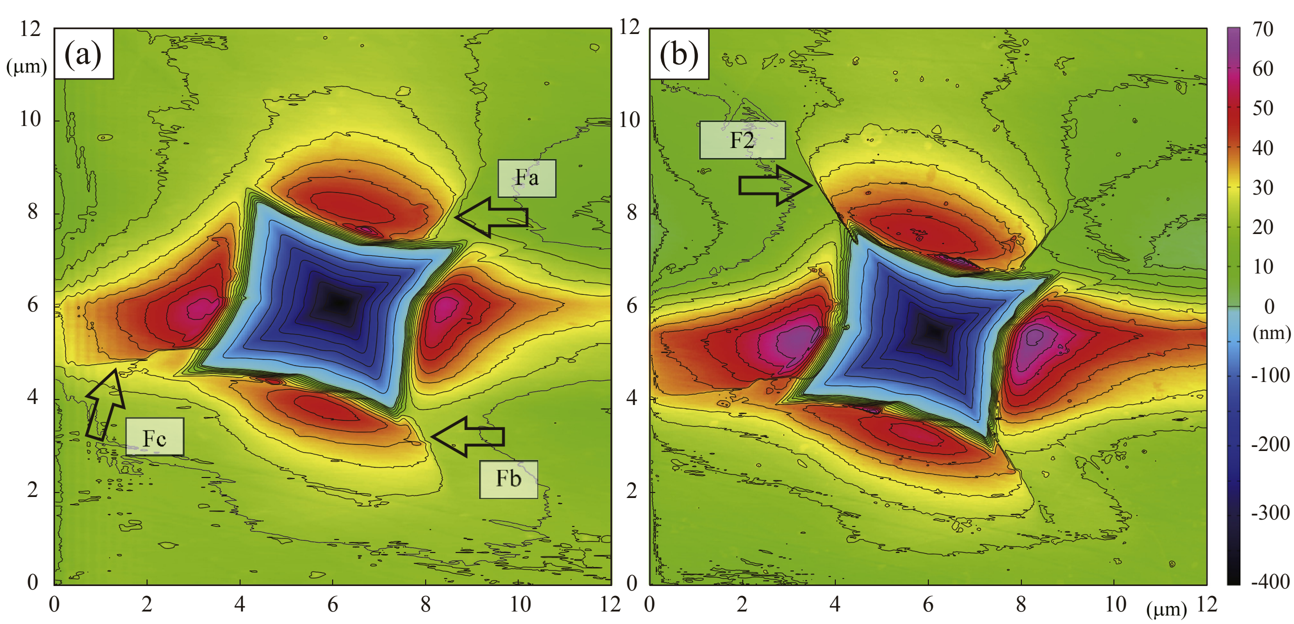

Fig. 1. Surface topographic map of the indented quartz single crystal. (a) Immediately after the nano-indentation test, and (b) 46 h after the first topographic mapping. Three arrows (Fa, Fb and Fc) in (a) and one (F2) in (b) indicate lineaments (faults). The colour scale on the right indicates height and depth of the topography. The contour interval is 5 nm for >0 nm and 50 nm for <0 nm, where the 0 nm level represents the flat surface of the quartz crystal before the nano-indentation test. A new fault has developed from the top-left corner of the indentation in (b). The dip of the fault appears vertical, with uplift to the right of the fault.