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Correlation of Deformation Textures with Laboratory Measurements of Permeability and Strength of Nojima Fault Zone Core Samples

Diane E. Moore[1], David A. Lockner[1], Hisao Ito[2], and Ryuji Ikeda[3]
[1]*U. S. Geological Survey, MS977, 345 Middlefield Road, Menlo Park, CA, 94025 USA*
[2]*Geological Survey of Japan, Tsukuba, Japan*
[3]*National research Institute for Earth Science and Disaster Prevention, Tsukuba, Japan*

ABSTRACT

The deformation textures observed in 22 core samples of intact and altered granodiorite from two drillholes into the Nojima fault zone are consistent with the permeability and strength data reported by Naka et al. (1998) for those samples. The highest measured permeability was in a sample subjected only to dilational cracking. More intense fracturing accompanying microshear development also produces relatively high permeability, if the fragments generated by the deformation are relatively large. In these rocks, the fracturing intensity is directly correlated with the amount of strength reduction. Progressive granulation of the fragmented rock generates fine-grained gouge of low shear strength and moderately low permeability.

The deformation and mineralization features observed in the sample set have been combined into a general model for the evolution of a gouge layer relative to its permeability and strength. Of the four possible fault strands encountered in the two drillholes, the GSJ and shallowest NIED fault strands appear to be currently active, whereas the deepest NIED fault strand was abandoned and has since been thoroughly sealed with mineral deposits. The middle NIED strand also shows some evidence of recent shearing, although the two examined gouge samples are overprinted by dilational cracking.

INTRODUCTION

Core samples of biotite-hornblende granodiorite from two drillholes into the Nojima fault zone were measured for permeability and strength by Naka et al. (1998; see also Lockner, this volume) in the rock deformation laboratory at the U.S. Geological Survey in Menlo Park, California. The hole drilled by the Geological Survey of Japan (GSJ) crossed a gouge-bearing fault at about 624 m, whereas the hole drilled by the National Research Institute for Earth Science and Disaster Prevention (NIED) crossed three possible fault strands at depths of about 1140 m, 1320 m, and 1800 m. Four to six samples from each fault strand were examined by Naka et al. (1998) (Table 1), along with representative samples of the country rock.

In order to compare the degree of deformation with the strength and permeability values, a thin section was prepared from each sample for petrographic examination. All but two of the samples were cut perpendicular to the axis of the cylindrical core samples; NIED sample 81-22A and GSJ 99-4 were cut parallel to the axis. This report shows (1) the correlation of the deformation and mineralization textures to the strength and permeability values, and (2) the position of each fault strand in an evolutionary sequence for a gouge core zone that was constructed from the petrographic observations.

FAULT ZONE STRUCTURE, PERMEABILITY, AND STRENGTH

The examination of exhumed faults (e.g., Chester and Logan, 1986; Chester et al., 1993; Evans et al., 1997), has shown that a fault zone commonly consists of a narrow (≤1 m wide) core zone of fault gouge, where shear strain is concentrated. The core is embedded in a significantly wider zone of deformed rock, termed the damage zone, in which the intensity of deformation gradually decreases towards the undeformed country rock. Chester and Logan (1986) found that strength increases regularly from the fault core to the country rock (Chester and Logan, 1986), whereas permeability reaches a maximum within the zone of damaged rock (Evans et al., 1997). Depending on the initial permeablity of the protolith — for example, a highly porous sandstone versus a low-permeability crystalline rock — the permeability of the gouge zone may be higher or lower than that of the country rock.

The strength and permeability data reported by Naka et al. (1998) and the textures of the Nojima fault rocks are consistent with this model of fault-zone structure and mechanical properties. The country rock has very low permeability and high strength. It contains few completely filled cracks and has little alteration. Naka et al. (1998) identified a 20–40 m-wide zone of high permeability associated with each fault strand that they correlated with the damage zone (the data are presented by Lockner, this volume). The range of deformation intensity associated with high permeability is illustrated by the two highest-permeability samples from the NIED drillhole (80-29,

Table 1. Samples examined in this study.

Sample #	Depth (m)	Description
GSJ Drillhole		
——	258.6	country rock; relict amphiboles
74-17	503.4	damage zone: microshear zones
91-6	582.0	2.5–10 mm-wide gouge-like band (old)*
98-31	623.6	banded gouge (old)
99-4	624.4	fine-grained gouge
101-2	634.1	two ≤6 mm-wide gouge-like bands
118-21	730.4	damage zone; relict amphiboles
NIED Drillhole		
12-1A	659.3	country rock; relict amphiboles
32-20	1063.7	damage zone: dilational fractures
34-27	1077.9	damage zone: microshear zones
43-37-1	1131.8	damage zone: gouge-like microshear zone
45-23	1140.1	fine-grained gouge
74-19	1278.6	damage zone: dilational fractures
76-17	1289.0	20 mm-wide gouge-like band
80-29	1307.5	damage zone: dilational fractures
81-22A	1312.0	coarse-grained banded gouge (old)
82-40	1320.3	damage zone: gouge-like microshear zones
85-15B	1332.2	coarse-grained gouge (old)
179-33	1798.2	old shear zone (see text)
181-34	1807.9	old shear zone
183-14C	1815.9	old shear zone
184-23	1821.9	old shear zone

* The gouge in samples labelled (old) is cut by mineral-filled dilational ± shear fractures.
The narrow gouge-like bands in 91-6, 101-2, and 76-17 are bounded by damage-zone rock.

Figure 1a; 43-37-1, Figure 1b). Sample 80-29 is not highly deformed but does contain a set of elongate dilational fractures that are partly filled with a Ca-zeolite (probably laumontite) and carbonate minerals containing varying amounts of Fe, Mg, and Ca. Growth textures of the secondary minerals suggest that the fractures have remained open for at least two episodes of crystal growth. The more highly deformed damage-zone rocks, which are generally associated with some shear fracturing, also have high permeability if the fragments remain relatively large. The quartz crystal in Figure 1b has been thoroughly fractured, and the pieces form a high-permeability network of voids and cracks.

With further increases in the intensity of shearing, the rock loses cohesion and the fractured rock is replaced by dense, fine-grained gouge (Figure 1c) that has permeability intermediate between the undeformed granodiorite and the damage-zone rocks. The strength data of Naka et al. (1998) are directly correlated with the degree of cohesion, such that the sequence of samples in Figure 1a–c has progressively decreasing strength (see Lockner, this volume).

GOUGE CORE EVOLUTION

Progressive deformation of the country rock to form a gouge layer destroys most traces of the layer's earlier history (e.g., Figure 1c). However, the variety of deformation and mineralization textures observable in the sample set of Table 1 can be combined into a generalized textural, permeability, and strength history of the gouge core zones. Overall, the first half of the sequence involves initial dilational fracturing of the granodiorite, followed by shear fracturing that increases in intensity and degree of localization until a gouge zone is formed. This part of the time sequence largely corresponds to the spatial sequence of deformation textures moving from the country rock through the damage zone to the gouge core. The second half of the time sequence is essentially the reverse of the first half, as the gouge zone is abandoned and eventually sealed.

The first deformation features to appear in damage-zone granodiorite are dilational cracks concentrated in quartz (see also Moore and Lockner, 1995) that typically consist of one prominent set of sub-parallel cracks (Figure 1a and d) and a subsidiary set that intersects the other at an angle of 60–90° (Figure 1d). Fluids flowing through the fractures after an earthquake cause some alteration of the igneous assemblage and deposit minerals on the fracture walls (Figure 1a). With increasing intensity of deformation, the igneous feldspars also begin to fracture extensively (Moore and Lockner, 1995). At this time, some of the earlier-formed dilational fractures undergo minor shear displacement. In Figure 1d the two intersecting shear fractures are parallel to the principal fracture sets visible in the large K-feldspar crystal. These two shears have developed from single fractures, but commonly closely spaced fractures pair up to form microshear zones (Figure 1e), with the fractures serving as boundary faults and the rock between them being more highly damaged than that outside the zone. Martel et al. (1988) and Segall and Pollard (1983) described similar fault-zone structures at outcrop scale in granitic rocks of the Sierra Nevada, California. In some of the Nojima fault samples, offsetting shears imply that the perpendicular shears were active at different times. However, most of them probably were active at the same time, leading to intensified fracturing of the granodiorite near their intersections.

As shearing becomes more heavily concentrated at one location, it becomes restricted to a single planar zone. Narrow gouge-bearing bands in NIED 76-17 and GSJ 101-2 intersect both sets of older microshears; such cross-cutting relations may be typical of the gouge layers. Continued shearing within these single layers eventually generates gouge (Figure 1c). Among the remaining rock fragments in the gouge, clasts of medium-grained laumontite and of carbonate minerals are evidence of the gouge's earlier history of dilational fracturing and alteration. In addition, some of the gouge samples contain clasts of earlier-formed gouge, indicating multiple episodes of slip within the well-developed gouge layer.

Fault offset does not remain localized along the same gouge zone, but rather shifts to other gouge layers over time. If the new site of localized shear is within the same fault strand, then the abandoned gouge layer becomes part of the damage zone of the new gouge core. As such, the older gouge layer would be limited to dilational fracturing and minor shearing. For example, the banded gouge of GSJ 98-31 (Figure 1c) has been cut by a series of narrow laumontite and carbonate-filled cracks, such as the one extending from left to right across the middle of the photo. Eventually, fault motion may shift to a completely new strand, leaving the old strand outside the damage zone of the new one. In the absence of permeability-enhancing deformation, the old gouge layers, along with the rest of the abandoned fault strand, are gradually sealed with mineral deposits.

Figure 2 is a schematic summary of the general trends in permeability and strength that would accompany the deformation sequence described above,

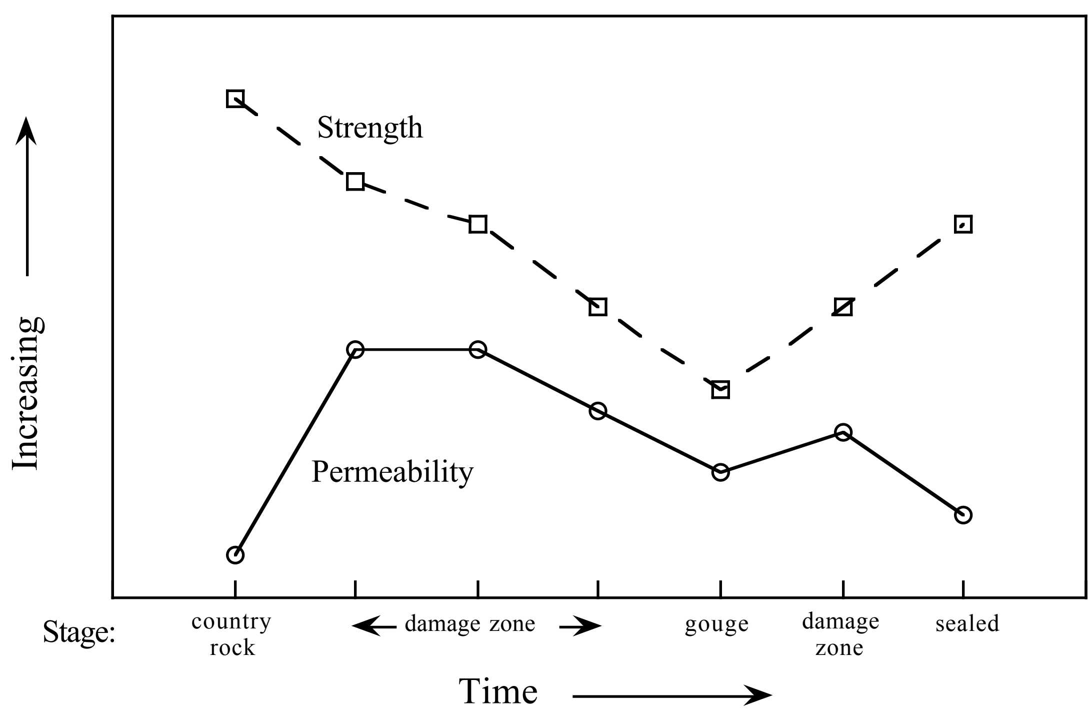

Figure 2. Relative changes in permeability and strength in the successive stages of the history of a gouge core zone (see text). The plots do not include the effects of individual earthquake cycles.

based on the data of Naka et al. (1998). The early stages leading up to gouge development correspond to the textural sequence in Figure 1a–c, and the accompanying changes in permeability and strength were described previously. When the gouge layer is abandoned as a site of localized shear, it becomes progressively indurated and strengthened as a result of sealing and alteration reactions. The two lines drawn in Figure 2 do not include the changes caused by individual seismic cycles (see Fig. 13 of Chester et al., 1993, p. 782). Sealing of fault rocks as a result of fluid-rock interaction will cause permeability to decrease and strength to increase between earthquakes.

POSITIONS OF THE FOUR FAULT STRANDS IN THE EVOLUTIONARY SEQUENCE

Of the four possible fault strands represented by the groups of samples in Table 1, the GSJ and the shallowest NIED strands are currently active. There have been some apparent shifts in the position of localized shear within the GJS strand, with one gouge sample (98-31) (Figure 1c) and a narrow band of gouge in a damage-zone sample (91-6) both being cut by mineral-filled dilational cracks. These older gouge layers are now in the damage zone surrounding the new gouge core in that strand. The middle NIED fault strand also is active in at least a subsidiary sense, although both gouge samples (81-22A and 85-15B) are overprinted by dilational cracks lined with mineral deposits. However, the narrow bands of gouge in 76-17 and 82-40 (Table 1) may have been sheared during the 1995 earthquake.

The deepest NIED fault strand is characterized by permeability and strength values approaching those of the country rock, and the mineralization textures suggest that it is an older, abandoned fault trace that would correspond to the final, sealed fault stage of Figure 2. This strand did not contain a gouge core; rather, shear may have been distributed among the many microshear zones (Figure 1d–e). Once shearing of this strand ceased, the extensive porosity in the microshears was gradually filled during several episodes of mineral growth (Figure 1f). The history of this strand would therefore lack the dip in permeability and strength corresponding to gouge formation in Figure 2; instead, the two parameters would change gradually from values characteristic of the first damage zone field to ones representative of the sealed fault.

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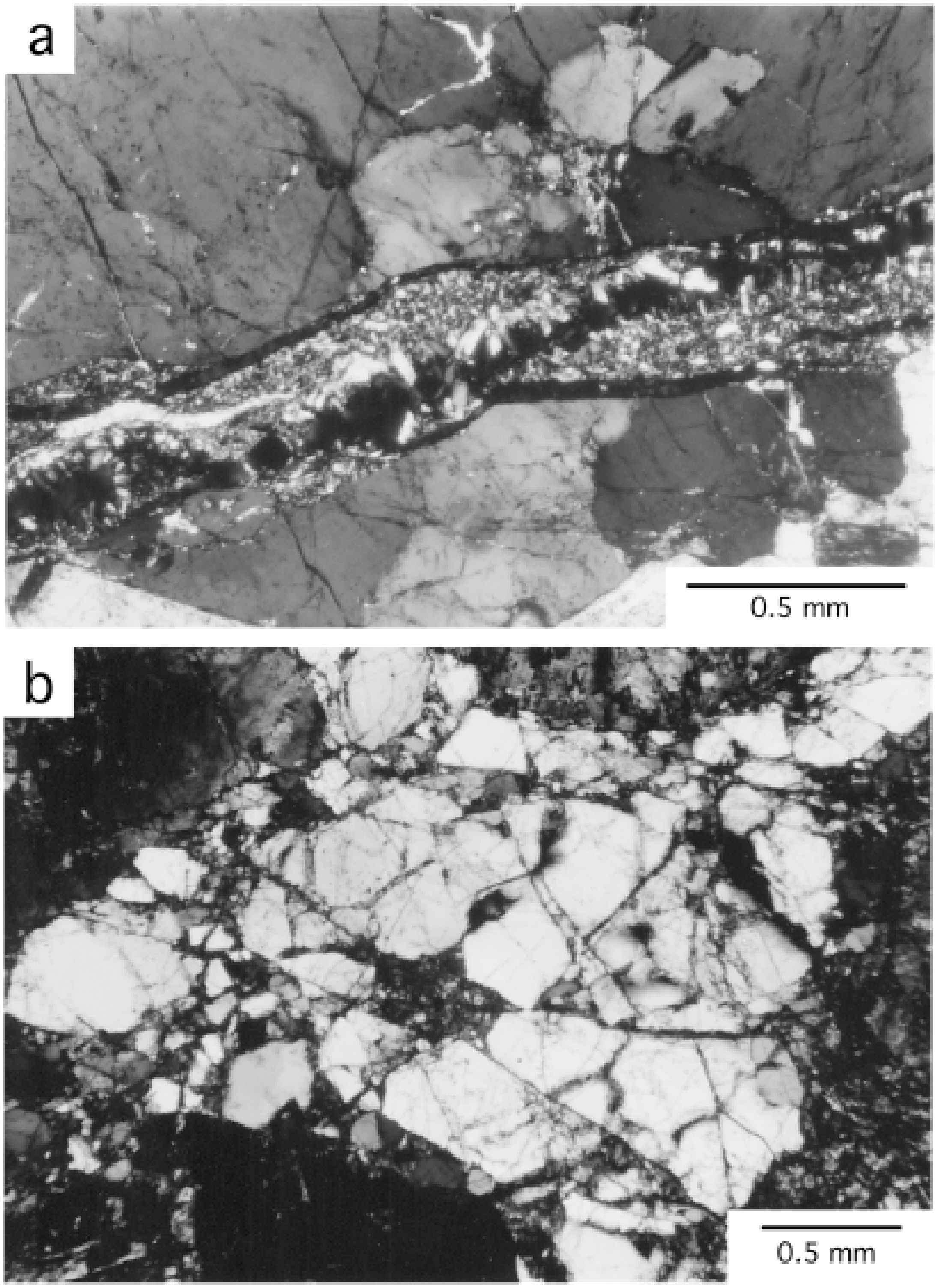

Figure 1. Photomicrographs of deformation and mineralization textures in core samples from the Nojima fault zone. a) The highest permeability measured by Naka et al. (1998) was in this NIED sample, 80-29, which contains a set of elongate dilational cracks that are lined but not filled with laumontite and carbonate minerals (crossed polarizers). b) Heavily fractured quartz in high-permeability NIED sample 43-37-1.

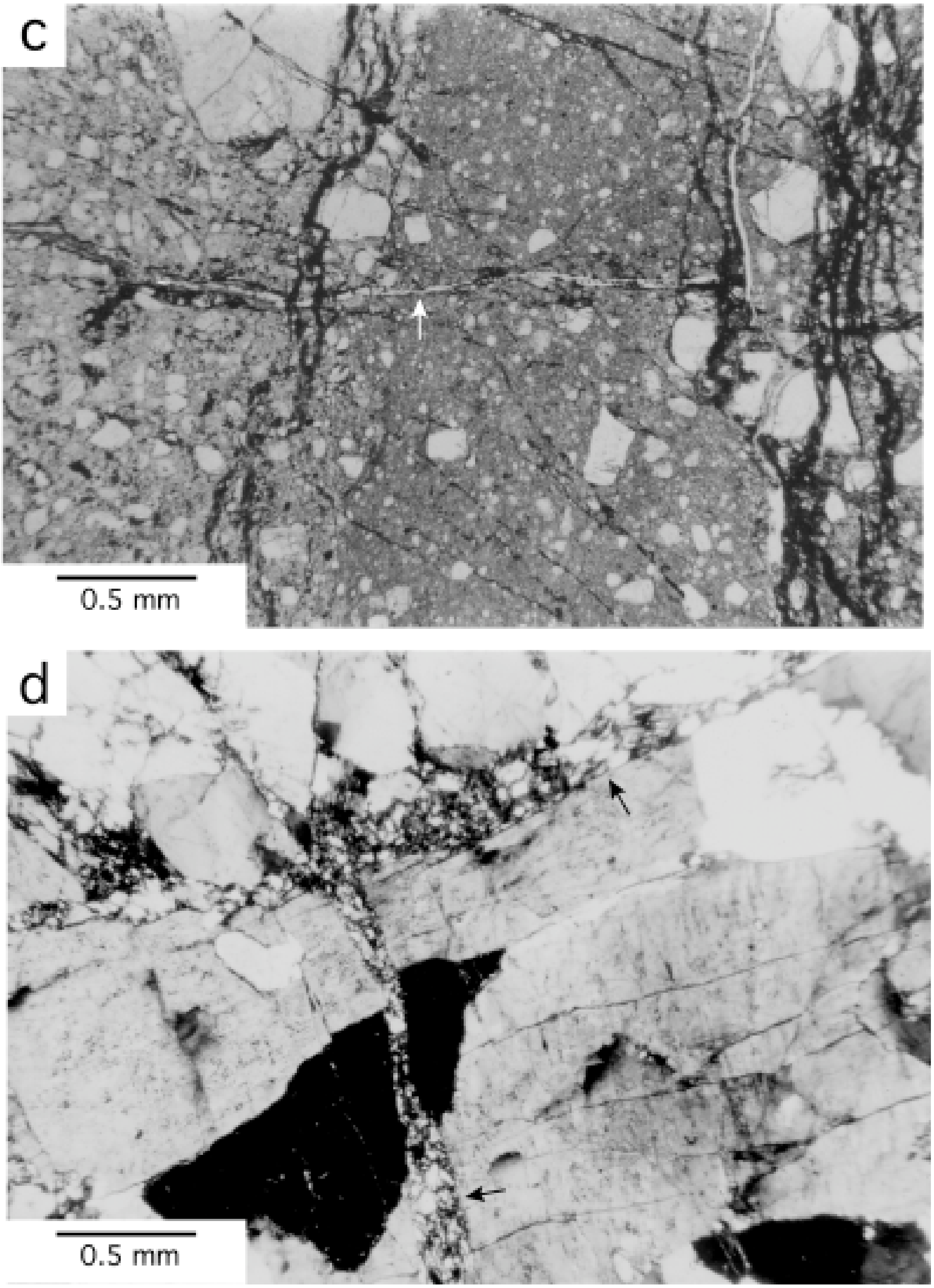

Figure 1, continued. c) Granulation of the igneous minerals leads to formation of fine-grained gouge of low strength and moderately low permeability. This gouge is cut by a dilational crack (indicated by arrows), filled with laumontite. The dark vertical lines contain carbonate minerals (GSJ 98-31, plane polarized light). d) Narrow microshears (indicated by arrows) parallel to the two prominent fracture orientations visible in the K-feldspar crystal at right (NIED 183-14C, crossed polarizers).

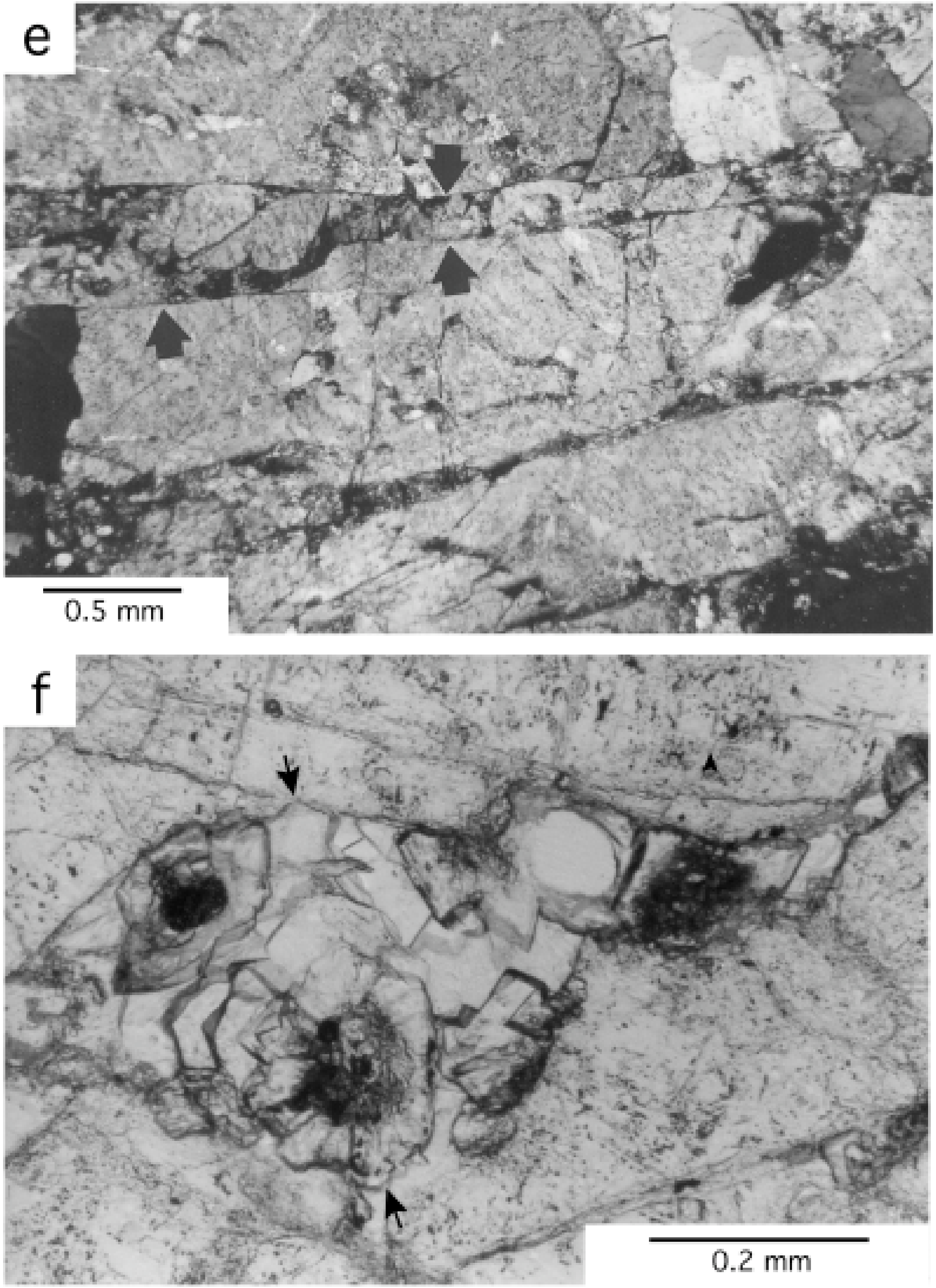

Figure 1, continued. e) Microshear zone (between arrows) whose boundary fractures appear to be pre-existing dilational fractures (NIED 181-34, crossed polarizers). Shear-zone width changes abruptly where the lower boundary steps over from one fracture to another. f) A microshear zone (boundaries indicated by arrows) of the 1800-m NIED fault strand has been sealed by multiple generations of carbonate crystallization. Note the concentric growth patterns of several of the rhombic crystals (NIED 183-14C, plane polarized light).