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Inclined layer-silicate microstructures and their use as a sense-of-slip indicator for brittle fault zones

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Abstract—This Short Note introduces a new microscale sense-of-slip indicator for brittle fault zones. The microstructure is developed within laminated quartz veins and consists of fault-parallel bands of layer-silicate minerals with their long axes and (001) planes consistently inclined in the transport direction. Like other microscale sense-of-slip indicators, this microstructure may prove most useful in situations where mesoscale criteria are either lacking or poorly developed. Because of its intimate association with fault-zone vein material, this microstructure may also help in deciphering the motion history of reactivated faults.

INTRODUCTION

BRITTLE fault systems provide important information on mountain building processes, particularly in areas of recent to active tectonics. They can be used, for example, to determine paleostress histories (Sébrier *et al.* 1988, Angelier *et al.* 1990), finite strain fields (Wojtal 1989, Cashman & Kelsey 1990), or the kinematic development of regional-scale structures (Price 1967). Most analyses of brittle fault populations require an understanding of the sense of slip along a fault in addition to fault and striae orientation. As a result, a number of sense-of-slip indicators have been recognized over the years, such as drag folds, oblique foliations, steps, secondary fracture patterns and gouge trails (see, for example, review in Groshong 1988, pp. 1346–1347).

Despite the abundance of catalogued sense-of-slip criteria, field geologists nevertheless encounter faults with either no or poorly preserved slip-sense features. Especially troublesome are reactivated faults where commonly observed features such as offset bedding and drag folds generally yield ambiguous results. In addition, some sense-of-slip indicators such as steps can be easily misinterpreted without careful examination of their mechanism of formation (Petit 1987).

In this Short Note, I describe a new microscale sense-of-slip indicator for brittle faults. The microstructure consists of fault-parallel bands or lenses of layer-silicate minerals with their long axes and (001) planes inclined in the transport direction. I have observed this microstructure in late-stage brittle faults in the Slate Belt of the Taiwan orogen and have found it to be a highly reliable and easily interpretable sense-of-slip indicator. A similar type of microstructure has been identified independently by Lee (1991) in faulted mafic igneous rocks, suggesting that this sense-of-slip indicator may be present in fault zones cutting a variety of rock types.

GEOLOGY OF THE FAULT ROCKS

Samples of fault rocks in this study are from exposures of the Miocene Lushan Formation along the Central Cross Island Highway in Taiwan, a Pliocene to Quaternary arc–continent collision (Ho 1988). In this part of the orogen, the interbedded slates, siltstones and sandstones of the Lushan Formation underwent prehnite–pumpellyite facies metamorphism based on illite crystallinity values from whole rock (Chen 1981, 1984) and <2 μm fraction (S. J. Tsao personal communication 1991) samples. Results of zircon fission track analyses (Hsieh 1990) support this finding, with the strata yielding partially annealed ages. The faults themselves, however, probably formed after peak metamorphism.

In the field, the faults are marked by <1 cm thick bands of laminated quartz, have well developed striae, and lie both parallel and oblique to bedding. Displacements across the faults are discontinuous in nature and the wall rock is locally fractured and brecciated, giving the faults an overall brittle character at this scale. Displacement magnitudes are difficult to determine because of the limited extent of the exposures and lack of distinctive beds. However, the minimal thickness of the fault-zone vein material and any associated gouge suggests small displacements, possibly of the order of tens of meters or less.

The sense of slip along the faults was determined independently of the inclined layer-silicate microstructures using a variety of traditional meso- and microscale features. Specific criteria included steps, asymmetric and drag folds, oblique foliations, extensional shear bands, secondary fractures, bent grains and fibrous releasing bends. At least one and typically three or four of these sense-of-slip indicators were identified for each fault, resulting in a high degree of confidence in the inferred motion sense.

MICROSTRUCTURES OF THE FAULT ROCKS

The laminated veins along the fault zones are composed of quartz and lesser amounts of opaque material and layer silicates (Fig. 1). These different mineral phases display a variety of microstructural features which generally enhance the overall laminated character of the veins. These features also show that solution mass transfer and recrystallization processes were important in building the microstructural fabric of these mesoscopically brittle faults. The following descriptions of these various microstructural features refer throughout to observations made in thin sections cut normal to the fault zones and parallel to the striae.

Quartz microstructures and crystallographic preferred orientation

Quartz constitutes the bulk of the vein material and typically displays a mosaic texture with the approximately equi-axed grains ranging in size from less than 1 μm (or optically unresolvable) to about 0.5 mm (Fig. 1a). Quartz fibers are only rarely present and these invariably have their long axes subparallel to the fault zone.

Both the mosaic and fibrous quartz grains exhibit strong crystallographic preferred orientations when viewed with a gypsum plate. Within the two-dimensional plane of the thin section, the *c*-axes of the quartz fibers appear aligned parallel to the fiber long axes and a large proportion of the *c*-axes of the mosaic quartz grains also appear aligned parallel to the fault zone. The strong crystallographic preferred orientation of the quartz fibers is likely the product of anisotropic growth kinetics with competitive crystal growth resulting in the occlusion of unfavorably oriented grains (Durney & Ramsay 1973, Cox & Etheridge 1983); in this case, the *c*-axis is the fast growth direction. The crystallographic preferred orientation of the mosaic quartz grains, however, is more puzzling.

I suspect the mosaic quartz grains are recrystallized fibers and the crystallographic preferred orientation largely inherited for two reasons. First, the crystallographic preferred orientation of the fibrous and mosaic quartz is essentially identical. Second, the quartz fibers exhibit a spectrum of microstructures that appear to capture the early stages of the recrystallization process. For example, some fibers display undulatory extinction and incipient subgrain development. Other fibers have undergone more extensive subgrain development and locally contain patches of new recrystallized grains. Rarely, these new grains have a grain-shape preferred orientation that mimics the host fiber. Together, these observations suggest the mosaic quartz grains represent areas where recrystallization was so extensive, it essentially obliterated all morphological evidence for preexisting fibers; only the crystallographic preferred orientation hints at their prior existence.

This interpretation appears to require the operation of dislocation creep, which is a thermally-activated process generally considered to be important in quartz only at temperatures in excess of about 300°C (Tullis 1990). Thermal history studies (Hsieh 1990), however, indicate that the wall rocks did not attain temperatures above the closure temperature of zircon fission tracks or about 200 ± 40°C at geologically reasonable cooling rates (Naeser *et al.* 1989). Perhaps the temperature was locally elevated along the fault zones as a result of frictional heating or circulation of hot fluids from depth. Fault-zone fluids may also have caused hydrolytic weakening and enhanced dislocation creep in the quartz (e.g. Tullis 1990). Alternatively, the recrystallization may have occurred post-faulting during static annealing; this interpretation is supported in part by the equant shape of the quartz grains.

Bands of opaque material

The opaque material is typically concentrated into bands that bound and largely define the individual quartz laminae (Fig. 1a). These bands of opaque material vary from ruler-straight to suture-like in appearance. In the former case, the opaque material probably decorates secondary slip surfaces whereas in the latter, it probably represents sites of quartz removal by solution mass transfer. At their narrowest, these opaque bands form barely recognizable discontinuities marked by strings of isolated inclusions. Thicker bands appear to be composed of several secondary minerals, including iron and calcium carbonates, iron sulphides and layer silicates. Where this secondary mineral development is particularly pronounced, the bands are up to 0.2 mm thick. Although these opaque bands generally run subparallel to the fault zone, they locally form irregular anastomosing networks; fragmented and rotated bands further complicate the fault zone fabric.

Layer-silicate microstructures and their use as a sense-of-slip indicator

Layer silicates within the quartz laminae consist of both chlorite and white mica which are arranged into two distinct types of microstructures. In the first type, the individual layer silicates radiate from a common point to form rosettes or fans. These layer-silicate rosettes and fans are typically organized into irregularly-shaped patches, although they may locally adopt a band-like appearance where they develop off the fault-parallel layers of opaque material. Although common, this layer-silicate microstructure provides no information on the sense of slip.

In the second type of microstructure (Fig. 1b), the layer silicates are arranged into bands that lie subparallel to the fault zones. These bands of layer silicates are

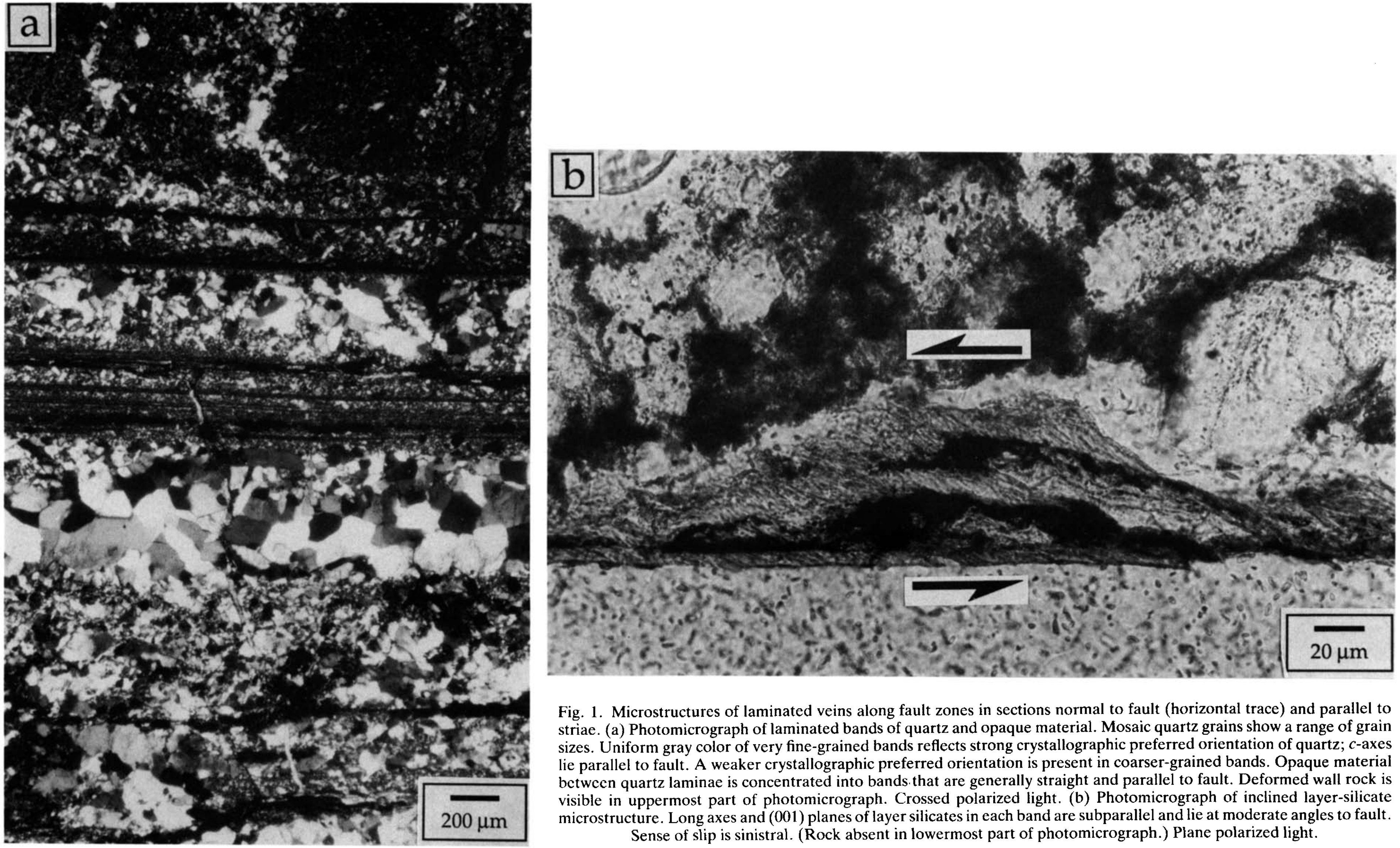

Fig. 1. Microstructures of laminated veins along fault zones in sections normal to fault (horizontal trace) and parallel to striae. (a) Photomicrograph of laminated bands of quartz and opaque material. Mosaic quartz grains show a range of grain sizes. Uniform gray color of very fine-grained bands reflects strong crystallographic preferred orientation of quartz; *c*-axes lie parallel to fault. A weaker crystallographic preferred orientation is present in coarser-grained bands. Opaque material between quartz laminae is concentrated into bands that are generally straight and parallel to fault. Deformed wall rock is visible in uppermost part of photomicrograph. Crossed polarized light. (b) Photomicrograph of inclined layer-silicate microstructure. Long axes and (001) planes of layer silicates in each band are subparallel and lie at moderate angles to fault. Sense of slip is sinistral. (Rock absent in lowermost part of photomicrograph.) Plane polarized light.

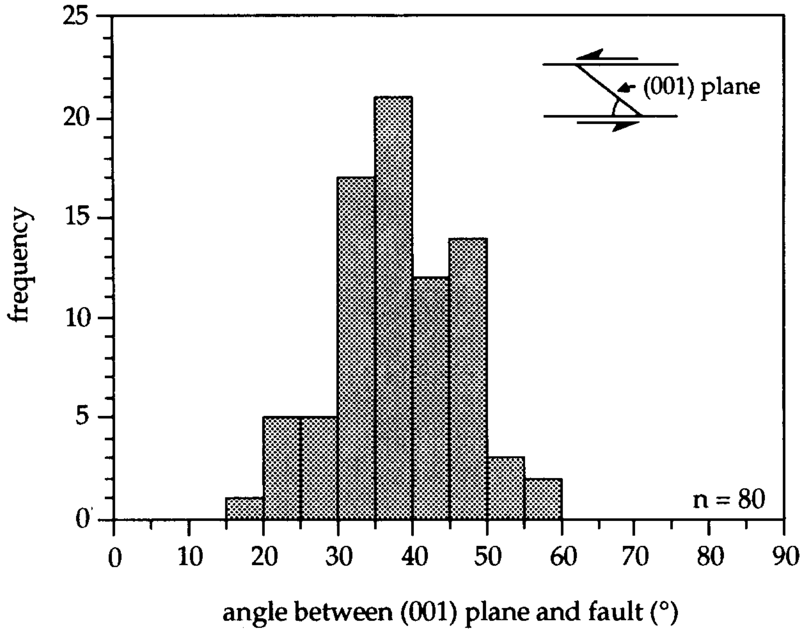

Fig. 2. Frequency histogram of angle between fault and (001) planes of layer silicates forming inclined layer-silicate microstructures. Inset shows angle convention with plane of measurement oriented normal to fault and parallel to striae. Histogram shows measurements for 10 different faults, with three to 13 inclined layer-silicate microstructures measured for each fault. All angles are plotted for sinistral sense of slip.

commonly localized adjacent to the layers of opaque material, and they vary in length from 50 μm to 1 mm and in thickness from 5 to 25 μm. The most striking feature of the bands, however, is the strong crystallographic and grain-shape preferred orientation of the layer silicates. Throughout an individual band, the long axes and (001) planes of the layer silicates are all approximately parallel and inclined to the band at moderate angles. Moreover, the sense of inclination of the layer silicates is the same for all the bands within a particular fault zone.

A comparison of this layer-silicate geometry with the fault-zone sense of slip indicates the (001) planes and long axes of the layer silicates are consistently inclined in the transport direction. The inclination angle of the layer silicates is also fairly restricted. For the various faults, the angle between the layer-silicates and the fault zone ranges only from about 20° to 55° with angles of 30° to 50° being most common (Fig. 2; rare kinked layer silicates were omitted from these measurements). Because these measurements are from a number of inclined layer-silicate microstructures in a variety of fault zones, they likely reflect the orientation of layer silicates that formed at different times along faults that accommodated various amounts of slip. The limited range in orientation of the layer silicates therefore suggests that they suffered little rotation during slip along the faults and probably grew parallel to the incremental extension direction. Finally, in a few bands, the layer silicates are gently curved such that their tips lie at lower angles to the band than their centers; this curvature is generally fairly subtle and best recognized by the sweeping extinction of the bent lattice. It resembles drag and, like the overall geometry of the layer silicates, reliably records the fault-zone sense of slip.

DISCUSSION

Although much remains to be learned about the processes and environmental conditions leading to the formation of inclined layer-silicate microstructures in mineralized fault zones, empirically, they appear to be a reliable sense-of-slip indicator. In the Taiwan fault zones, they are present in laminated quartz veins that experienced both solution mass transfer and extensive recrystallization. Morphologically, the layer silicates are somewhat analogous to slip-parallel quartz and calcite fibers that develop along irregularities in a fault surface (Durney & Ramsay 1973, Elliott 1976, Gamond 1983). However, the layer silicates nucleated and grew at moderate rather than very low angles to the fault zone. The layer silicates also resemble oblique foliations in clay-rich shear zones (Morgenstern & Tchalenko 1967, Platt & Leggett 1986, Chester & Logan 1987, Maltman 1987) in the sense that both are inclined in the transport direction. Unlike oblique foliations, however, the layer silicates are newly formed minerals that appear to fill dilatant microfractures. The inclined layer-silicate microstructures are probably most similar to a type of oblique extension vein described by Cox & Etheridge (1983, 1989) in rocks from the Mount Lyell area of Tasmania. These veins also consist of oriented layer silicates that lie at moderate angles to the vein walls; however, they formed as a result of cleavage- rather than fault-related displacements.

As a sense-of-slip indicator, the inclined layer-silicate microstructures may prove most useful in situations where mesoscale criteria are either lacking or difficult to interpret. They may also help in deciphering the motion history of reactivated faults. For example, field relations may indicate that mineralization occurred during only one episode of motion along a set of reactivated faults or that mineral laminae built up during two or more episodes of motion along a single fault. Because of their intimate association with fault-zone vein material, inclined layer-silicate microstructures are potentially more informative in these cases than sense-of-slip indicators developed within the wall rock. Inclined layer-silicate microstructures may also signal more complex motion histories than previously inferred from field relations. For example, reversals in the sense of inclination of the layer silicates in different mineral laminae strongly suggest multiple episodes of slip. Further work may yield additional insights into the ways in which inclined layer-silicate microstructures can be used to better understand the kinematics of brittle fault zones.

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