Analysis of pinnate joints in the Mount Desert Island granite: Implications for postintrusion kinematics in the coastal volcanic belt, Maine

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ABSTRACT

The Mount Desert Island granite is cut by fractures displaying one of four types of surface morphology: (1) smooth to undulatory; (2) stepped in the form of en echelon cracks; (3) striated with linear fibers; and (4) irregular with cataclastic grains. These surfaces belong to joints, host fractures with pinnate joints, reactivated joints or fractures, and deformation bands (shear fractures), respectively. Pinnate joints, like striations on slickensides, are structures indicative of the orientation of the slip vector and sense of shear on host fractures. Although fractures in the Mount Desert Island granite cluster into two major sets (N20°W and N45°E), host fractures with pinnate joints and shear fractures favor the N45°E orientation. A kinematic analysis of the pinnate joints indicates a predominantly dextral strike-slip sense of movement on northeast-trending fractures. This result agrees with previous work suggesting that a prominent postintrusion tectonic event in southeast Maine consisted of dextral strike-slip motion on northeast-trending faults.

INTRODUCTION

Pinnate joints are a set of en echelon cracks propagating away from mesofaults at small angles (Hancock, 1985; Hancock and Barka, 1987). These en echelon cracks intersect the host fault normal to the slip vector and subtend an acute angle with the host fracture that closes in the direction of displacement of the fault block containing the pinnate joints (Price, 1966; Hancock, 1985). Although Hancock (1985) showed pinnate joints propagating into the extensional side of a locking-point fault, pinnate joints are commonly found on adjacent sides of shear fractures in granite (Fig. 1). When associated with large fracture surfaces in granite, pinnate joints form the treads of a steplike morphology on the fracture surface (Fig. 2). Pinnate joints are mesoscopic analogues of microscopic feather fractures (Friedman and Logan, 1970) and microcracks cutting quartz grains next to cataclastic fault gouge (Engelder, 1974). As is the case for pinnate joints, the slip vector in cataclastic gouge is normal to the intersection of the microcracks and the host fault zone.

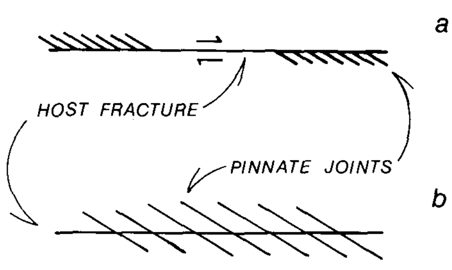

Figure 1. Schematic cross sections through host fracture with pinnate joints. a: Pinnate joints associated with locking-point fault in Cooma complex, Australia. b: Host fracture with pinnate joints in Boulder batholith, Little Cottonwood Canyon, Utah.

Recent literature documents several techniques for determining the tectonic stress tensor from slip along faults (e.g., Angelier, 1979; Etchecopar et al., 1981; Reches, 1987; Hardcastle, 1989). These techniques are based largely on the inversion of fault-lineation data assuming that fault slip occurs in the direction of the resolved shear stress. One purpose of this paper is to point out that a regional compilation of host fractures with pinnate joints may also be used to infer the approximate orientation of paleostress fields.

Fractures in granite and other crystalline rocks rarely display the delicate plumose morphology more commonly seen on the surface of joints in siltstones. Consequently, the literature does not offer many details concerning structures that geologists might encounter on the surfaces of fractures in granite. Another purpose of this paper is to fill a gap in the literature on the surface morphology of fractures in granite.

SURFACE MORPHOLOGY OF FRACTURES IN GRANITE

I attempted to identify some characteristics of the surface morphology on fractures in granite on Mount Desert Island, Maine, by mapping 15 outcrops of granite within an 85 km^2 area in the high peaks of Acadia National Park between Acadia and Champlain Mountains (Fig. 3). This area is underlain by two plutons of petrographically uniform, medium-grained granite that have been dated as early Late Devonian (Chapman, 1968). Each outcrop was documented by describing the surface morphology of the most prominent fractures of each fracture set. By using this technique, four distinct morphologies were identified; then the general attitude of all fracture sets in these outcrops was recorded by measuring the attitude of up to ten members of each set.

The first impression developed on Mount Desert Island was the degree to which some outcrops of granite are shattered; many surfaces indicate slip. This observation supports the notion that some of the fractures that Chapman and Rioux (1958) called joints developed as shear ruptures. Of the four distinct surface morphologies present on fractures in the granite of Mount Desert Island, only one has surface characteristics unique to joints. This morphology, common on Mount Desert Island, is represented by a spectrum of relatively smooth surfaces that vary from planar to slightly undulatory and that have depressions 1–3 mm deep on a wavelength of 10–30 cm. There is neither evidence of the plumose morphology common to siltstones (e.g., Bahat and Engelder, 1984) nor evidence of slip on the planar surfaces or within the undulations.

The other three morphologies reflect an element of shear displacement. First are the striated and lineated surfaces characteristic of joints or faults reactivated in shear. Fiber growth or cataclasis are two of the main processes rendering a slickensided character to these surfaces. Such morphology is indicative of considerable slip along fracture surfaces, which some call mesofaults (e.g., Hancock, 1985). The origin of these fractures is uncertain; they may have propagated either as cracks or as shear ruptures. Second are surfaces covered with cataclastic granite that has been completely comminuted without the development of slickensides. In cross section, this type of fracture resembles braided shear fractures in sandstone (e.g., Engelder, 1974; Aydin and Johnson, 1978). These features, which Aydin and Johnson (1978) called deformation bands, are one of the most likely indicators of initial shear rupture in rock (Engelder, 1982). The third morphology, the focus of this paper, is characterized by a series of congruent steps several millimetres to 2 cm in height and spaced 5–30 cm apart (Fig. 2). In detail, the treads of these steps are indistinguishable from the spectrum of relatively smooth surfaces characteristic of joints. Each step has the same sense and amount of rotation relative to the plane of the host fracture. In a cross section through the host fracture, these steps have the form of en echelon cracks that die out in the matrix of the granite and show no shear offset. In three dimensions, this steplike morphology has the characteristics of a mesofault with pinnate joints as described by Hancock (1985) and Hancock and Barka

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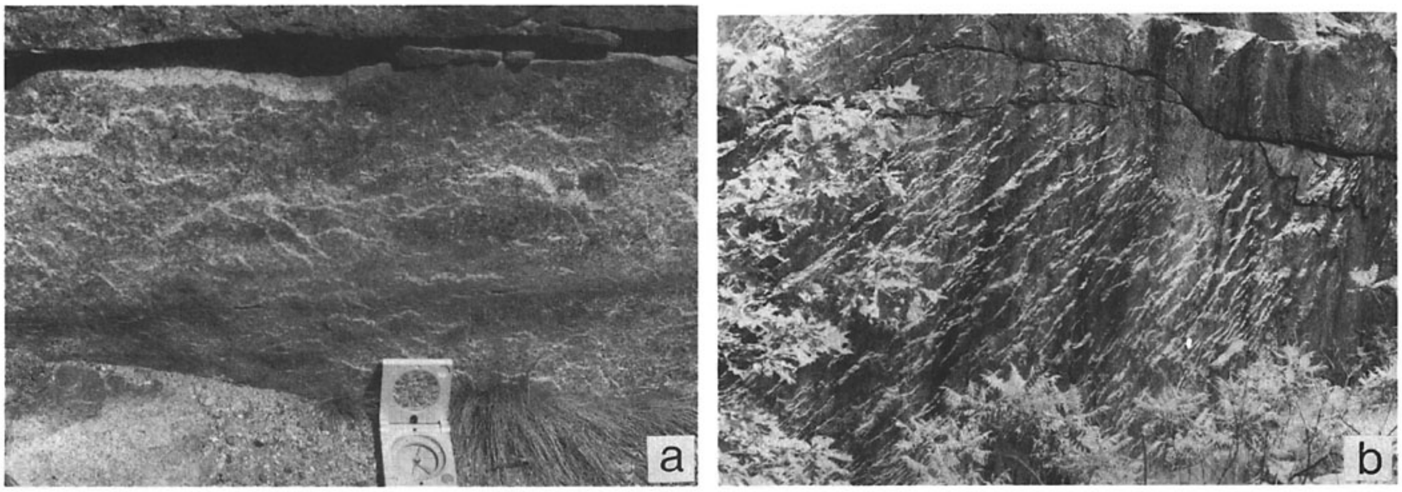

Figure 2. Host fractures with pinnate joints. Pinnate joints form treads of steplike morphology on surface of host fracture. Slip vector is normal to intersection between treads and host fracture. a: Mount Desert Island Granite, Maine, showing strong component of dip slip. Compass for scale. b: Conway Granite, New Hampshire, showing oblique slip with strong left-lateral component. Face 30 m wide by 10 m high. Latter outcrop near Redstone Quarry at Conway, New Hampshire, is one of finest examples of host fracture with pinnate joints in eastern United States.

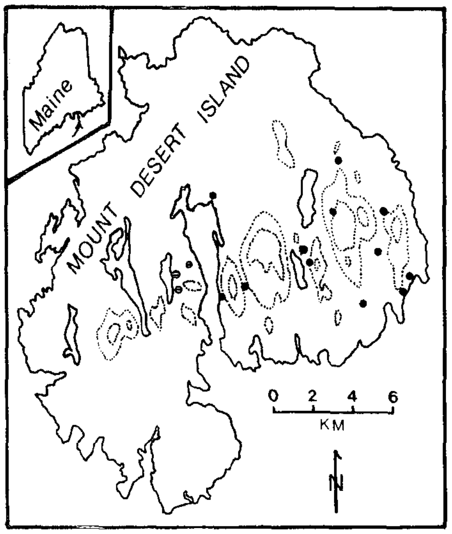

Figure 3. Simplified geologic and relief map of Mount Desert Island, Maine (after Chapman and Rioux, 1958). Dotted topographic contours are 130 and 260 m, respectively. Dots are station locations for this study.

(1987). Because of this resemblance and the lack of shear offset on the steps, the steps in the granite are called pinnate joints. A collection of steps such as seen in Figure 2 constitutes a host fracture. In some instances, the pinnate joints have opened slightly to give a visible shear offset to the host fracture. If the pinnate joints propagated normal to σ_3, then the plane of the host was subjected to a component of shear stress during propagation. For this reason, the host is a fracture having the properties of a shear rupture, even though shear offset is commonly not apparent.

PINNATE JOINTS AS A KINEMATIC TOOL

Pinnate joints were measured in association with 64 host fractures and then used as a kinematic tool to determine the orientation and sense of slip for the host fractures. This use is justified for the following reason: The host fracture is often reactivated in shear as indicated by the development of slickenside striations and fibrous lineations of minerals on steps. These striations and lineations are often within 10° of the slip vector determined by using the normal to the intersection of the pinnate joints and the host fracture. The sense of slip association with fibers and striations is in the same direction as the closure of the acute angle between the pinnate joints and the host fracture.

Field analysis starts by measuring the attitude of the host fracture as roughly defined by steps on the pinnate joints. A board against the steps serves to mark the plane of the host fracture whose orientation may then be measured by compass. Because steps are often spaced less than 20 cm apart, this procedure does not require a very large board. A compass may be used directly against individual pinnate joints to measure their attitude. The plane of the host fracture and the pinnate joints are then plotted in lower hemisphere stereographic projection (Fig. 4a). The orientation of the slip vector is located on a stereonet at 90° from the intersection of the plane of the host fracture and the pinnate joints.

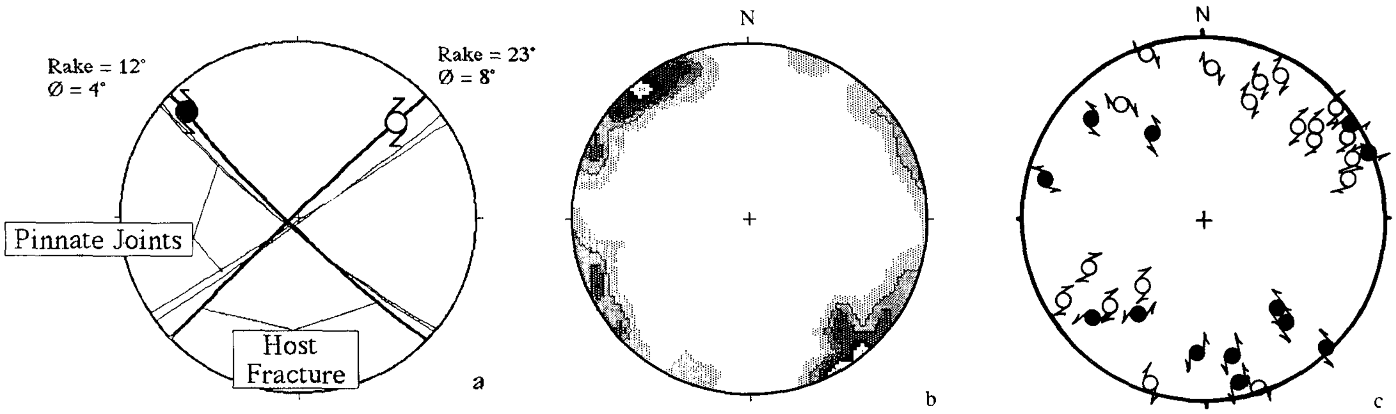

Figure 4. a: Lower hemisphere stereographic projection of planes to two host fractures (heavy lines) and associated pinnate joints. Symbol for left-lateral slip is black. b: Poles to 84 fractures showing some degree of slip. Data include host fractures with pinnate joints, as well as fractures showing striated and fibrous surfaces. Contour intervals are 2%/1% area. c: Orientation of slip lineations with sense of slip inferred from 32 host fractures with associated pinnate joints. Symbol for left-lateral slip is black.

The acute angle between the pinnate joints and the host fracture closes (i.e., points) in the direction of displacement for the block containing the pinnate joints. In most cases, pinnate joints form an angle of less than 8° with the host fracture (Fig. 5a).

Fractures showing slip lineations generally dip more steeply than 45° and most commonly strike northeast-southwest (Fig. 4b). The slip vectors on these fractures show a large component of strike-slip motion, and 64% have rakes of less than 30° (Fig. 5b). A kinematic analysis of Mount Desert Island may be further refined by considering the sense of slip inferred from pinnate joints (Fig. 4c). The number of host fractures trending toward the northeast is larger than in other orientations. Of the host fractures striking between N10°E and N75°E, 79% show a dextral sense of slip. Furthermore, 62% of the host fractures striking between north-south and N80°W show a sinistral sense of slip. These observations may be summarized to say that dextral strike-slip motion on northeast-southwest–trending fractures is most common within the granite of Mount Desert Island.

FRACTURE SYSTEM OF MOUNT DESERT ISLAND

In an early study of Mount Desert Island, Chapman and Rioux (1958) identified a fracture system containing three joint sets that trend east-west, N40°E, and N20°W, respectively. They made no attempt to identify differences between these three fracture sets. Because there is some ambiguity in Chapman and Rioux's (1958) use of the term "joint," I will use the term "fracture" in referring to their work. The term "joint" is restricted to those discontinuities along which there was no visible shear offset during crack propagation. A joint, of course, can be reactivated to slip, as is indicated by slip lineations on many pinnate joints. On the basis of the correlation between a strong topographic grain striking N15°W and a well-developed fracture set of about the same orientation, Chapman and Rioux (1958) concluded that the glacially derived topography of Mount Desert Island was to some extent controlled by vertical fractures (Fig. 3). Other examples of the correlation between well-developed fracture or joint sets and glacially carved topography are recorded in the Adirondack Mountains of New York (Chadwick, 1939; Plumb et al., 1984) and the Finger Lakes of central New York (Engelder and Geiser, 1980).

Although all three of Chapman and Rioux's (1958) fracture sets appear in some outcrops, a rose diagram of the strike of all fractures measured during my study shows just two major sets (Fig. 6a). Fractures showing dextral slip prefer the N45°E direction, whereas fractures showing no indication of slip or shear (i.e., joints) are associated with each of the major sets (Fig. 6b). Fractures of the N20°W set are most likely to have smooth surfaces indicative of jointing. These joints, which form with a regular spacing, are roughly parallel. The two major fracture sets differ in their dip and tendency to cluster near one orientation. The N20°W joint set has a larger concentration (8.8%/1% area vs. 5.8%/1% area) and clusters closer to vertical. This set correlates with the glacially derived topographic trends of the high-peaks area. The major fracture sets defined by strike alone are actually composed of a vertical subset, as well as subsets that dip in opposite directions. In individual outcrops, subsets may intersect at an angle of more than 30°.

Basalt dikes cut the Mount Desert Island granite with a consistent orientation of about N20°W and are parallel to the N20°W fracture set. A plagioclase phenocryst separation from a basalt dike at Hall Quarry gives a plateau age of 350 Ma (Dan Lux, 1988, personal commun.). The propagation direction of both dikes and the N20°W joint set correlate with a residual stress as indicated by (1) rare dikes showing a curved growth leading to propagation parallel to the N20°W direction and (2) curved crack propagation toward N20°W from drill holes in granite quarries at Hall Quarry. In several places, dikes are cut by northeast-trending pinnate joints, and the associated host fractures offset the dikes from a few millimetres to several tens of centimetres. This is the strongest evidence that N20°W joints and dikes propagated before rupture along N45°E fractures.

DISCUSSION

On the basis of surface morphology, the Mount Desert Island granite has three distinct fractures that span the spectrum from joints to faults. The smooth to mildly undulatory surfaces are indicative of joints (mode I cracks) that propagated under effective tensile stresses. Crosscutting relations suggest that some of these joints and associated dikes propagated early. Cataclastic surfaces that appear as deformation bands in cross section are indicative of classic shear fractures formed under large differential stresses. Between these two in a spectrum of fractures are host fractures linking pinnate joints. Although each pinnate joint is a crack without shear offset, a minor amount of shear offset on host fractures (<1 cm) suggests that the host propagated in a plane subject to shear stress. Because any one of these three types of fractures can display striations and linear fibers indicative of slip, a fibrous or slickensided surface is not a separate class of fracture. Although all four morphologies occasionally occur on a single outcrop, most outcrops are dominated by one of the morphologies.

A shear fracture starts with the propagation of small flaws in the direction of σ_1 (Scholz, 1968). Final failure accompanies the linking of these small flaws along a shear plane, which in the laboratory is commonly 25°–30° to σ_1. The host fractures of the Mount Desert Island granite pre-

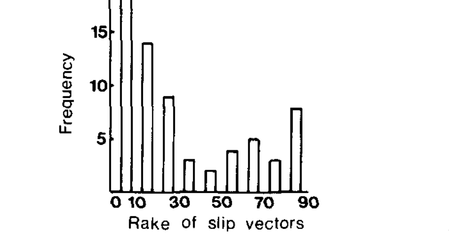

Figure 5. Frequency diagrams. a: Angle between 53 host fractures and associated pinnate joints. b: Rake of slip vector for lineations on 69 fractures.

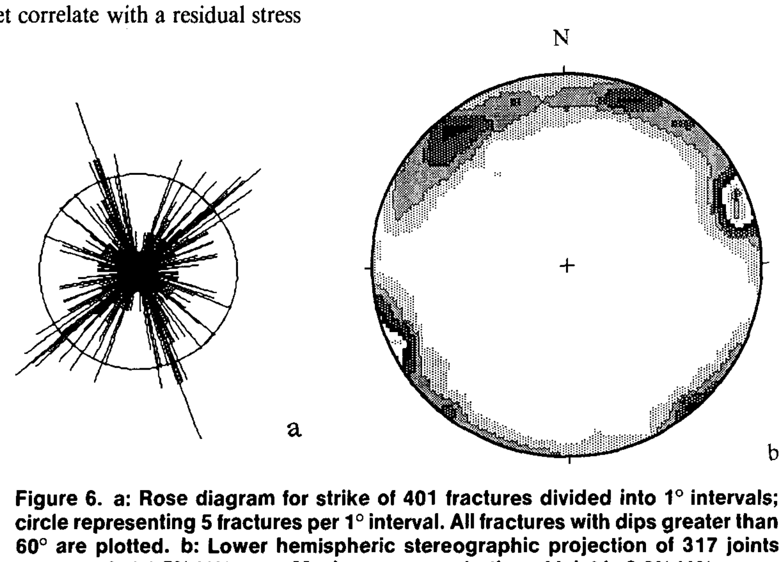

Figure 6. a: Rose diagram for strike of 401 fractures divided into 1° intervals; circle representing 5 fractures per 1° interval. All fractures with dips greater than 60° are plotted. b: Lower hemispheric stereographic projection of 317 joints contoured at 1.5%/1% area. Maximum concentration of joint is 8.8%/1% area.

sumably form by the linking of pinnate joints in the same manner as observed for shear rupture of laboratory specimens. However, the small angle (<8°) between the pinnate joint and the host fracture and the marked absence of cataclastic material indicate that the host is not like a classic "laboratory" shear fracture that forms at an angle of greater than 25° to σ_1. At low confining pressures, laboratory specimens have a tendency to fail along fracture planes at a smaller angle to σ_1 and by axial splitting where extension fractures form in the absence of macroscopic tensile stress (Wawersik and Brace, 1971). Given the small angle between the host fracture and pinnate joints, it is possible that these features are low-confining-pressure phenomena that fill the spectrum of brittle behavior between crack propagation and shear rupture at 25°–30° to σ_1.

In a qualitative analysis of Figure 4c, the orientation of a paleo σ_1 might be found by bisecting the two clusters (i.e., dextral and sinistral) of slip lineation data. This analysis, which treats the fractures with pinnate joints as conjugate shear fractures, suggests that σ_1 was oriented about east-west during the rupture of the Mount Desert Island granite. However, the clusters are not conjugate in the strict sense because both sets do not appear in the same outcrop. Likewise, the acute angle between the clusters is too large for fractures with pinnate joints at an average of 8° from the host. Slip lineation techniques for determination of paleostress–stress tensor orientation from a given fault population might be applied to a regional analysis of pinnate joints as long as it is understood that orientation of fractures with pinnate joints reflects the kinematics of initial rupture rather than slip reactivation in the direction of the resolved shear stress.

Pinnate joints are similar to features that other authors have called riedel shears (e.g., Angelier et al., 1985). The classic notion is that riedel shears form at a small angle (~20°) to the shear plane, whereas tension fractures form at about 45° to the shear plane (e.g., Blès and Feuga, 1986). The riedel shear model does not account for the situation where the shear fracture develops within a few degrees of σ_1. If they are unrelated to Hertzian fracturing during wear-groove development (e.g., Engelder, 1976), I would surmise that many steplike features on fracture surfaces are the manifestation of pinnate joints and not riedel shears.

The analysis of fractures with pinnate joints on Mount Desert Island suggests the development of a northeast-striking fabric reflecting a component of dextral shear. This sense of shear on faults is prominent throughout southeastern Maine in geologic features including the Lucerne pluton (Wones, 1978) and Norumbega fault zone (e.g., Ludman, 1986). Starting in late-Middle Devonian or Late Devonian time, a series of anastomosing dextral strike-slip faults developed in eastern New England, Maritime Canada, and Newfoundland (Webb, 1969). Wrench fault basins continued to fill into Pennsylvanian time (Bradley, 1982). Although they show negligible displacement, the host fractures with pinnate joints of Mount Desert Island may reflect the sense of dextral shear that affected all of the east coast of North America during the late Paleozoic (Ferrill and Thomas, 1988).

CONCLUSIONS

Granites of Mount Desert Island, Maine, are cut by fractures displaying one of four types of surface morphology. Two major fracture sets trending N20°W and N45°E cut the granite. This paper documents the use of pinnate joints in association with host fractures as a kinematic indicator of orientation and sense of slip on fractures throughout a region. On the basis of the analysis of pinnate joints, I conclude that a northeast-trending fracture set is dominated by strike-slip motion showing dextral slip. The north-northwest fracture set is more likely to be an early joint set formed before or in association with the intrusion of mafic dikes.

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