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REPLY

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During mapping of fractures on the Appalachian Plateau, I found convincing evidence that most of them propagated in the principal stress plane as mode I cracks (joints). The following seven observations are sufficient to infer that shear fracturing was not common during the development of regional sets of vertical joints on the Appalachian Plateau. Regional sets are those that persist from outcrop to outcrop over a broad region. Rocks of the Appalachian Plateau contain examples of shear fractures that have shallow dips, but both Scheidegger [1978] and Engelder [1982] restrict their attention to vertical joints.

Scheidegger's comment [this issue] and Scheidegger [1978] imply that regional sets of fractures develop with trends compatible with strike-slip faulting and hence requires that the intermediate principal stress of the contemporary stress field is vertical. Such a stress configuration is reported for only 28 of 88 deep (>100 m) stress measurements in North America and elsewhere [McGarr, 1980]. Although a stress state compatible with strike-slip faulting appears to occur in less than 50% of the upper crust, to test Scheidegger's notion [this issue] I shall assume that the intermediate principal stress is vertical on the Appalachian Plateau, and I shall focus attention on those regional fractures that exist in planes of high shear stress relative to a maximum horizontal stress striking ENE. In the vicinity of Syracuse and Binghamton, New York, fractures oriented in planes of high shear stress are labeled sets I and II by Parker [1942] and Engelder [1982].

A complex tectonic history is apparent from strain markers and vertical joints found within rocks of the Appalachian Plateau [Engelder and Geiser, 1980; Engelder, 1982]. In brief, cross-fold (set I) joints and strike (set II) joints are geometrically related to folds and associated with strain developed during the Alleghanian Orogeny. Calcite-filled set I joints propagated synchronously with the development of Alleghanian cleavage and hence predate the contemporary stress field by as much as 220 Ma. Other set I joints and set II joints postdate the calcite-filled set I joints but may predate set III joints, which propagated in the plane of zero shear stress relative to the contemporary stress field [Engelder, 1982]. Additional minor joint sets are local, and do not correlate from outcrop to outcrop.

From the following seven observations I infer that shear fractures are not common among vertical joints of the Appalachian Plateau:

1. Calcite-filled joints show no shear offset. Figure 1 shows a set Ia joint striking 010° in the Tully Limestone north of Ithaca, New York. The calcite-filled joint cuts a fossil whose separated halves show no significant shear offset in the plane of the joint. Despite being in a plane of high shear stress relative to the contemporary stress field, the joint formed as a mode I crack during the Alleghanian orogeny [Engelder and Geiser, 1980] and has not been reactivated in shear motion. This joint is typical of set Ia joints in this area.

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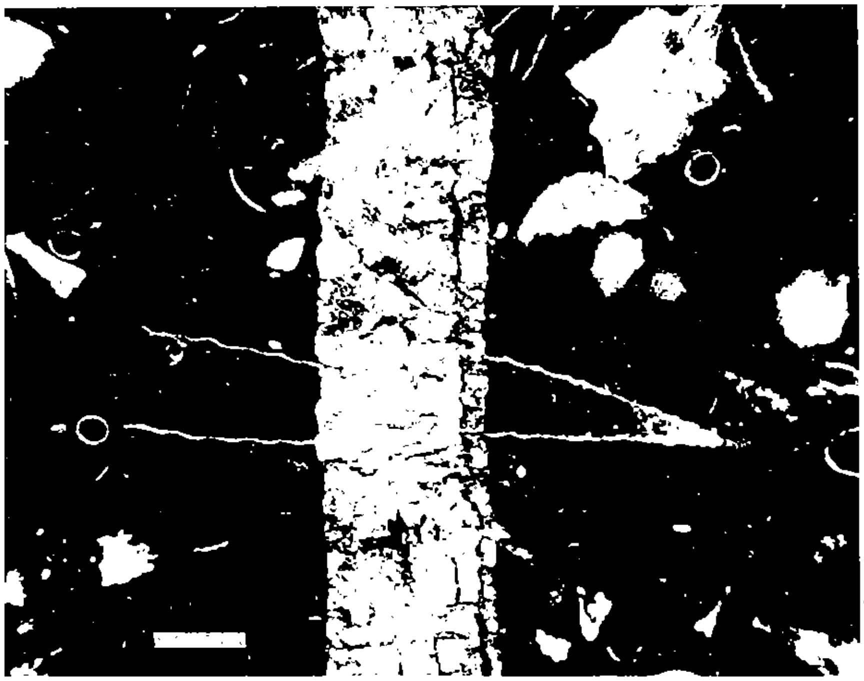

Fig. 1. Set Ia joint with calcite-filling cutting fossil. Sample was taken from the Tully Limestones north of Ithaca, New York. The thin section was cut parallel to bedding. Scale bar 1 mm.

2. Compression directions indicated by strain markers are parallel to the calcite-filled joints. The fact that set Ia joints propagated during the Alleghanian Orogeny (Late Paleozoic) is demonstrated by the crosscutting relationships between calcite-filled joints and the solution cleavage (Figure 2). The orthogonal relation of solution surfaces and calcite-filled joints in principal stress planes is compatible with the mechanical model for the crack-anticrack pair [Fletcher and Pollard, 1981]. The correlation of the normal to the solution cleavage and the plane of the calcite-filled joint suggests strongly that the joint propagated in a plane of zero shear stress as a mode I crack.

3) Plumose surface morphology is preserved on joint faces. The plumose morphology on set Ia and Ib joints indicates that they opened by propagating in two directions to give the joints a bilateral symmetry (Figure 3). This surface morphology contrasts sharply with slickensided surfaces indicative of shear offset, which is always unidirectional. The presence and preservation of plumose patterns indicates that the set Ia and Ib joints formed with the dominant motion normal to the joint face.

4) Nonparallel joints are not contemporaneous, whereas conjugate shear fractures must be contemporaneous by definition. For a given state of stress only one plane is perpendicular to the least compressive stress, whereas two planes may satisfy a shear fracture criterion. Thus nonparallel joints should not be contemporaneous if they are mode I cracks. On the Appalachian Plateau the relative age of set I and II joints is not the same throughout the stratigraphic section of Upper Devonian rocks (Figure 4). Using the criterion that younger joints abut older joints, the relative age of joint sets may be inferred. In the deeper and more eastern portion of the New York Plateau, the cross-fold joints (both sets Ia and Ib) propagate prior to the strike joints (set II). Above the West Falls Group the opposite sequence of development is

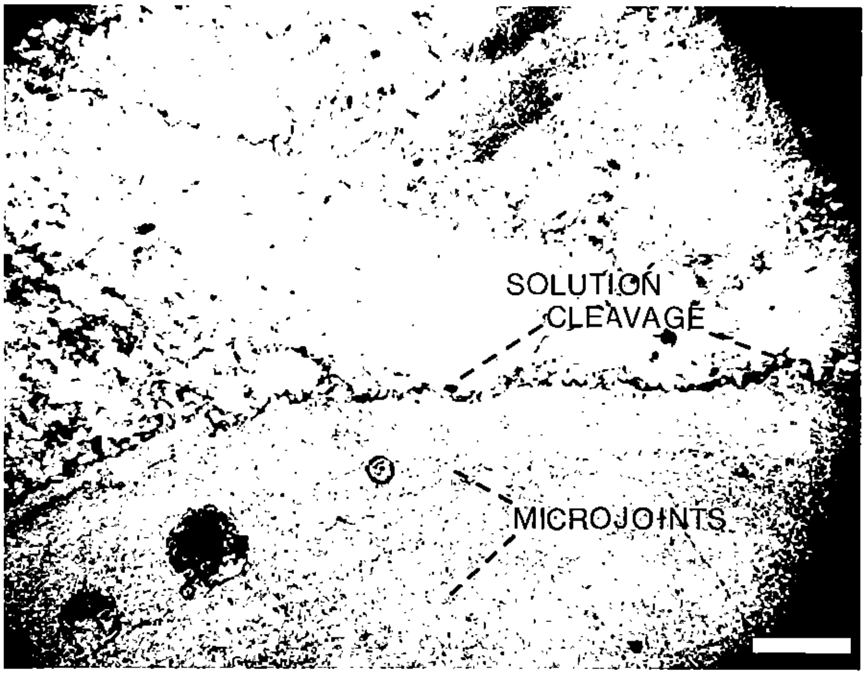

Fig. 2. Solution cleavage crosscutting calcite-filled microjoints in the West Falls Group. Sample was taken 2 km west of Smithboro, New York. The thin section was cut parallel to bedding. Scale bar 1 mm.

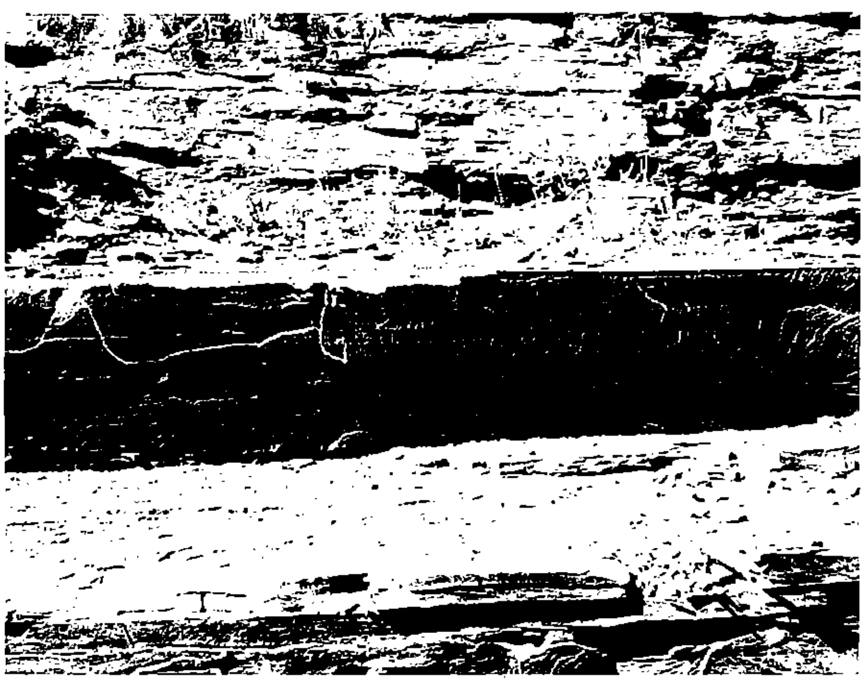

Fig. 3. A plumose pattern on a set Ib joint showing bilateral propagation. This outcrop in the Sonyea Group is on Route 414 1 km southwest of Watkins Glen, New York. Thickness of bed is 44 cm.

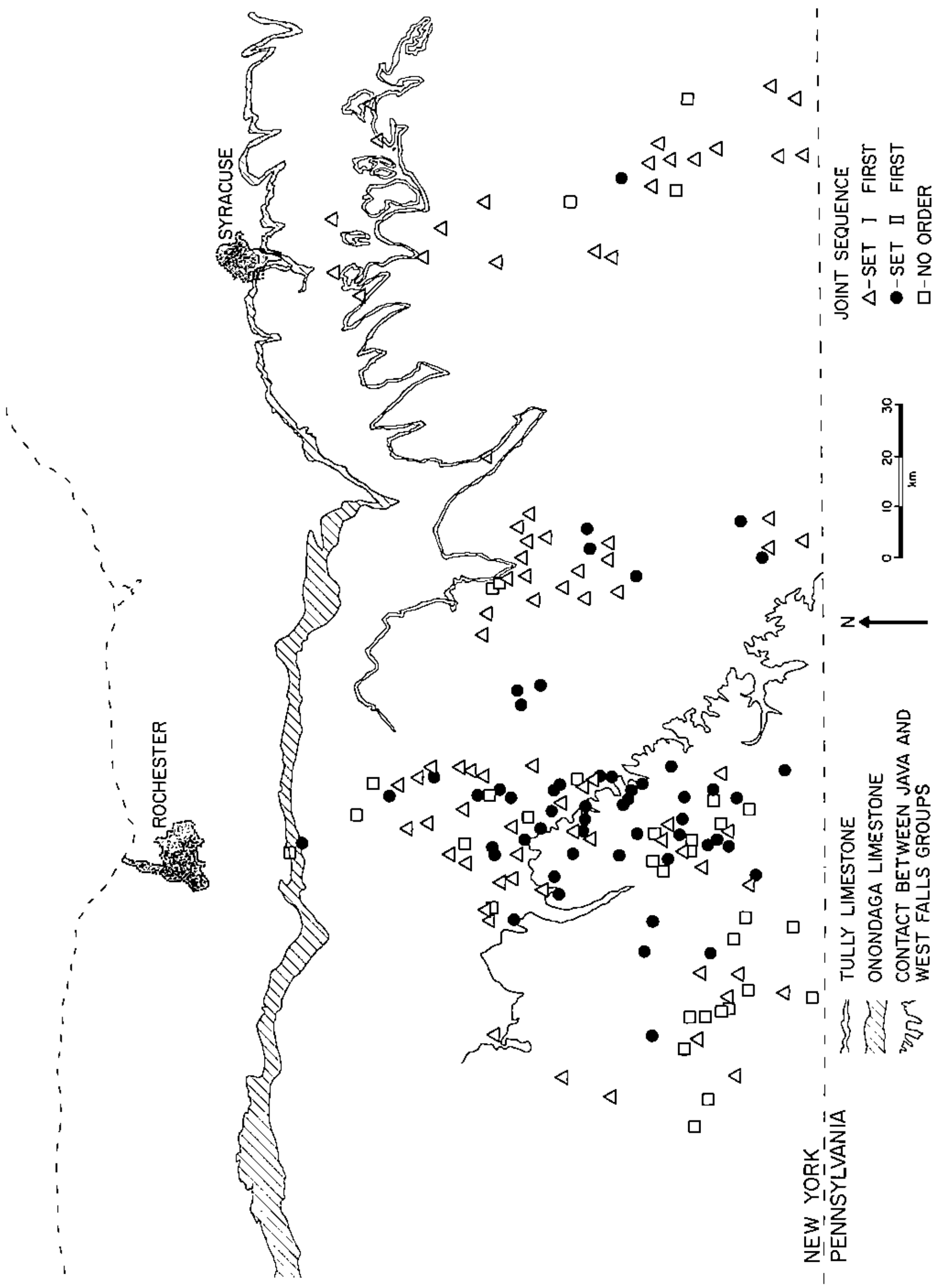

Fig. 4. A map of western New York showing the butting relationship between set I and set II joints.

Fig. 5. The mud-crack geometry in the Canadaway Group. This outcrop is in the bed of the Genesee River 200 m. north of the Route 19 Bridge at Belmont, New York. Width across the bottom of the photo is 2 m.

more common (set II before set Ib). This supports Engelder and Geiser's [1980] hypothetical sequence for the development of joints during and after the Alleghanian Orogeny. Joints deeper in the Upper Devonian section formed contemporaneously with the Alleghanian Orogeny, whereas those in the upper portion of the Devonian section formed later during relaxation accompanying erosion. Recent work by Bahat and Engelder [1982] suggests that the set Ib joints can be divided into two distinct sets. Thus set Ib joints above the West Falls do not belong to the same joint set as those Ib joints in the Syracuse to Binghamton area.

5) Magnitude of stress difference in the upper crust is too small. Compilations of data from hydraulic fracture stress measurements show that within the upper 2 km the differential stress rarely exceeds the frictional strength of rock [Brace and Kohlstedt, 1980]. Laboratory fracture experiments indicate that in order for shear fracturing to be common in the upper crust, the differential stress has to be double the values measured in the northeastern United States. This suggests that shear fracturing may be restricted to extreme tectonic environments such as fault zones and high-amplitude folds and, therefore, could not be responsible for regional joints in weakly deformed rock.

6) Some beds have vertical joints with a mud-crack pattern in plan view. A mud-crack pattern of vertical joints is further evidence that some beds of the Appalachian Plateau were not subject to a differential stress high enough to cause shear fracturing (Figure 5). The mud-crack pattern suggests that horizontal stresses in some beds were nearly equal in all directions and that the effective stress was low enough to cause cracking in the absence of a well-defined horizontal stress field.

7) Set III parallel the contemporary stress field. A genetic relationship between set III joints and the contemporary stress is inferred from the fact that the joints and the plane of the least principal stress are coaxial. Because set III joints propagated in a plane of zero shear stress relative to the contemporary stress field, I suggest that they are mode I cracks, not shear fractures.

In my field experience it is far more difficult to prove that a fracture formed by shear rupture. The feature that I call a breaded shear fracture [Engelder, 1974, Figure 6] may be one of the most likely indicators of shear rupture. Another indicator would be the presence of microscopic feather fractures within the host rock [Friedman and Logan, 1970]. These features are not common on the Appalachian Plateau.

Scheidegger's comment [this issue] lists three examples of evidence for the origin of fractures in shear, yet not one is definitive. Pebbles are cut and strata of various ages and facies are transected only demonstrate shear motion, but the motion could have occurred after formation of the fracture as a mode I crack. Because such cracks are weak surfaces, later shear motion is a reasonable event to consider. Conjugate joint sets are a possible consequence of two separate extension events at different orientations.

Both Scheidegger [1978] and Engelder [1982] suggest that there is a genetic relationship between selected regional joints and the contemporary stress field within the lithosphere of Eastern North America and that from this relationship the orientation of a regional stress field may be predicted. The difference is that Scheidegger fails to predict the ENE maximum horizontal stress found between Illinois and New York [Scheidegger, 1978, Figures 3 and 4].

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