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Horizontal slip along Alleghanian joints of the Appalachian plateau: evidence showing that mild penetrative strain does little to change the pristine appearance of early joints

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Abstract

Some Alleghanian joints in black shales of the Geneseo and Middlesex Formations of the Catskill Delta complex, Finger Lakes district, New York, slipped horizontally up to 8 cm. Horizontal slip is measured by the offset of ENE-striking joints. Alleghanian joints striking 330–350° display a right-lateral slip with an average value of 1.9 cm, while joints striking 004–010° slip in the left-lateral sense with an average value of 1.3 cm. The maximum horizontal stress (S_H) driving this slip falls between 350° and 004°, the orientation of local Alleghanian layer-parallel shortening as indicated by both disjunctive and pencil cleavage. By commonality of orientation, we infer that slip on Alleghanian joints is driven contemporaneously with layer-parallel shortening. If so, the offset ENE-striking joints predate the Alleghanian stress field. These observations mean that both pre-Alleghanian and early Alleghanian joints persist through a period of penetrative strain.

Keywords: stress; slip; joints; Alleghanian; Appalachian plateau

1. Introduction

Multiple cross-fold joint sets in the Devonian Catskill delta complex of the Appalachian plateau reflect a change in horizontal stress orientation during a progressive Alleghanian deformation (Engelder and Geiser, 1980). From the Finger Lakes district of the New York plateau south to the Anthracite district of the Pennsylvania valley and ridge, observations indicate that the regional change in horizontal stress orientation was clockwise during the Alleghanian Orogeny (i.e., Nickelsen, 1979; Geiser and Engelder, 1983; Gray and Mitra, 1993; Younes and Engelder, 1999). One consequence of this clockwise progression is that early-formed Alleghanian joints are subjected to a right-lateral shear traction that would invariably develop on change in stress orientation. In the anthracite district there is abundant evidence for right lateral shear in the form of lineated slip surfaces (Gray and Mitra, 1993). However, horizontal slip on early Alleghanian joints in the Finger Lakes district of the plateau is so rare that it went undetected until recently.

Previous evidence for such a shear traction on early joints of the Appalachian plateau comes from fringe cracks that develop when early parent joints are subjected to a later bedding-parallel shear couple (Younes and Engelder, 1999). Despite this evidence, no measurable slip was detected along any parent joints hosting either twist hackles or kinks for two reasons. First, identifying bedding-parallel slip on

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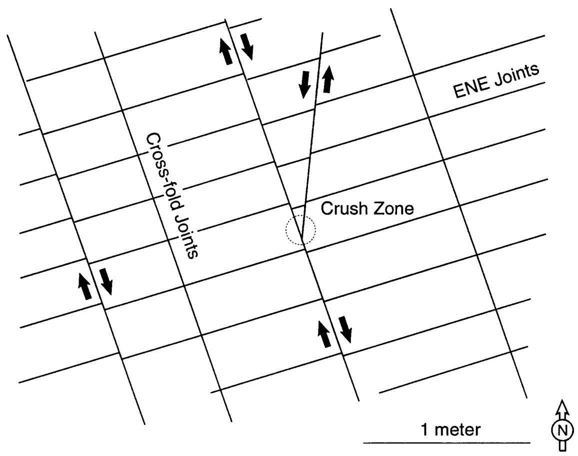


Fig. 1. Schematic map view of the arrangement of two sets of cross-fold joints relative to the ENE joints at Squaw Point on the west wide of Seneca Lake. With few exceptions in the Finger Lakes district of New York, joints striking west of north show right-lateral slip whereas joints striking east of north show left-lateral slip.

vertical joints is difficult in homogeneous rock without markers. Small amounts of slip ($\approx$1 cm) can go undetected. Second, a small shear traction might not drive slip much beyond its elastic limit. One analysis suggests that parent cracks in shale of the plateau were subject to a shear stress of $<$1 MPa (Younes and Engelder, 1999). However, during work by Younes and Engelder (1999), we discovered that some cross-fold joints display a small amount of layer-parallel slip (i.e., a few millimeters to several centimeters) as indicated by the offset of joints from a systematic ENE set that cross-cut the Alleghanian joints (Fig. 1). The purpose of this paper is to document slip on early-formed cross-fold joints of the Appalachian plateau. We then address the broad question of whether early-formed joints survive as unfilled cracks through a later episode of penetrative strain affecting the host rock. The persistence of an ENE joint set through a later period of penetrative strain has important implications for Devonian tectonics on Appalachian plateau.

2. The ENE joint set

ENE joints are best developed in the black shales of the Geneseo and Middlesex Formations in the Finger Lakes district, New York (i.e., Sheldon, 1912; Parker, 1942; Loewy, 1995). Although Sheldon (1912) referred to these joints as 'strike' joints, they are relatively uniform in orientation over a region in excess of 2500 km^2 and not consistently aligned with local fold axes of the plateau and, therefore, identified as joint set III by Parker (1942). Furthermore, the ENE joints are not late stage release joints as is the case for the strike joints of set II (i.e., Parker, 1942; Engelder and Geiser, 1980; Engelder, 1985). Devonian black shales also contain well-developed cross-fold joint sets (i.e., dip joints of Sheldon, 1912; set I joints of Parker, 1942) that are generally more widely spaced than the ENE joints (Hagin, 1997).

In general the cross-fold and ENE joint sets are mutually cross-cutting. The lack of a clear abutting relationship leads to great difficulty in the interpretation of timing of propagation of the ENE set relative to the cross-fold, a puzzle for 20 years (i.e., Engelder and Geiser, 1980). Over this period, we were distracted by the notion that an unfilled joint set subparallel to the plane of flattening would somehow be obliterated by the mechanisms of penetrative strain during the Alleghanian Orogeny. So, we thought that the ENE joint set was post-Alleghanian. This notion was reinforced by the observation that the ENE joint set is parallel to S_H of the contemporary tectonic stress field in North America, suggesting a neotectonic origin (i.e., Engelder, 1982; Hancock and Engelder, 1989). Gross and Engelder (1991) and Engelder and Gross (1993) refined the criteria for identifying neotectonic joints in the Devonian section of New York and concluded that the ENE joints in the black shale of the Genesee Group did not fit these criteria. Throughout this early work, the mutual cross-cutting of Alleghanian joints still left the possibility that the ENE set pre-dated cross-fold joints and other Alleghanian structures. With this paper, we reevaluate the timing of the propagation of the ENE joint set by testing the hypothesis that the driving mechanism for slip on cross-fold joints of the Finger Lakes district dates from Alleghanian orogeny.

3. Field observations

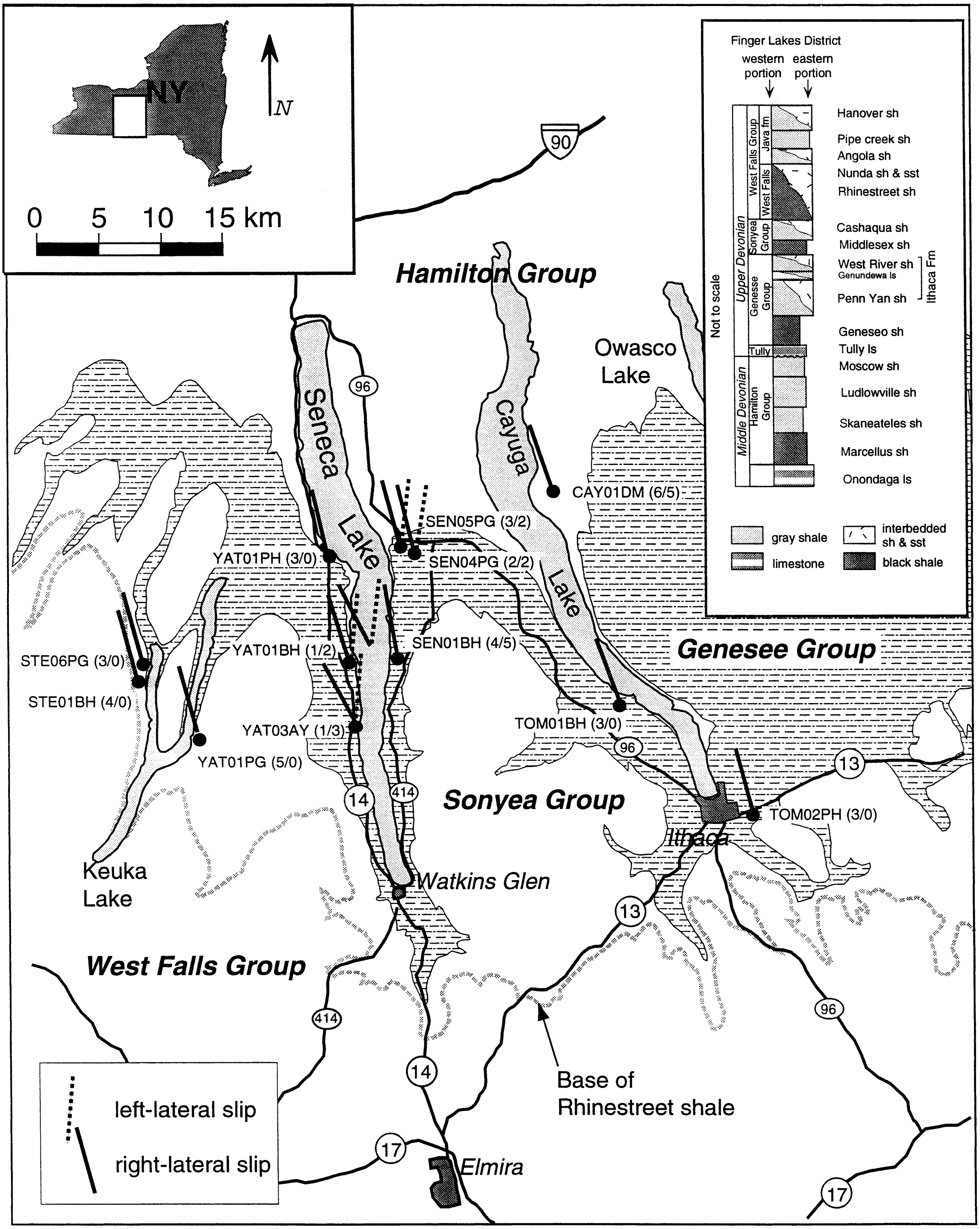
We conducted a systematic search throughout black shales of the Finger Lakes district for joints showing evidence of slip. One striking characteristic of the slip surfaces is the lack of any evidence for either frictional wear or fibrous mineral growth. A second striking characteristic is that the ENE set never slips to offset cross-fold joints. Slip is indicated exclusively by the offset of ENE joints. To see this offset, high quality pavement surfaces are required and we know of about two dozen such outcrop pavements throughout the Finger Lakes district (Loewy, 1995; Hagin, 1997). Of these high quality pavement outcrops, 12 contain cross-fold joints that have slipped to offset the ENE joint set (Fig. 2). Eight outcrops are located in the Geneseo Formation, a black shale which crops out just above the base of the Genesee Group, and three outcrops are located in the Middlesex Formation, black shale which crops out just above the top of the Genesee Group. The twelfth outcrop is located in the Moscow Formation, a gray shale near the top of the Hamilton Group.

Upon discovering a cross-fold joint with slip, we measured its orientation and that of the offset ENE joints. Then we measured the offset on each ENE joint with a vernier caliper and noted its sense of slip along a scanline parallel to the cross-fold joint (Fig. 3). Even on the best pavement surfaces we were rarely able to trace a cross-fold joint for more than 5 m. Although we were never able to trace a slipped joint to its tip, we have the sense that slip behaves in one of two ways. First, the joint may behave like an isolated fault with maximum slip at the center of the joint trace and with slip decaying towards both ends (e.g., Cowie and Scholz, 1992). The other possibility is that slip at the joint tip is taken up by a kink in which case slip may be uniform along the length of the joint (e.g., Younes and Engelder, 1999). If the slip decreases from a maximum in both directions, we presume that we have sampled a joint near the center of its trace (e.g., the right-lateral joint in Fig. 3A). If slip gradually decreases along its entire trace length, we presume that we sampled between its center and a tip (e.g., two left lateral joints in Fig. 3A). In many instances slip was uniform (±2 mm) along the exposed length of the joint (e.g., several examples in Fig. 3B). Here we suspect that slip was taken up at the tip by a kink (see Younes and Engelder, 1999). All of this conjecture is a consequence of each slipped joint having a horizontal dimension longer than its outcrop trace length.

In 11 out of the 12 outcrops we found that cross-fold joints striking east of north displayed left-lateral slip and those striking west of north displayed right-lateral slip (Fig. 4). These are outcrops of either Geneseo or Middlesex black shale. In the 12th outcrop consisting of gray shale of the Moscow Formation (CAY-01-DM) a joint set striking 342° displayed both senses of slip but also showed less slip for either sense (average <3 mm) than was found elsewhere. In further data analysis only outcrops (i.e., the remaining 11) containing joints with an average slip >5 mm were considered. In these outcrops we found 46 joints with slip and only one joint showed a sense of slip reversed from the general rule of conjugate shear as illustrated in Fig. 1. That exception to the rule had a maximum slip <4 mm. Thirty-two joints showed right-lateral slip and 14 showed left-lateral slip. The 13 left-lateral joints (i.e., 1.3 cm with the joint showing the wrong orientation for this sense of slip not counted) showed an average slip significantly smaller than the average slip for the 32 right-lateral joints (i.e., 1.9 cm). Five of 11 outcrops contained conjugate joints showing both senses of slip (Fig. 1). The average slip on right-lateral joints exceeds the average slip on left-lateral joints in four out of these five outcrops, a result that is consistent with a box and whisker analysis (Fig. 5). The strike of joints showing right-lateral slip ranged from 330° to 350° and the strike of joints showing left-lateral slip ranged from 004° to 011° (Fig. 4).

4. Discussion

Although slip on cross-fold joints took place after the ENE joint set propagated, the timing of its propagation is debatable. By understanding of the boundary conditions that might generate the shear traction necessary to drive slip on cross-fold joints, we can constrain the timing of propagation for the ENE set. Whatever the boundary conditions, they must generate a S_H with an azimuth between 351° and 004°. We consider two possible sets of boundary conditions. First, slip can occur in response to near-surface stresses that are induced by glacial shove during scouring of the Finger Lakes. If the slip is Pleistocene, then the


NY
N
0 5 10 15 km
90
Hamilton Group
Finger Lakes District
western portion
eastern portion
Hanover sh
Pipe creek sh
Angola sh
Nunda sh & sst
Rhinestreet sh
Cashaqua sh
Middlesex sh
West River sh
Genundewa ls
Penn Yan sh
Ithaca Fm
Geneseo sh
Tully ls
Moscow sh
Ludlowville sh
Skaneateles sh
Marcellus sh
Onondaga ls
West Falls Group
Java fm
West Falls
Sonyea Group
Genesse Group
Tully
Hamilton Group
Upper Devonian
Middle Devonian
Not to scale
gray shale
limestone
interbedded sh & sst
black shale
Owasco Lake
Seneca Lake
Cayuga Lake
96
CAY01DM (6/5)
SEN05PG (3/2)
SEN04PG (2/2)
YAT01PH (3/0)
YAT01BH (1/2)
SEN01BH (4/5)
STE06PG (3/0)
STE01BH (4/0)
YAT03AY (1/3)
YAT01PG (5/0)
TOM01BH (3/0)
Genesee Group
13
TOM02PH (3/0)
14
414
Sonyea Group
Ithaca
Keuka Lake
Watkins Glen
West Falls Group
Base of Rhinestreet shale
left-lateral slip
right-lateral slip
17
Elmira

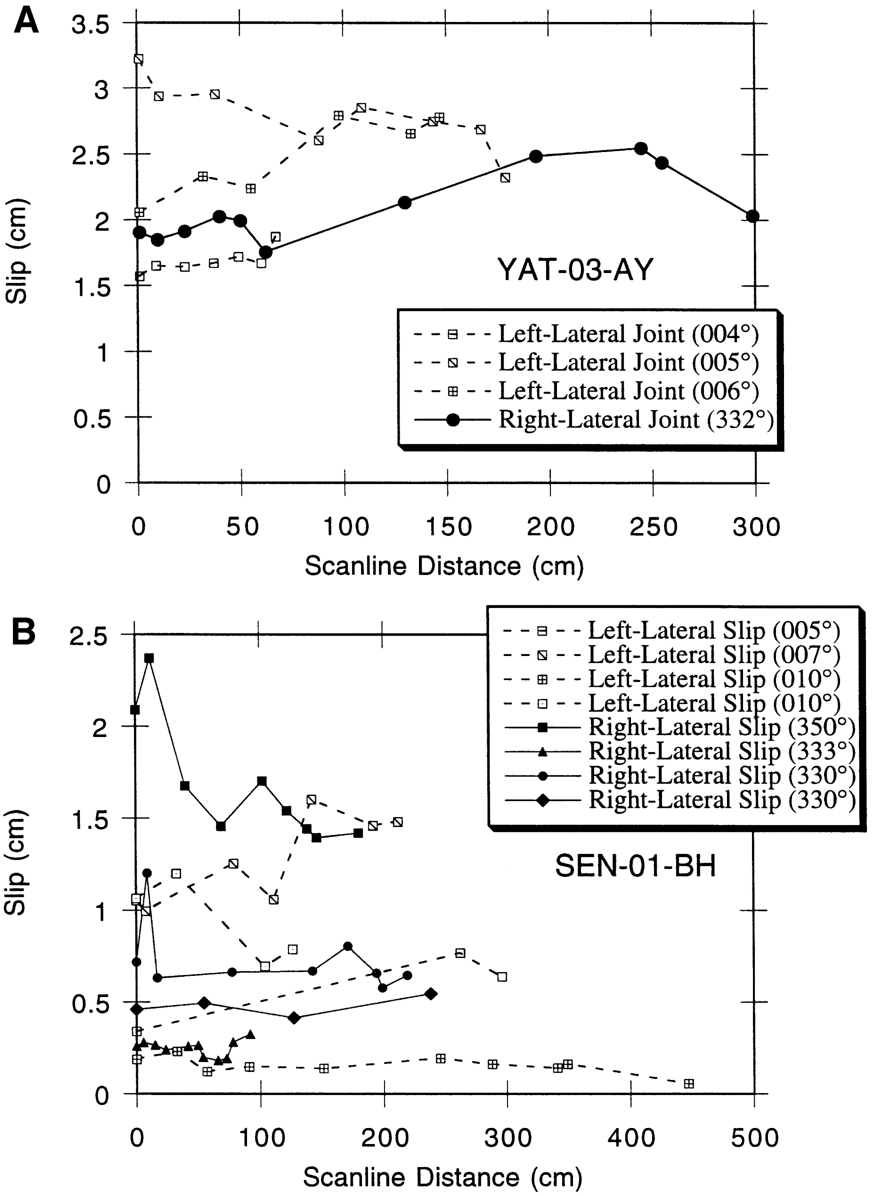


Fig. 3. (A) Slip versus scanline distance along cross-fold joints in the black shales of the Geneseo Formation at Squaw Point (YAT-03-AY) on the west shore of Seneca Lake. Neither end of any scanline represents the tip of a joint. Each data point represents one ENE joint that has been offset. (B) Slip versus scanline distance along cross-fold joints in the black shales of the Geneseo Formation at Lodi Point (SEN-01-BH) on the west shore of Seneca Lake. This outcrop has one joint with a sense of slip inconsistent with its orientation and data from this joint is not shown.

Fig. 2. Geological map of the Finger Lakes district showing the outcrop distribution of the Hamilton, Genesee, Sonyea, and West Falls Groups. The location of 12 outcrops are indicated with the orientation of joints that have slipped in either a right-lateral or left-lateral sense. The parentheses after each outcrop name indicates the number of joints showing either sense of slip (# right-lateral/# left-lateral). The base of the Rhinestreet shale marks the boundary between the West Falls and Sonyea Groups.

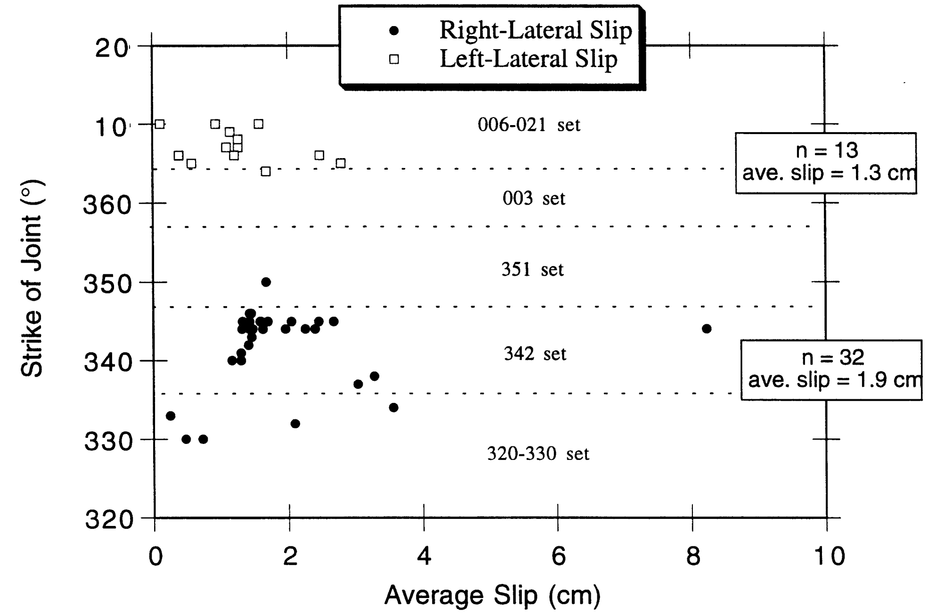


Fig. 4. Average slip on cross-fold joints in black shale of the Finger Lakes district, New York plotted according to strike of joint. Dotted lines bound the approximate range in orientations of five cross-fold joint sets identified by Younes and Engelder (1999).

ENE joint set could be relatively young. Second, slip can occur in response to deep-seated stresses that accompanied plate tectonic processes during Alleghanian tectonism. If slip is Alleghanian, the propagation of the ENE joint set must be pre-Alleghanian. The following explanation gives our rationale for favoring slip on joints during Alleghanian tectonics.

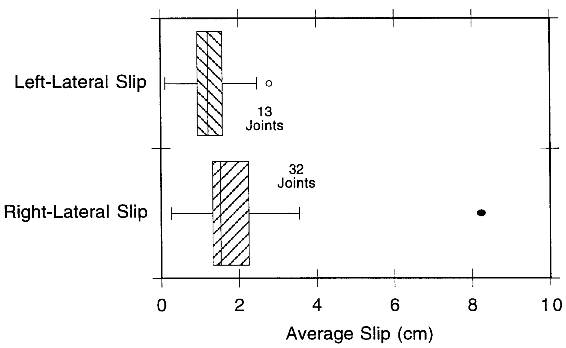


Fig. 5. Box and whisker plot for average slip on cross-fold joints in black shale of the Finger Lakes district, New York. The joints have been sorted according to sense of slip as indicated by offset ENE joints. A box and whisker plot indicates a significant difference in slip between the two data sets when the 50th percentile for the left-lateral data set as indicated by a central line within a box falls outside the 25th percentile for the right-lateral data set as indicated by the left edge of a box.

4.1. Slip by glacial shove

We first considered slip on cross-fold joints to be a manifestation of local glacial shove or crustal rebound as the glaciers receded during the Pleistocene. A glacial-shove hypothesis is attractive because the trend of the Finger Lakes follows cross-fold joint sets indicating that glacial scouring of the Finger Lakes was joint controlled. This hypothesis was also fueled by earlier work showing that some ENE joints in the northeastern United States are neotectonic and, hence, not present during Alleghanian tectonics (Hancock and Engelder, 1989; Gross and Engelder, 1991; Engelder and Gross, 1993). If the ENE joints of the Finger Lakes district are neotectonic, slip offsetting the joints also had to be neotectonic.

Glacial shove can occur in response to a stress induced by scouring of the Finger Lakes. In this case the maximum horizontal stress, S_H, is assumed to parallel the local reach of each lake (Fig. 6). This assumption is based on the Hertzian crack model for frictional drag of asperities where maximum compression in the substrate is in the direction of the slip of the asperity (Lawn, 1967). A glacier carving into a valley of the Finger Lakes district is assumed to act much like a Hertzian indenter and if so, glacial flow in the direction of the local reach of each lake generates a near-surface S_H in that direction. If the stress of glacial shove is responsible for the conjugate slip along joints in the shale, then the direction of glacial scour should produce left-lateral slip on joints that strike clockwise from the local reach and a right-lateral slip on joints that strike counterclockwise. North of Ithaca on the west side of Cayuga Lake there are joints showing the opposite sense of slip from that predicted by the glacial shove mechanism (area A in Fig. 6).

There are other reaches of both Senaca and Cayuga Lakes that parallel the direction of one of the cross-fold joint sets. Along these reaches, joints would have been parallel to the direction of S_H and, thus, should not have slipped (Points B and C in Fig. 6). To explain the slip in these latter cases, the local stress from glacial friction might have curved away in a southward direction from the central portion of the reach of each lake as is shown in the upper right key of Fig. 6. If so, reach-parallel joints to the west should have displayed a dextral slip whereas reach-parallel joints on the east side of the lake should have displayed a sinistral slip. Along the central portion of Senaca Lake, lake-parallel joints on both sides show sinistral slip (area B in Fig. 6) and to the north, lake-parallel joints on both sides show dextral slip (area C in Fig. 6).

The conjugate joint sets have a uniformly oriented acute angle regardless of the position of the local reach of the Finger Lakes. While it may be argued that this is largely a manifestation of the joints available for slip, there are other sets in the region that could have slipped in the event of local changes in the direction of S_H due to glacial shove. We do not see a pattern of conjugate slip that is consistent with near-surface stresses arising from glacial shove. Hence, we reject the glacial shove hypothesis for slip on Alleghanian cross-fold joints.

The post-glacial rebound hypothesis is not very attractive either. The orientation of post-glacial popups in New York State is one measure of the orientation of S_H during rebound upon deglaciation. The S_H driving post-glacial popups is the same as the contemporary tectonic stress field (i.e., ENE) (Engelder and Sbar, 1977).

4.2. Slip during the Alleghanian orogeny

The development of Alleghanian cross-fold joint sets within the Catskill Delta complex of the Finger Lakes district follows a temporal sequence starting with a 320–330° set and progresses to a 342° set, then a 351° set, and then a 003° set (Younes and Engelder, 1999). In the eastern portion of the Finger Lakes district a 006–021° joint set propagates about the time the 342° joint set propagated in the west. Superimposed on this pattern are several other joint sets including the ENE set (Sheldon, 1912) and a 000° set associated with continuing slip on the Clarendon-Linden zone (R. Jacobi, 1998, personal communication). Slip has occurred on joints falling in four of these sets: 320–330°, 342°, 351°, and 006–021°. The organization of joints displaying a conjugate sense of slip leads us to conclude that slip took place on earlier joints when the Alleghanian maximum horizontal stress (S_H) was between 350° (10° west of N) and 004° (4° east of N).

There are two Alleghanian structures arising from a later-stage S_H with a vergence direction in the angular interval between 350° and 004° in the Finger Lakes district. Layer-parallel shortening ($\approx 10\%$) in the form of both stylolitic and pencil cleavage is a manifestation of this later-stage Alleghanian compression (Engelder and Geiser, 1979). A compilation of the data on vergence direction for layer-parallel shortening structures taken from Fig. 2 of Engelder and Geiser (1979) cluster about 356° between longitudes encompassing the Finger Lakes district (i.e., 76°00′ and 77°15′) (Fig. 7). A later-stage Alleghanian S_H is also apparent from the direction of propagation of kinks from parent joints (Younes and Engelder, 1999). Fifteen outcrops contain parent joints with kinks including 11 with kinks consistent with right-lateral slip on parent joints and 4 with kinks consistent with the left-lateral slip on parent joints. Assuming that all kinks arise from a common later-stage S_H, the central point of the cluster is 001° (Fig. 7). Finally, the S_H for residual stress in the Tully Limestone at Ludlowville is oriented at 004° (Fig. 6). In summary, three different manifestations of later-stage Alleghanian compression show that the orientation of S_H fell

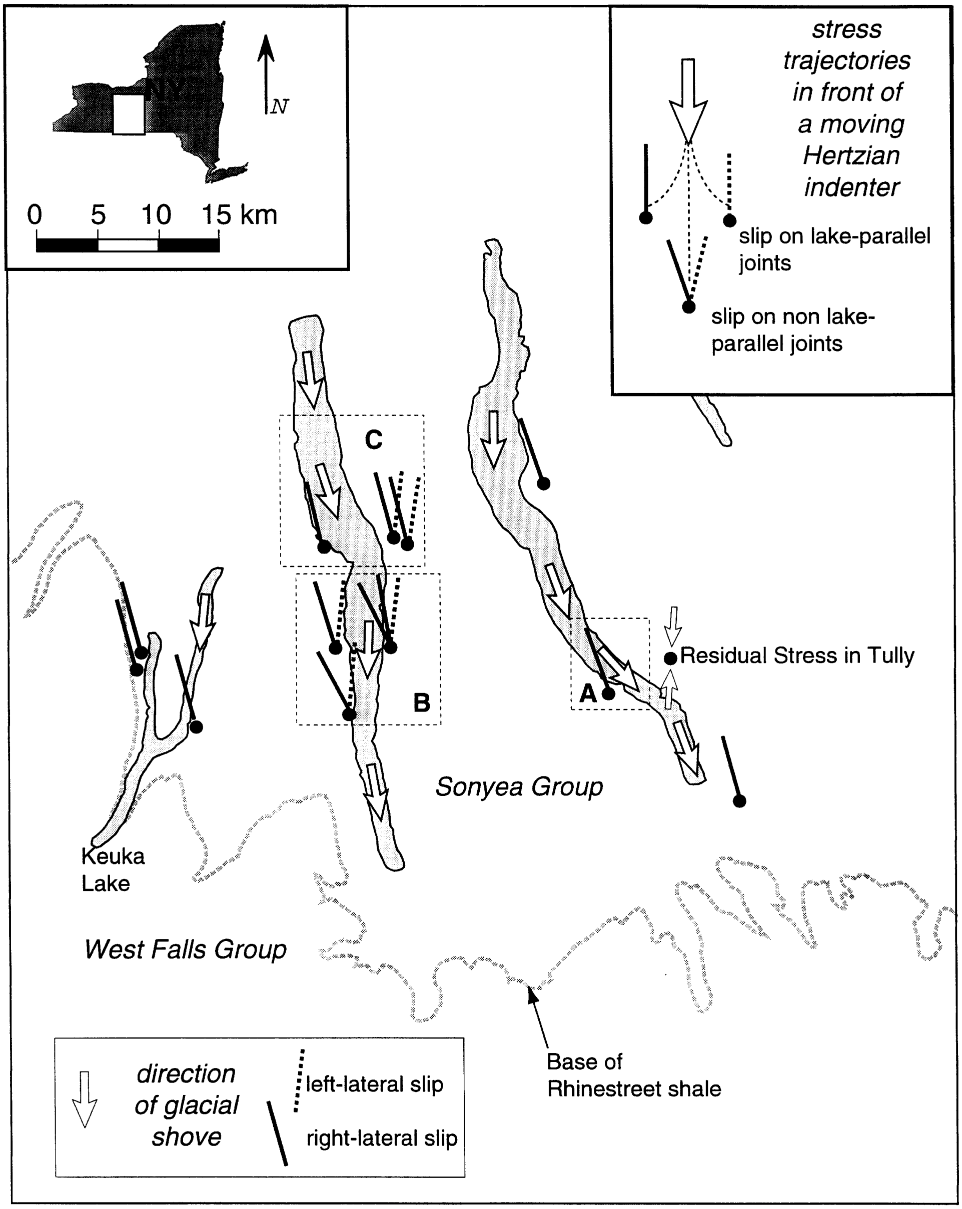


Fig. 6. The direction of glacial shove while carving the lakes in the Finger Lakes district. Local maximum horizontal stress (S_H) developed under the weight of the glacier is assumed to be parallel to the glacial shove (white arrows). In the upper right key, joints are superposed on hypothetical maximum horizontal stress trajectories in front of a sliding indenter. The orientation for S_H for residual stress in the Tully Limestone is given by arrows (Engelder and Geiser, 1984).

within the acute bisector the conjugate slip surfaces in the Devonian black shales of the Finger Lakes district. This later-stage Alleghanian compression was strong enough to impart a penetrative fabric on the rocks of the Appalachian Plateau (i.e., Engelder and Geiser, 1979).

Average slip was greater on those joints displaying a right-lateral sense (Figs. 4 and 5). Slip on all joints

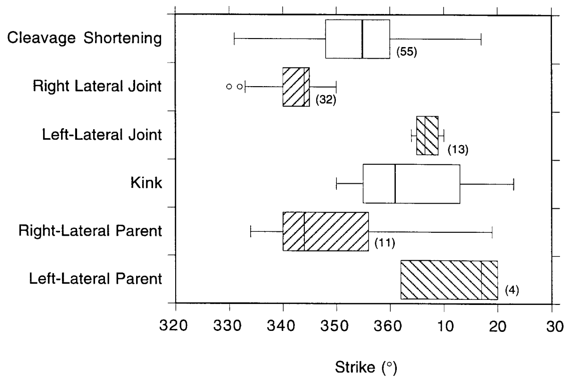


Fig. 7. Box and whisker plot for the orientation of various structures on the Appalachian Plateau: the direction of cleavage shortening (Engelder and Geiser, 1979), the strike of right-lateral and left-lateral joints (this paper); the strike of kinks (Younes and Engelder, 1999); the strike of right-lateral and left-lateral parent joints hosting kinks (Younes and Engelder, 1999).

was driven when the orientation of S_H was roughly 357° as indicated by the shortening direction for cleavage in the Finger Lakes district and the direction for kink propagation. Joints displaying a left-lateral sense

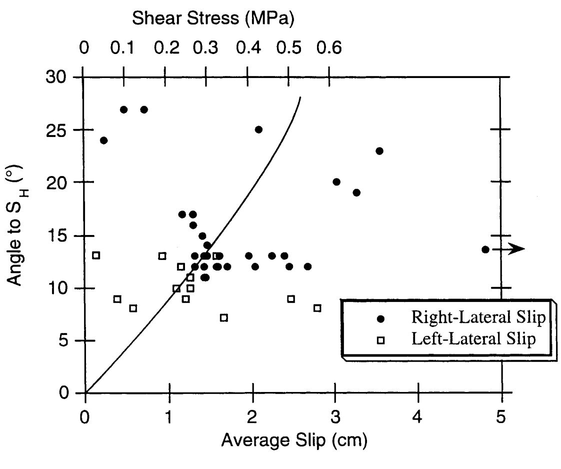


Fig. 8. Slip on cross-fold joints in black shale of the Finger Lakes district as a function of angle between strike of that joint and the hypothetical orientation of S_H at the time of slip, based on mean orientation of the direction of cleavage shortening (Engelder and Geiser, 1979). The hypothetical orientation for $S_H$is taken as 357° which is the bisector between joints showing right-lateral slip at 350° and joints showing left-lateral slip at 004°. The solid curve on the diagram is the shear stress on joints in black shale of the Finger Lakes district assuming that S_H was oriented at 357° and using Younes and Engelder's (1999) estimate for differential stress in shale (i.e., 1.3 MPa).

of slip are found no more than 13° from this orientation for S_H whereas joints showing right-lateral slip are found as much as 27° from the bisector (Fig. 8). On average, the larger slip takes place on that group of joints oriented at a higher angle to S_H as indicated by later-stage Alleghanian structures. Our interpretation is that, on average, the slip magnitude on right-lateral joints reflects the higher resolved shear stress to which that group was subjected.

4.3. *Survivability of joints during the development of penetrative strain*

Engelder and Geiser (1980) were confronted with compelling evidence that some cross-fold joints developed as a pre-cleavage event (i.e., their Figs. 9 and 11). However, in 1980, they doubted that joints could survive as unfilled cracks during a period of 10% layer-parallel shortening. Without evidence to confirm survivability through an event of penetrative deformation, they hypothesized that jointing in a pre-cleavage orientation was controlled by a residual stress and, therefore, actually propagated during a post-cleavage event. Our data show that joints do survive as unfilled cracks (i.e., surfaces of discontinuity) and that Engelder and Geiser (1980) were incorrect in calling upon a residual stress to control post-Alleghanian jointing in a pre-cleavage orientation. Now it is clear that slip on early cross-fold joints is driven by an S_H associated with the main episode of cleavage development. Early cross-fold joints not only survived the episode of penetrative strain but also slipped without any mark associated with the frictional wear commonly associated with slip surfaces (e.g., Petit, 1987).

The absence of frictional wear on the joints with a few centimeters of slip suggests that the joints were not in hard contact during slip despite the high normal stress associated with 2–3 km of overburden during the Alleghanian orogeny. Near-frictionless slip is consistent with the notion that these structures slipped while subject to very low effective normal stresses. Indeed, there is a robust data set suggesting that fluid pressures were abnormally high during the Alleghanian orogeny (i.e., Evans et al., 1989; McConaughy and Engelder, 2000). The absence of fibrous growth is consistent with data showing that the fluid under high pressure was a natural gas such as methane, a fluid from which fibrous vein material is not deposited (Lacazette and Engelder, 1992). In this case, survivability is linked to a low effective normal stress across the joints filled with a chemically inert fluid.

4.4. Acadian tectonics

The offset of the ENE joint set during Alleghanian slip means that the ENE set propagated in a stress field predated the classic Alleghanian orogeny. Penetrative strain during Alleghanian orogeny includes a flattening against the plane of the ENE joints. Tectonic compression normal to a preexisting joint is known to produce a stylolitic-like cleavage in the plane of the joint (Srivastava and Engelder, 1990). No stylolitic-like cleavage has developed on the face of the ENE joints. In black shales of the Appalachian plateau, a chemically inert natural gas under high pressure may have acted to suppress the development of cleavage by pressure solution, a mechanism dependent on diffusion in water. This leaves all ENE joints in a pristine state during Alleghanian layer-parallel shortening.

The ENE joint set reflects a homogeneous stress field of such a regional extent that it could represent a major orogenic event. A major pre-Alleghanian orogenic event affected Devonian rocks to the east where mountains of the Acadian orogeny provided a source for the sediments of the Catskill Delta complex are found (Ettensohn, 1985). The orientation of the ENE joint set correlates with a prominent set of veins in the Silurian Lockport Formation, a dolostone in western New York (Gross et al., 1992). Both the ENE veins in the Lockport Formation and the ENE joints in the black shales are consistent with the cratonward projection of an Acadian stress field extending from New England toward the craton (Gross et al., 1992). We now propose that the ENE joint set of the Appalachian Plateau is a manifestation of high fluid pressure developed during burial of the Catskill Delta before the onset of the Alleghanian orogeny. The cause of high fluid pressure may have been a combination of disequilibrium compaction by stratigraphic loading and one of several mechanisms leading to an increase in fluid volume or a change in the solid-to-volume ratio (Osborne and Swarbrick, 1997)

5. Conclusions

Slip on cross-fold joints in black shale of the Finger Lakes district, New York, occurs as a conjugate pair responding to an S_H oriented about 357°. This orientation is the same as that driving layer-parallel shortening during the Alleghanian orogeny on the Appalachian plateau. Stress reached this orientation during progressive rotation from earlier positions where the earlier cross-fold joints propagated. As ENE joints were offset by slip on the cross-fold joints, we conclude that the ENE joints are pre-Alleghanian and most likely correlate with an Acadian stress field. Finally, we infer that both pre-Alleghanian and early Alleghanian joints can survive as open cracks through a period of penetrative strain.

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