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SURFACE MORPHOLOGY ON CROSS-FOLD JOINTS OF THE APPALACHIAN PLATEAU, NEW YORK AND PENNSYLVANIA

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ABSTRACT

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On the Appalachian Plateau of New York and Pennsylvania plume patterns are present on surfaces of all cross-fold joints that cut siltstones, but they are not common on either cross-fold joints or strike joints cutting shales. Near Watkins Glen, New York, joints cutting siltstones display two types of plumose patterns; each particular type correlates with a specific cross-fold joint set. The more easterly striking cross-fold joints (345°, i.e., N15°W), cutting thin siltstone beds embedded in thicker shale formations, have straight plume patterns with axes parallel to bedding. More westerly striking cross-fold joints (335°), cutting thick siltstone beds, have curved plume patterns with axes that either curve or show fan-like rhythmic patterns that alternately increase and decrease in intensity. Joints cutting only shales exhibit no distinct surface morphology other than long arcuate arrest lines. The fan-like rhythmic patterns of plumes suggest that these joints formed by a cyclic process (perhaps related to pore pressure variations) rather than by one massive rupture.

INTRODUCTION

During a study of regional joints in the vicinity of Ithaca, New York, Sheldon (1912) recognized that certain joint sets favored certain lithologies. Strike joints were common in shales but less well-developed in interfingered siltstone beds. In the same region of the Appalachian Plateau, Parker (1942) noted that plumose markings were rare on strike joints but commonly occurred on cross-fold joints. These studies and those elsewhere (e.g., Stearns, 1968; Nelson and Stearns, 1977) make it clear that the host lithology is an important parameter in influencing the development of regional joint sets as well as their surface morphology.

In this paper we characterize the surface morphology, plumose markings in particular, on joints within the lightly deformed Upper Devonian shales and

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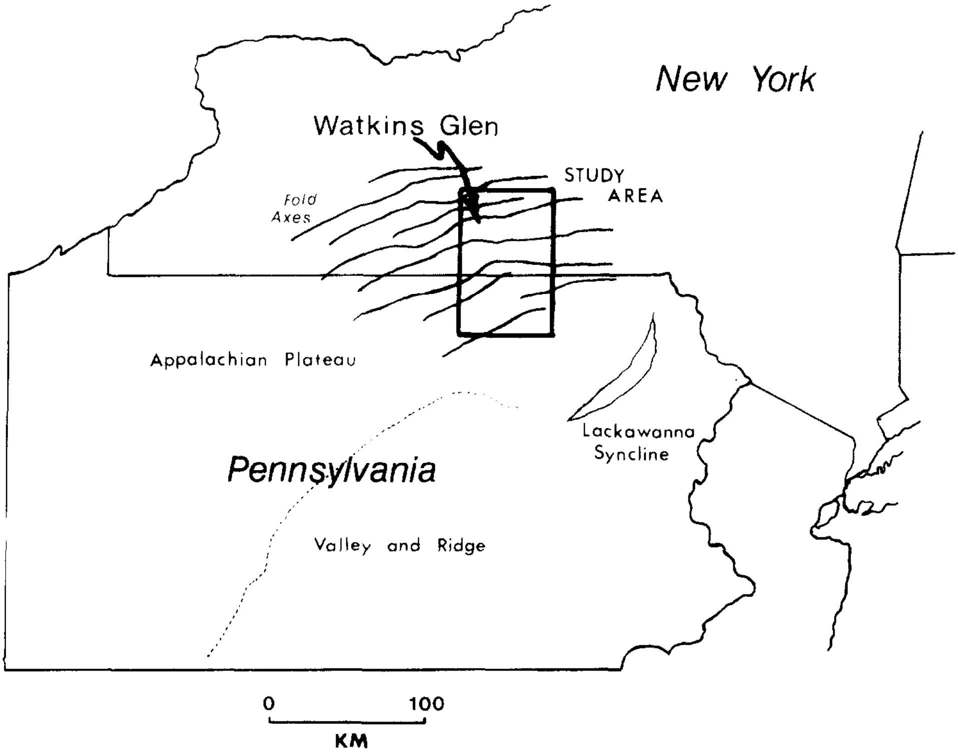

Fig. 1. Study area on the Appalachian Plateau of New York and Pennsylvania.

siltstones of the Southern Tier of New York and northern Pennsylvania (Fig. 1). Our purpose is to elaborate on the details of the lithological control of joint propagation and joint surface morphology. In particular, we focus on the differences in surface morphology between various cross-fold joint sets discussed in Sheldon (1912), Parker (1942), and Engelder and Geiser (1980). This is to further emphasize that the cross-fold joint sets mapped by Engelder and Geiser (1980) are fundamentally different from each other. Despite the large number of descriptions of the markings on joint faces (Hodgson, 1961; Roberts, 1961; Syme-Gash, 1971; Kulander et al., 1979) none adequately distinguishes the end members of the family of plumose markings observed on the Appalachian Plateau.

The surface morphology of joints was examined at outcrops in the vicinity of Watkins Glen, New York (Fig. 1). The key outcrop is at Watkins Glen in a road cut at the intersection of Routes 14 and 414 where two cross-fold joint sets are well exposed for more than two hundred meters along Route 414 (Figs. 1 and 2). In 26 m of vertical section shales separate more than nine siltstone layers of thicknesses from 15 cm to more than 3 m. The thicker siltstone layers are themselves divided into several beds. Cross-fold joints in the shales strike 345° (N15°W) whereas those in

Fig. 2. Two cross-fold sets at Watkins Glen, New York. The upper joint in shales strikes at 345° whereas the lower joints in siltstone strike 335°.

the thicker siltstones strike 335° (N25°W). In this outcrop maximum shortening indicated by deformed fossils parallels the joints in shales.

JOINT SURFACE MORPHOLOGY AND PLUMOSE MARKINGS

Background

The plume pattern on a joint constitutes all "delicate tracery of feathery lines" (Woodworth, 1896) diverging from either a straight or sinuous axis. By the late 19th century geologists recognized that the feather (plume) patterns on joints contain information about the process of joint propagation (Woodworth, 1896). Plumes form on the surface of extension fractures (joints) where the plume records the development of the joint whose rupture front is perpendicular to the barbs of the plume (Fig. 3). Within the study area evidence is overwhelming that the joints formed in extension rather than shear (Engelder, 1982). The term plume pattern is used over feather-fracture because the recent literature favors the former (Hodgson, 1961; Kulander et al., 1979; Bahat, 1979).

Within rocks in the vicinity of Watkins Glen the geometry of the plume axis gives rise to three variations: the straight or s-type plume (Fig. 3A); the curving or c-type plume (Fig 3B); and the rhythmic c-type plume (Fig. 3C). The straight plume has a linear axis parallel to bedding. Because the plume is contained within individual

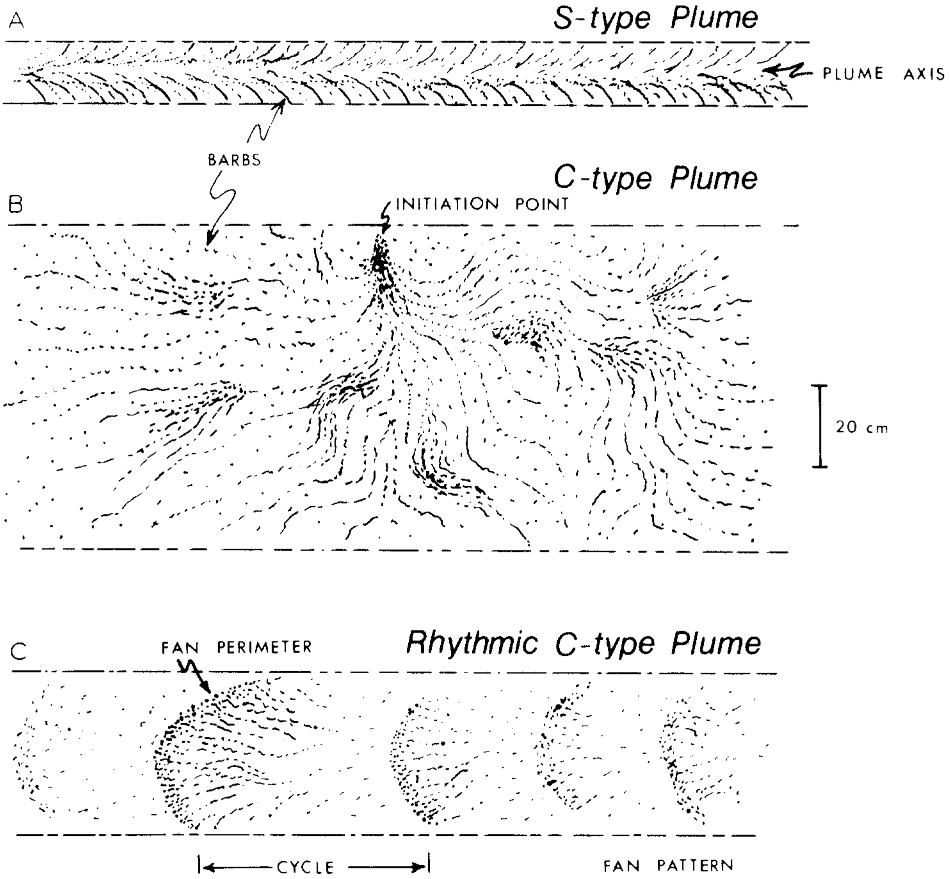

Fig. 3. Various plume patterns observed on the siltstones of the Appalachian Plateau. A. Straight plume. B. Curving plume. C. Rhythmic plume. Barbs on each pattern are individual traces or fine lines within the plume that mark the direction of local fracture propagation. Fan perimeters in C designate loci of arrest lines. They convex toward the direction of fracture propagation.

beds, it extends horizontally a greater distance than vertically. Its barbs reach outward from the axis in the vertical joint plane toward the upper and lower boundaries of the bed. The direction of each barb away from the axis marks the local direction of propagation of the joint. The plume axis is seldom in the center of the bed so that the barbs above and below the axis are asymmetrical. Kulander et al., (1979, p. 42) refers to barbs as twist hackles whereas Bahat (1979, 1982) prefers to restrict the use of the term hackle to those joint surfaces that have formed at critical conditions (of stress intensity or crack velocity) where the hackles are morphological expressions of bifurcation. Because the velocity of rupture is unknown barb is used in this text.

The curving plume (c-type) commonly has an axis which divides into several branches that in turn may divide. Because the axis curves, the barbs tend to be more irregular than in the straight plume. Curving plumes generally have a horizontal length to height ratio less than that for straight plumes. A variation of the c-type plume is the rhythmic plume which consists of a series of barbs that fan repeatedly along a joint surface (Fig. 3C). Each fan pattern gradually increases in intensity (surface topography increases to accent fan) until a convex perimeter is reached at which the fan pattern vanishes. The perimeter is convex toward the direction (Fig. 3C) of propagation, and it signifies an arrest location on the fracture surface (Kulander et al., 1979).

In many outcrops with two cross-fold joint sets, one tends to cut through shales, while the second one cuts through siltstones. In the vicinity of Watkins Glen the s- and c-plumes form preferentially on joints with orientations of 345° and 335°, respectively. The curving and rhythmic plume patterns are grouped into the c-type because they form either on the same joints or adjacent parallel joints.

Barbs within both the s- and c-plume patterns radiate from a point believed to be the initiation point from which the fracture propagated. Near Watkins Glen most joints with plumes have an initiation point at bedding plane boundaries. In contrast, joints with rhythmic plumes usually have initiation points within the beds. Joints with initiation points at bedding plane boundaries commonly propagate bilaterally from the initiation point. Rhythmic plumes move bilaterally away from an initial initiation point but appear to stop and then restart from initiation points within beds. These initiation points within beds are secondary points from which the rupture propagates unilaterally.

Surface morphology on joints striking 345°

The best example of a joint in this orientation is one cutting a 4 m thick shale layer with a 21 cm thick siltstone intercalated near the top of the shale (Figs. 2 and 5A). The joint in the shale has no plume patterns on a scale visible to the unaided eye. This is true even on fresh joint surfaces where no erosion or weathering has taken place. There are, however, some large arcuate lines with a radius of curvature of several meters (Fig. 5B). These are termed arrest lines and mark the position where a large joint propagating from left to right slowed its rate of propagation and possibly stopped (Bahat, 1979; Kulander et al., 1979). These arrest lines have a topography which trends normal to direction of fracture propagation. The topography is a series of arcuate hills and valleys with surfaces out of the plane of the joint.

On all joints striking 345° the only well-defined plume patterns occur on surfaces of siltstone intercalations in shales, and are invariably s-type. A 21 cm thick siltstone layer displays a joint with a long (48 m) plume and several shorter plumes (Fig. 5). Joint initiation occurred at 5 points along 100 m of exposure at the upper-layer boundary or close to it. The axis of the plume has a slight waviness within 30 cm of the initiation point before propagating parallel to bedding. This waviness, which is witness to the fact that s- and c-type plumes belong to the same family, seems to reflect initial conditions of inconsistent stress differences ($\sigma_1 - \sigma_2$, where σ_1 is the horizontal compression parallel to the fracture surface, and σ_2 is the vertical compression also parallel to this surface) prior to reaching stress stability along the horizontal axis of the plume.

Within siltstones intercalated in shale joints with plumes propagate towards each other from opposite directions (Fig. 4). A large band of subvertical arrest lines in the shales is seen just below the location where the two plume patterns, indicating opposite direction of propagation, meet in the 21 cm thick intercalated siltstone bed (Fig. 5). This close proximity suggests that the propagation and arrest of the joint ruptured both the shales and siltstone simultaneously.

Surface morphology on joints striking 335°

Joints in this orientation are confined to the thicker siltstone beds and do not extend downward or upward into the adjacent shale beds. Plumes in the siltstone beds are commonly the short and wavy c-type with initiation points at the bottom of

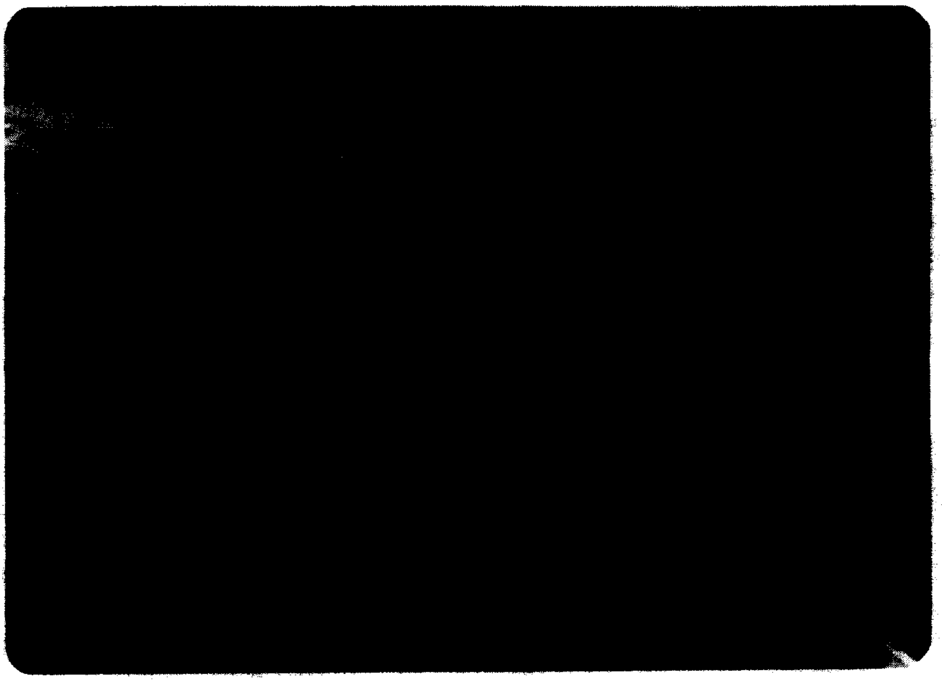

Fig. 4. Contact between two planes of the same joint intersect at very low angles. Plume markings indicate that fractures approach each other.

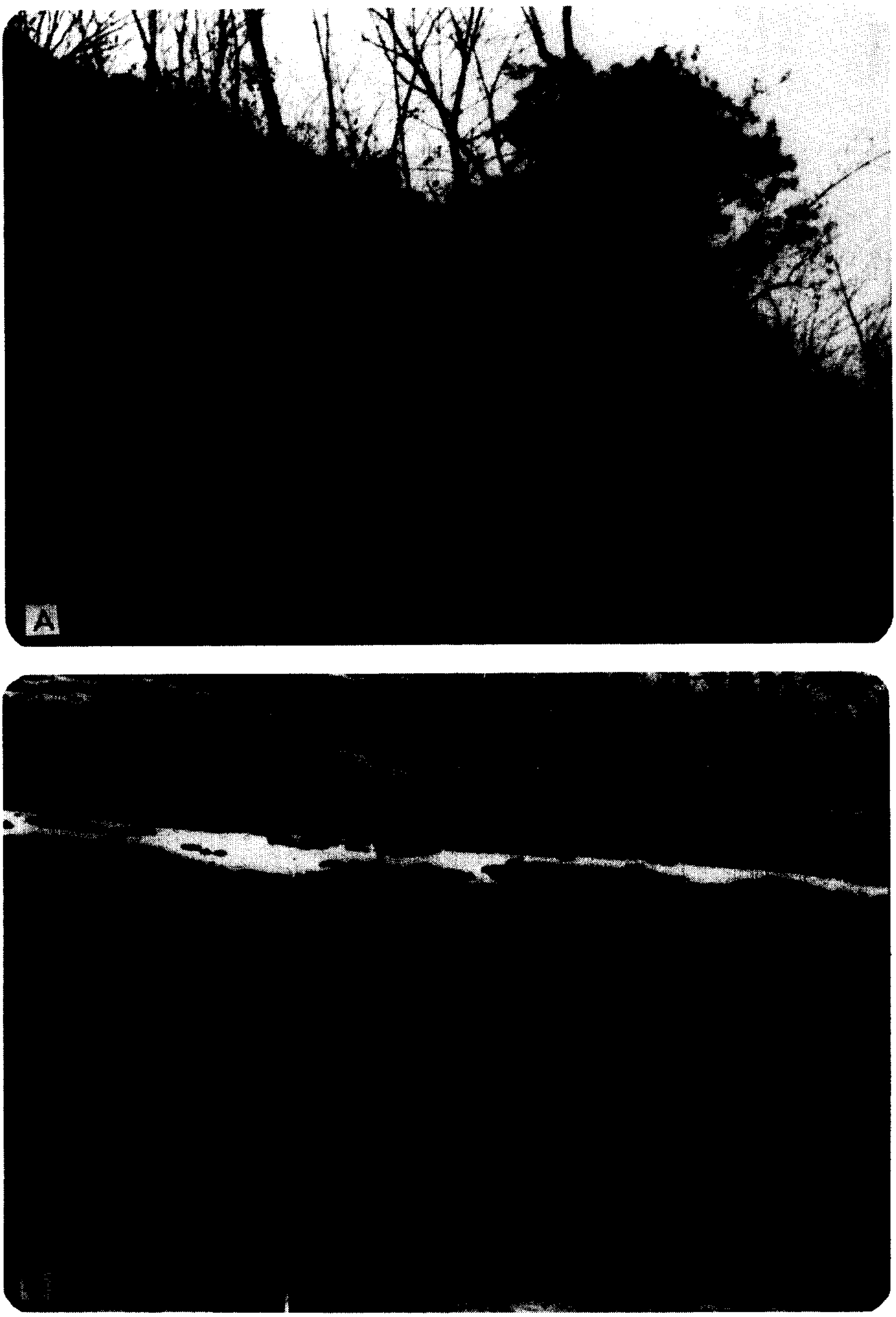

Fig. 5. Photograph of joint cutting the shale in Fig. 2. (A) Note straight plume in siltstone bed and lack of plumes in shales below siltstone; B) note large arrest lines in shales (right from feet scale), just below curve abutting (shown by arrow).

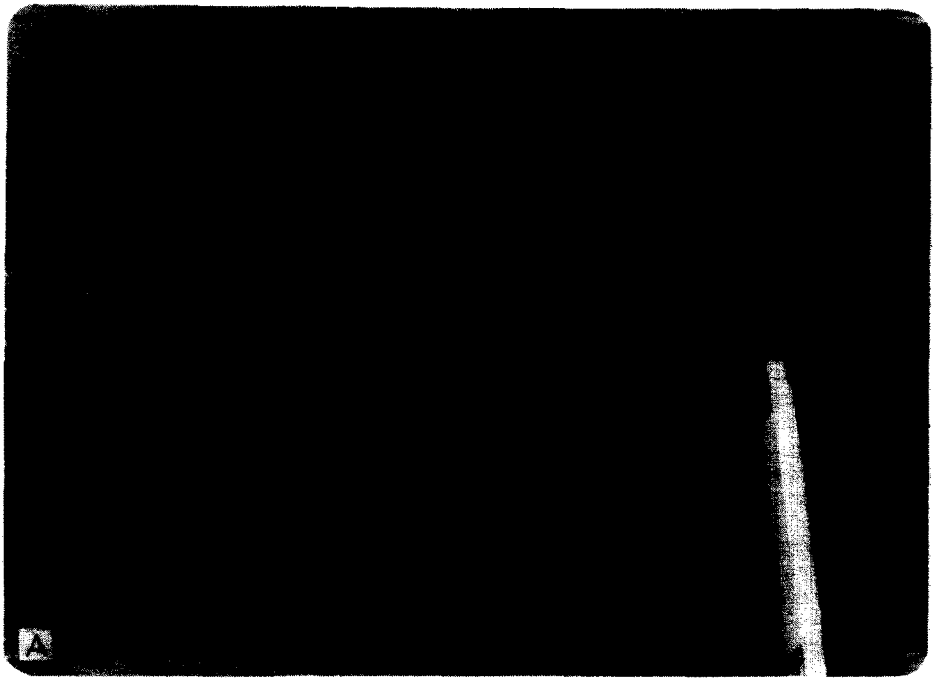

Fig. 6. A. Photograph of c-type plume pattern on adjacent joint surfaces from the outcrop shown in Fig. 2. The plume pattern in each of two layers is different indicating the independent propagation of each joint. Thickness of lower layer 18 cm.

B. Photograph of c-type plume pattern on a joint surface within the outcrop shown in fig. 2. Thickness of layer in the middle is 54 cm.

the bed on layer boundaries (Fig. 6). This is in contrast with joints striking 345° where the initiation point is often on the top of the bed (the joint in Fig. 6B is an exception).

In two adjacent siltstone beds (Fig. 6A) separated by several thin layers of shales, c-type plumes initiate at the lower boundaries and spread towards left and right. In the upper bed the plume axis has a larger curvature near the initiation point than that further away. Thus, the plume axis straightened as fracture propagation progressed. In the same bed the axis of the plume is 6 cm above the bottom of the bed, whereas this distance is 8 cm in the lower bed.

Three consecutive beds with the middle bed 54 cm thick (Fig. 6B) exhibit c-type plume patterns that are confined to each bed. Fracture propagation terminated at a bed boundaries. In the top and bottom beds propagation direction is horizontal from left to right (SE–NW). In the middle bed initiation of the plume is 7 cm from the top boundary, an unusual position for the initiation points on joints striking 335° within this outcrop (the usual position is at the bed's lower boundary). The plume flares bilaterally downward. Perhaps the most characteristic feature of the plume is its asymmetry caused by variations in the different plume axes. Towards the right the plume axes undulate with 22 cm (wave lengths) and 10 cm amplitudes. Diagonally downwards to the right the plume axes have 22 cm wave lengths and 4 cm amplitudes. Plume axes are not well defined toward the left. Downward, plume axes are approximately straight. Termination of the plume pattern along a curved perimeter (arrest line) is seen on the left side (at contact with scale, Fig. 6B). The radius of this perimeter is 35 cm. The maximum distance from the initiation point to the perimeter at the lower layer contact is 55 cm. Further left (extreme end of figure) there is another series of arrest lines.

For c-type plumes in other outcrops, fracture initiation points may occur at either upper or lower boundaries. Plume axes often curve more near initiation points and straighten as fracture propagation progresses. Plumes most commonly are confined to a single bed but may extend through several adjacent rock beds (because at time of fracture bedding planes were not effective stress boundaries). Separate c-type plumes on adjacent beds often show entirely different patterns (indicating that they fractured separately).

C-type plumes also show rhythmic increases and decreases of intensities where a change in intensity is often characterized by a change in roughness of the barbs from a topographic relief of about one mm to a relief low enough to render the surface smooth to the unaided eye (Fig. 7). In an intense part of a pattern the details of various individual barbs are orthogonal to the arrest lines. In two siltstone beds separated by thin shales, the plume geometry indicates that fracture propagation was from right to left in the upper bed and from left to right in the lower bed (Fig. 7A). Three fans are visible in the upper bed (Fig. 7A). The relief of the plume barbs gradually builds up to maximum in these fans and then abruptly vanishes. The perimeter of the fans is curved in a variety of ways. For instance, the second fan in

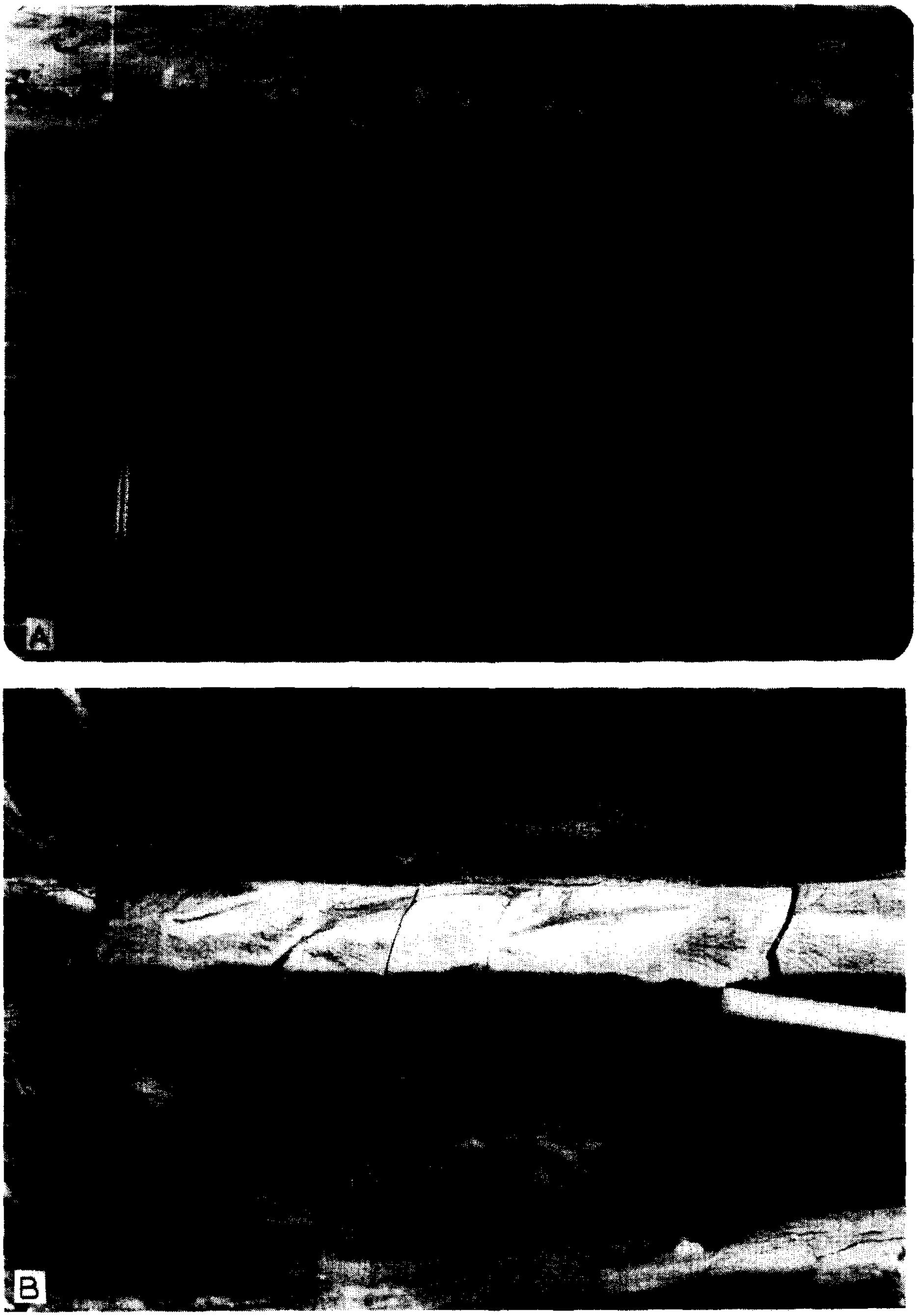

Fig. 7. A. Cyclic fracture propagation in a siltstone represented by a rhythmic plume pattern. This pattern is shown schematically in Fig. 3C. Same outcrop as shown in Fig. 2. Note that the rhythmic pattern is horizontally oriented and confined to an arc of about 180°, rather than a full circle. Thickness of upper layer 36 cm.

B. Rhythmic pattern in a bed 7 cm thick. A sudden drop of plume intensity occurs about 5.5 cm left of the edge of centimeter scale. Outcrop at the intersection of routes 79 and 414 west of Watkins Glen.

TABLE I

Characterization of plume patterns on surfaces of cross-fold joints

Fig. No.	Bed thickness (cm)	Plume style	Propagation direction	l_p (cm)	l_m (cm)	W	Wave length (cm)	Radius (cm)
5A	21	s-straight	bilateral					
6A (upper)	19	c-wavy	bilateral	53	58	0.09		
6A (lower)	18	c-wavy	bilateral	39	45	0.15		
6B (right)	54	c-wavy	bilateral	58	72	0.24		
6B (left)		c-wavy	bilateral	47	55	0.15		35
7A (upper)	36	c-rhythmic	unilateral				27, 43	8, 16, 10
7A (lower)	23	c-rhythmic	unilateral					
9	60	s-straight (approx.)	unilateral	520	525	0.009		

l_p is the length of the plume parallel to bedding, l_m is the maximim length of the plume axis, W is plume waviness. Rhythmic patterns are also characterized by wave-length of the cyclic process and radius of curved perimeter. Radius is measured as well in wavy plumes of strong curvature.

the upper bed is close to semicircular, whereas the first and third fans, each branch into two plume perimeters.

The distances between fan perimeters of the first and second, and second and third cycles in the upper bed (wave lengths) are 27 and 43 cm, respectively. The radii of the three fans in the upper bed are 8 cm, 16 cm, and 10 cm for the upper right branch, middle, and lower left branch, respectively. The distances between areas of maximum intensity on these three plume fans above the lower bed boundary are 12 and 23 cm for the two branches of the first fan (from right), 16 cm for the second cycle, and 11 and 25 cm for the two branches of the third. Fans occur on joints in siltstone beds as thin as 7 cm in other outcrops (Fig. 7B).

We characterize the plumose patterns in siltstone by the parameter called plume waviness W, which is given by:

$$W = \frac{l_m - l_p}{l_p}$$

where l_p is the length of the plume parallel to bedding and l_m is the maximum length of the plume axis. l_m may be much longer than l_p for c-type plumes. Results for several patterns are summarized in Table I.

DISCUSSION

Fracture mapping

An outcrop east of Watkins Glen at the intersection of routes 79 and 414 contains three cross-fold joint sets (Fig. 8). This outcrop suggests that Engelder and Geiser's

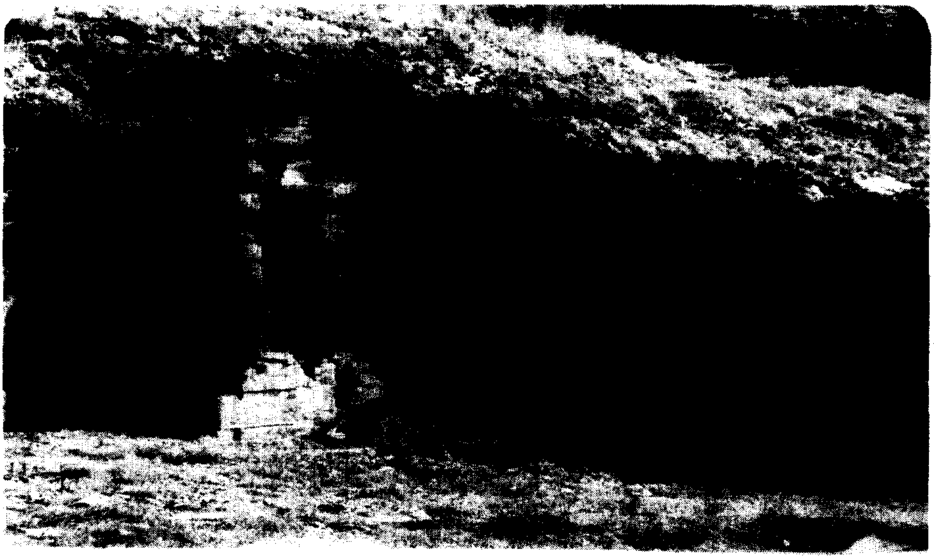

Fig. 8. Two joints intersecting in the outcrop at the intersections of routes 414 and 79 west of Watkins Glen. The two joint strike 335° (left) and 004° (right). A third crossfold joint is seen striking at 348° (low center).

(1980) two cross-fold joint sets may in fact be divided into three joint sets striking 335°, 348°, and 004°. However, outcrops with three joint sets are rare compared with outcrops with either one or two cross-fold joint sets. As indicated in the previous section the two types of plumose patterns show a preference for particular cross-fold joint sets. Throughout the Watkins Glen region the broad, short and wavy c-type plumose markings characterize the exposures of the 335° joint set (with infrequent exceptions). Plumose patterns on the 348° joint set surfaces are highly variable and appear both as narrow and straight s-type as well as c-type patterns, the latter being less common. Plumes are rare on the 004° joint surfaces. Where present they are s-type, and are most often found on 5–10 cm siltstone beds within thicker shale units. The division of joint set Ib (Engelder and Geiser, 1980) into two joint sets (335° and 345°) is supported by the consistent difference in plumose patterns on those two joint sets at Watkins Glen.

The rhythmic fracture process

The rhythmic plume pattern (Fig. 7) implies a periodic process of repeated episodes of crack propagation. The absence of hackles (morphological expressions of bifurcation) and the common arrest lines along plume patterns suggest that these propagations are probably slow (Bahat, 1979, 1982). If it is due to a slow stress corrosion process (Scholz, 1972) low fracture-stresses may be sufficient (Mould and Southwick, 1959). Plumose markings are typical to mud-cracks that developed slowly in water containing sediments (Bahat, 1979) probably without excessive pore pressure.

Although, it is not known to what extent this cracking requires high pore pressure, the periodic crack propagation satisfies Secor's model for natural hydraulic fractures (1969). Secor visualized "that the growth of a tension fracture at depth in the earth's crust is macroscopically a slow process, consisting in detail of numerous short quick episodes of crack propagation interspersed with longer periods of quiescence during which the pore fluids from the surrounding rock percolate into the crack and wedge it open". We expressed above our doubts regarding the "quick" episodes, but we leave open the possibility that these joints were formed under low effective stress.

CONCLUSIONS

Based on the geometry of the plume axes, we distinguish two end members to the family of plume patterns found on joint faces in siltstones of the Appalachian Plateau: straight (s-type) and curved (c-type).

Typical features of the s-type plume are:

(1) s-type plumes are strictly parallel to bedding, and horizontal where bedding is horizontal;

(2) relatively long and extend horizontally in both directions away from the initiation point;

(3) found in siltstone intercalated in shales;

(4) initiated at layer boundaries, and do not cross them; and

(5) associated with large arrest lines (curved undulations up to 4 m long) in shales; the convex side of the arrest line is directed towards the trend of propagation indicated by the plumes in the adjacent siltstones.

Typical features of the c-type plume are:

(1) axes curve extensively;

(2) relatively short and propagate bilaterally with the exception of rhythmic plumes that appear to propagate unilaterally;

(3) generally found in thicker siltstone beds;

(4) initiated at layer boundaries and may occasionally cross them;

(5) associated with small arrest lines (up to 60 cm long) in siltstone, generally in concordance with the change in intensity of plume patterns; and

(6) associated with plume patterns of varying intensity.

As a rule, s-type plumes with axes sub-parallel to the bedding (Fig. 4) commonly occur in thin siltstone beds intercalated within thicker shales. On the other hand, the

Fig. 9. Plumes on fracture surfaces in siltstone, Montour Falls, New York. Non-characteristic almost straight patterns are observed in these thick layers. Thickness of upper layer is 60 cm.

c-type plumes (Figs. 6 and 7) commonly occur in thick layers of siltstones. There are, however, exceptions to this rule. For example, Fig. 9 shows sub-parallel plumes with slightly curved axes in two thick siltstone layers (on joints striking 349°). The 60-cm thick upper bed contains the longest s-type plume observed in a thick siltstone bed (5.2 m). Hence, various transitions from s-type plumes often appear as the thickness of the siltstone bed increases.

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REFERENCES

Bahat, D., 1979. Theoretical considerations on mechanical parameters of joint surfaces based on studies on ceramics. Geol. Mag., 116: 81–92.

Bahat, D., 1982. Extensional aspects of earthquake induced ruptures determined by an analysis of fracture bifurcation. Tectonophysics, 83: 163–183.

Engelder, T., 1982. Reply to a comment on "Is there a genetic relationship between selected regional joints and contemporary stress within the lithosphere of North America"? by A.E. Scheidegger. Tectonics, 1: 465–470.

Engelder, T. and Geiser, P., 1980. On the use of regional joint sets as trajectories of paleostress fields during the development of the Appalachian Plateau, New York, J. Geophys. Res., 85: 6319–6341.

Hodgson, R.A., 1961. Regional study of jointing in Comb Ridge–Navajo mountain area. Arizona and Utah. Am. Assoc. Pet. Geol. Bull., 45: 1–38.

Kulander, B.R., Barton, C.C. and Dean, S.L., 1979. The application of fractography to core and outcrop fracture investigations. Rep. to U.S. D.O.E., Morgantown Energy Technology Center, METC/SP-79/3, 174 pp.

Mould, R.E. and Southwick, R.E., 1959. Strength and static fatigue of abraded glass under controlled ambient conditions. J. Am. Ceram. Soc., 42: 582.

Nelson, R.A. and Stearns, D.W., 1977. Interformational control of regional fracture orientations. Rocky Mount. Assoc. Geol. Symp., pp. 95–101.

Parker, III, J.M., 1942. Regional systematic jointing in slightly deformed sedimentary rocks. Geol. Soc. Am. Bull., 53: 381–408.

Roberts, J.C., 1961. Feather-fracture and the mechanics of rock jointing. Am. J. Sci., 259: 481–492.

Scholz, C.H., 1972. Static fatigue of quartz. J. Geophys. Res., 77: 2104–2114.

Secor, Jr., D.T., 1969. Mechanics of natural extension fracturing at depths in the earth's crust. Proc. Conf. Res. Tectonics, Geol. Soc. Can., 68-52: 3–48.

Sheldon, P., 1912. Some observations and experiments on joint planes. J. Geol., 20: 53–79.

Stearns, D.W., 1968. Certain aspects of fracture in naturally deformed rocks. In: R.E. Riecker (Editor), NSF Adv. Sci., Seminar in Rock Mechanics, Spec. Rep., Air Force Cambridge Res. Lab., Bedford, Mass., pp. 97–116.

Syme-Gash, P.J., 1971. A study of surface features relating to brittle and semibrittle fracture. Tectonophysics, 12: 349–391.

Woodworth, J.B., 1896. On the fracture system of joints, with remarks on certain great fractures. Boston Soc. Nat. Hist. Proc., 27 (1): 63–183.