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Characteristics of joint propagation across layer interfaces in sedimentary rocks

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Abstract—Interfaces between dissimilar layers play a fundamental role during joint propagation in layered sedimentary rocks, limiting the vertical extent and physical continuity of joint traces. Joints do, however, communicate across interfaces between dissimilar layers, forming an overall composite joint, which is the collection of vertically aligned but discrete joint segments. Detailed fractographic analysis of the surface features of these segments reveals several characteristics of the incremental propagation of a composite joint in the alternating siltstone and shale turbidite sequence of the Genesee Group of the Appalachian Plateau, central New York. (1) Joint segments confined by interfaces are arranged in-plane with each other in a sequential manner for layers of similar properties. (2) Out-of-plane arrangement is common for propagation across thin or discontinuous inhibiting layers. (3) Thick inhibiting layers do not allow communication among joints occurring in adjacent layers above and below. (4) If the thick inhibiting layers fractured, usually these joints initiate at the tip of a pre-existing joint, in an adjacent layer, and propagate away with a slightly different orientation. An analysis of the maximum principal stress in an unjointed layer, due solely to a joint in an adjacent layer, separated by a thin resistant layer, provides a conceptual basis for understanding the incremental nature of composite joints and their step-like geometry.

INTRODUCTION

JOINTS, one of the most common deformational features of sedimentary rocks, have been the focus of numerous studies by both geologists and engineers. Several workers have pointed out that layer interfaces disrupt joint propagation, or that joints are selectively confined to certain lithologies, commonly with differing orientations and spacings (Shelton 1912a,b, Parker 1942, Price 1959, Hodgson 1961b, Nickelsen & Hough 1967, Engelder & Geiser 1980). However, the actual kinematics of joints propagating across interfaces between similar and dissimilar rocks needs further study. In this paper, we document the behavior of individual joints near layer interfaces, as well as the interaction and communication among joints in different layers, primarily by analyzing the diagnostic surface features in the sedimentary rocks of the Appalachian Plateau, near the Finger Lakes, central New York, and by modelling joint propagation across similar and dissimilar layers.

The motivations for this study are manifold. First, physical continuity of joints from one layer to another has a profound effect on oil, gas, water and contaminant migration. Therefore, a better understanding of the three-dimensional connectivity of joint systems in layered rocks can provide economical and practical benefits. Second, a change of orientation and spacing of joints in adjacent layers can be better understood by delineating the interrelationship between joints in different layers by documenting the order of formation and the propagation direction of these joints. The latter objective is relevant for inferring the state of stress from joints, which is a common practice by geologists and geophysicists. Third, for more than a century, the spectacular joint system of the Appalachian Plateau has been the focus of many intensive studies, often with controversial results. One controversy has to do with the interpretation of the different orientation of joints in adjacent layers of differing lithology. Although this particular problem will be addressed in a follow-up paper, here it suffices to say that a better documentation of joint propagation across interfaces between these layers should provide new constraints on the existing hypotheses on the origin of joints with different orientations.

Joints of the Appalachian Plateau

In the Appalachian Plateau, near the Finger Lakes region, central New York (Fig. 1), a well-developed joint system has attracted the attention of geologists at least as

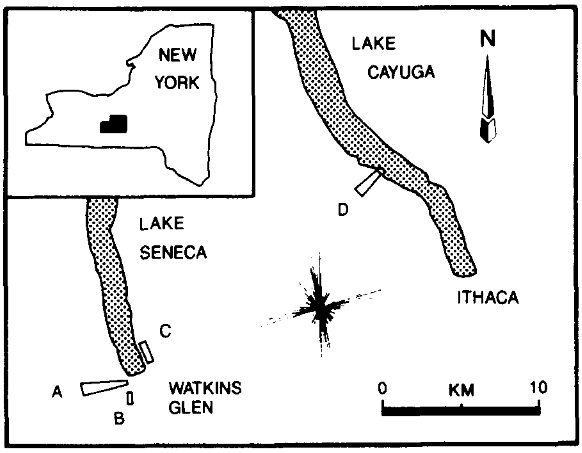


Fig. 1. Location of study area in New York State (inset) and the specific outcrop sites used for field observations. A, Watkins Glen State Park; B, roadcut along Route 14 just south of Watkins Glen; C, roadcut along Route 414 just east of Watkins Glen and Lake Seneca; and D, Taughannock State Park.

far back as the middle 19th century. Hall (1843) recognized most of the features of joints that still capture the attention and inquiry of many present day observers, such as the control of drainage patterns and erosional cliffs by joints. Hobbs (1905) correlated the observed drainage patterns of the entire Finger Lakes region with those of joint orientations at several localities around Cayuga and Seneca Lakes. Shelton (1912a) focused her study on small-scale areas around the southern portion of Lake Cayuga, where she collected a large amount of joint orientation data. Based on these data, she grouped the joints into distinct sets and correlated them with local folding. Parker (1942) also measured joint orientations throughout central New York and combined many small-scale observations from different locations to develop a picture of the regional joint system. Parker concluded that the joint system was formed as two conjugate sets of shears and a set of tension joints, independently of, and earlier than, the folds and faults. This interpretation was based on geometric similarities with experimentally-formed conjugate fractures (Daubree 1879) and theoretical ideas popular at the time (Bucher 1920). Nickelsen & Hough (1967) disputed the conjugate shear concept by identifying the nature of displacement across joint sets in the central Appalachians, and invoked the idea of overlapping joint domains to explain the observed joint pattern as the cumulative record of multiple jointing episodes.

Engelder & Geiser (1980) and Engelder (1985) used the joint orientations of the region for inferring paleostress fields and produced a dynamic and kinematic model for the evolution of the New York Plateau. Bahat & Engelder (1984) classified joint surface features and noted a difference between the characteristics of joint sets that are parallel to fold axes (strike joints), and at a high angle to fold axes (cross joints). Engelder (1985), Engelder & Oertel (1985) and Evans *et al.* (1989) provided data on the mechanical condition of the shales and siltstones of the Appalachian Plateau and used this information to justify the limits, orientations and ages of the joint sets and the associated stress systems. Engelder & Lacazette (1990) have investigated the role of natural hydraulic fracturing for the formation of joints in the Appalachian Plateau. Thus, it is quite apparent that the joint system of the Appalachian Plateau has attracted a great deal of attention from many points of view, and for many years.

Surface morphology of joints

The surface morphology of joints provides a unique record of the kinematics of joint growth, from initiation to subsequent propagation and ultimate arrest. Additionally, interaction with bedding interfaces and other joints may also be described by mapping and analyzing the limits and pattern of joint surface features. These unique features of joint surfaces in rock have been documented and classified in the geologic literature for many years (Woodworth 1896, Hodgson 1961a, Roberts 1961, Bankwitz 1965, Kulander *et al.* 1969, Bahat & Engelder 1984, Kulander & Dean 1985, DeGraff & Aydin 1987; see Pollard & Aydin 1988 for details). The experimental basis of similar features is found in the engineering literature (Preston 1929, Murgatroyd 1942, Kies *et al.* 1950, Sommer 1969, Frechette 1972).

The most fundamental features of a joint surface include an initiation point and the associated hackle, which have been collectively termed a *plumose structure.* In the layered siltstone and shale of the Appalachian Plateau, the initiation points are almost always located at bedding interfaces, or more specifically, at fossil inclusions, pyrite concretions, voids, cusps, flute casts, and burrows along the bedding interfaces. Hackle, the linear topographic features formed parallel to the local propagation direction, and perpendicular to the joint front, are remarkably well developed on these fine-grained rocks. For example, Fig. 2(a) shows a photograph of a single joint formed in a single siltstone bed. The initiation point, located by following converging hackle lines toward a common point, occurs at a cusp along the lower interface with shale. From a hackle pattern, successive joint fronts can be reconstructed graphically (Kulander *et al.* 1979, Kulander & Dean 1985, DeGraff & Aydin 1987). This is shown in Fig. 2(b) for the same joint in Fig. 2(a) by marking equal, but arbitrary, increments from the initiation point to the top of the siltstone bed and drawing curves that start at the marks and remain perpendicular to the hackle lines everywhere. Producing successive joint fronts in this manner reconstructs the growth kinematics of this joint. The resulting pattern can then be analyzed using the principles of fractography to elucidate the kinematic history of jointing and to interpret certain mechanical conditions during joint growth. That is, the joint in Fig. 2 initiated at the bottom of a siltstone layer, at a cusp, and propagated vertically upward and laterally outward. Upon reaching the upper interface with shale, further vertical propagation was inhibited. Notice that the plume axis, the line from which hackles diverge, results from the distortion of the joint front from a circular arc to one that is elliptical. Propagation then proceeded laterally in both directions until conditions for joint propagation were no longer met.

Following DeGraff & Aydin (1987) and Aydin & DeGraff (1988), who used this simple but powerful technique for studying the incremental growth and sequential lateral development of columnar joints in volcanic rocks, we shall employ this technique to determine fundamental characteristics of joint propagation across interfaces between dissimilar layers in sedimentary rocks.

FIELD OBSERVATIONS

The specific study area includes outcrops situated around the southern tip of Lake Seneca and along Taughannock Creek, near Lake Cayuga (Fig. 1). These sites are especially well suited for this study, because joint surfaces are well exposed and preserved. Our

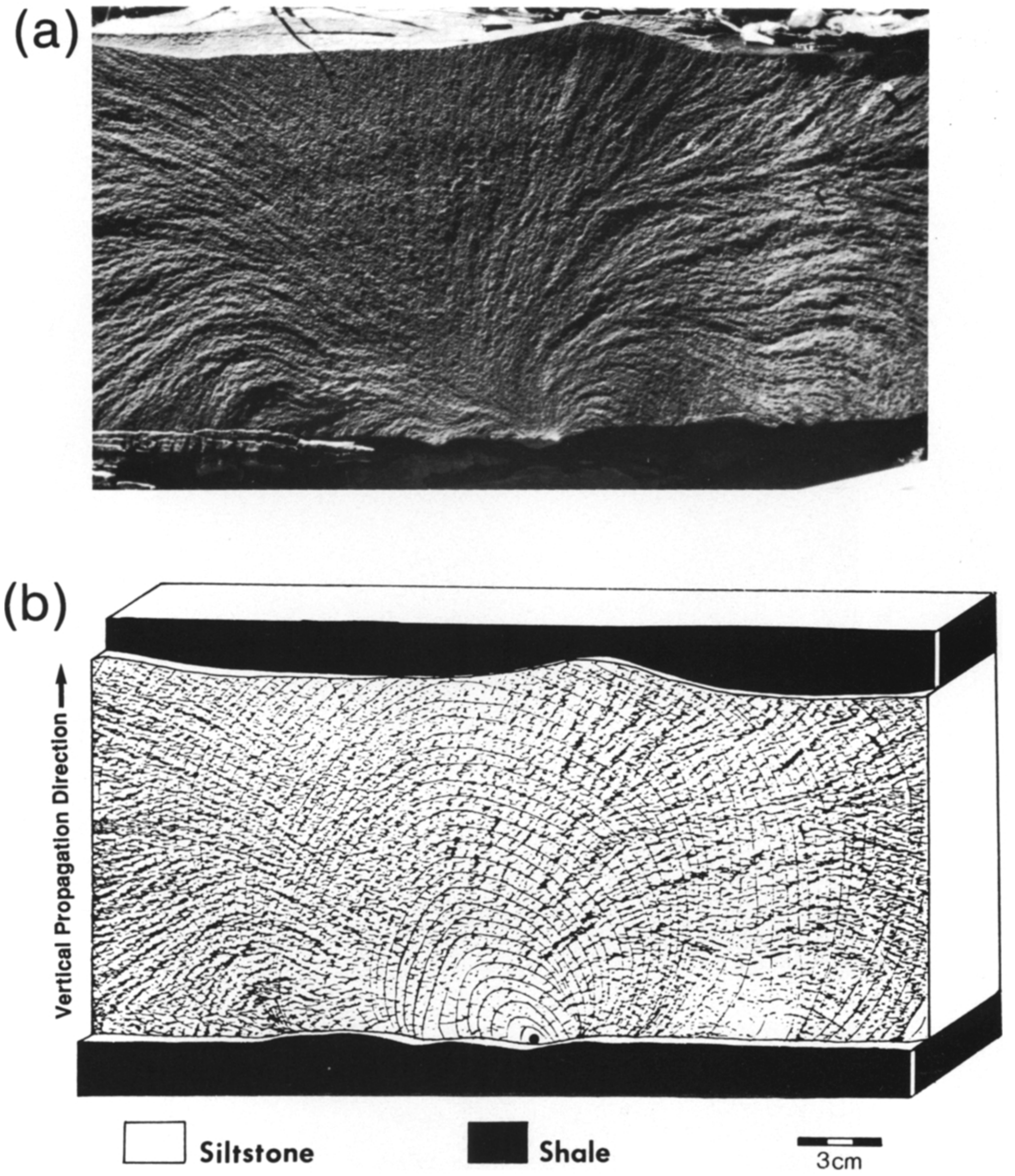


Fig. 2. Single plumose patterns and the reconstruction of joint fronts from the observed hackle patterns. (a) Photograph of a joint confined to a siltstone layer. (b) Graphic representation of the same joint with the characteristic surface features highlighted. Shown here is the initiation point (dot) at a lower cusp, and the associated hackle (dark discontinuous lines). Joint fronts were reconstructed by drawing continuous curves that remain everywhere perpendicular to the hackle. Each new front was equally, but arbitrarily, incremented along the plume axes.

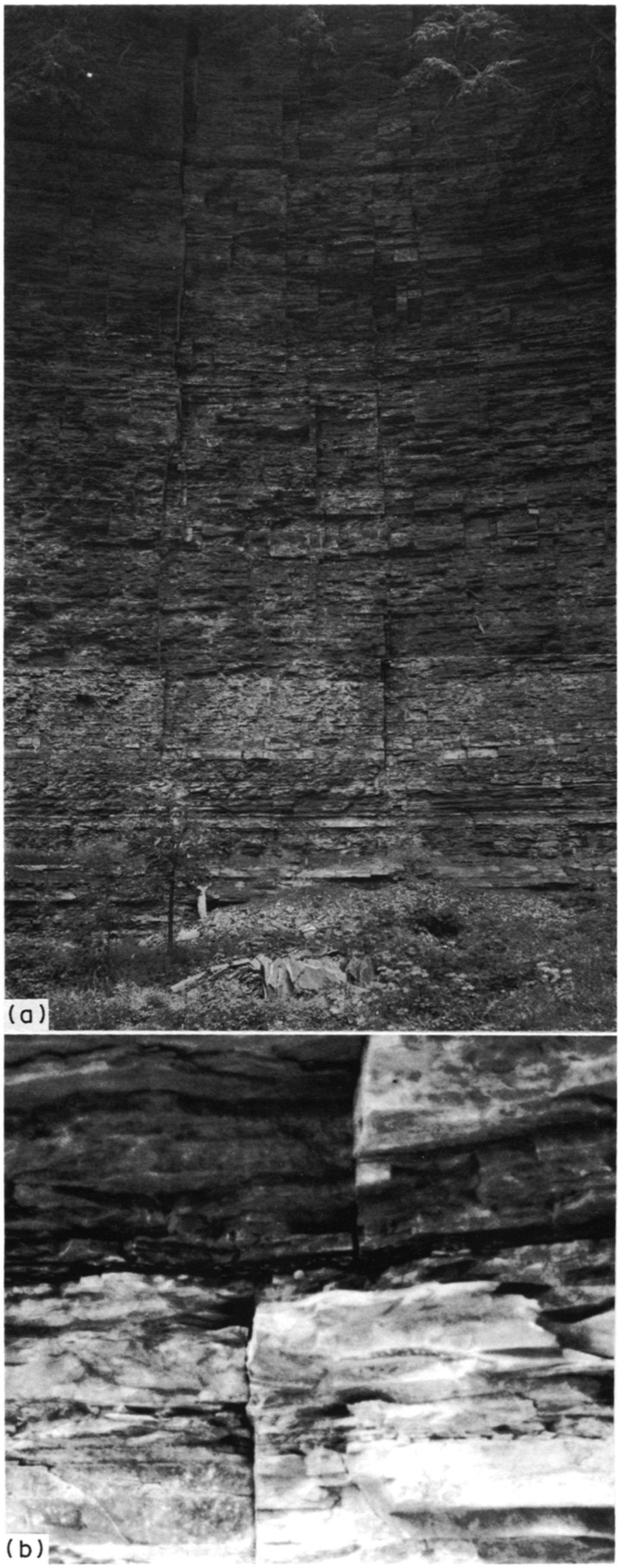
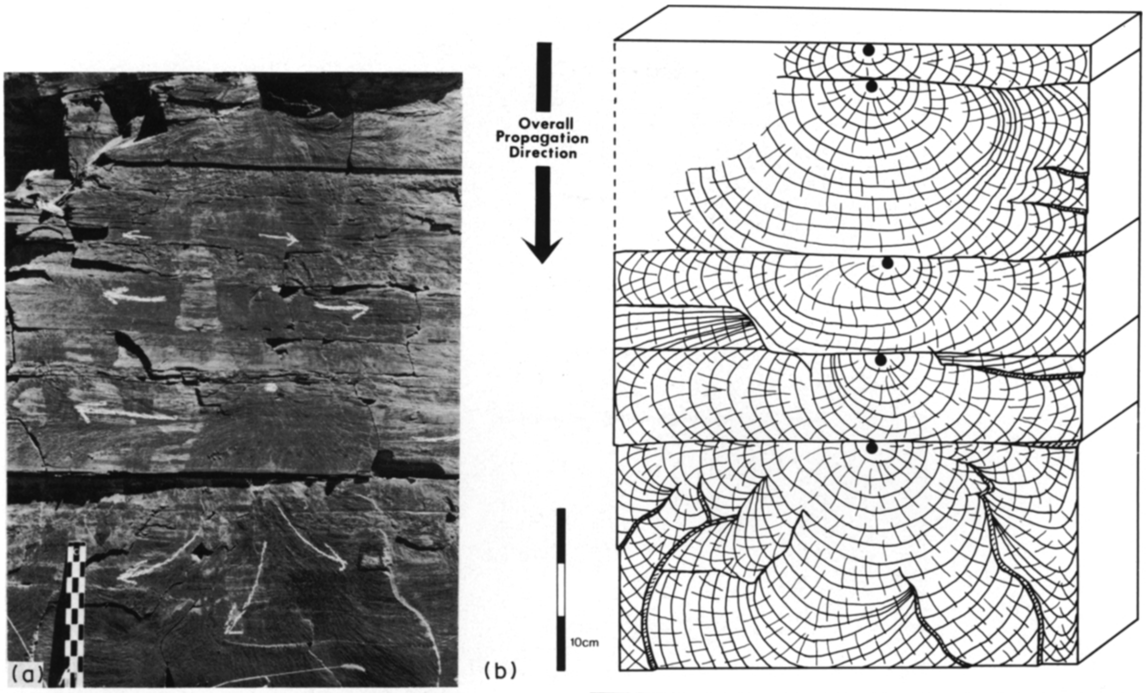


Fig. 3. (a) Along strike (profile) view of vertical joints in the alternating siltstone and shale turbidite sequence within the Ithaca Formation of the Genesee Group. Note that the large apparently throughgoing vertical joint traces appear to be discontinuous, and the discontinuities appear to coincide with bedding interfaces. Height of cliff face is 60 m. (b) Close-up view (0.5 × 0.5 m) of joint discontinuity across a thin shale layer.



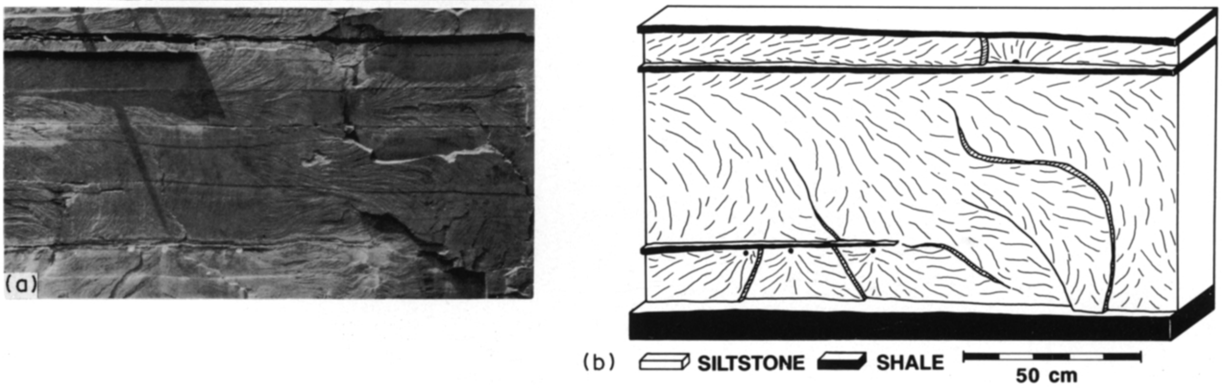


Fig. 4. (Top.) Composite joint in several siltstone layers. (a) Photograph of the outcrop face. Some features are highlighted by chalk. (b) Graphic representation of the same surface, showing the initiation points, hackle traces, and reconstructed joint fronts. Symbols used are explained in Fig. 2. Each individual siltstone layer has its own plumose structure, indicating independent fracturing of each layer. Note the vertically aligned, in-plane arrangement of the individual joint segments. Also, note the vertical alignment of the initiation points, which are all located at the top of each layer and, furthermore, are consistently placed where an above-approaching joint first intersects the next layer. This implies an overall systematically downward propagation of this composite joint.

Fig. 5. (Bottom.) Influence of a shale lens on joint propagation in siltstone. (a) Photograph of outcrop. (b) Schematic drawing. On the left, downward joint propagation in siltstone is inhibited by the discontinuous shale lens. New joints initiate just below the shale lens (dots). On the right-hand side, joint propagation in siltstone proceeds past the extension of the shale lens to the right, until the next inhibiting shale layer is met.

(a)

(b)

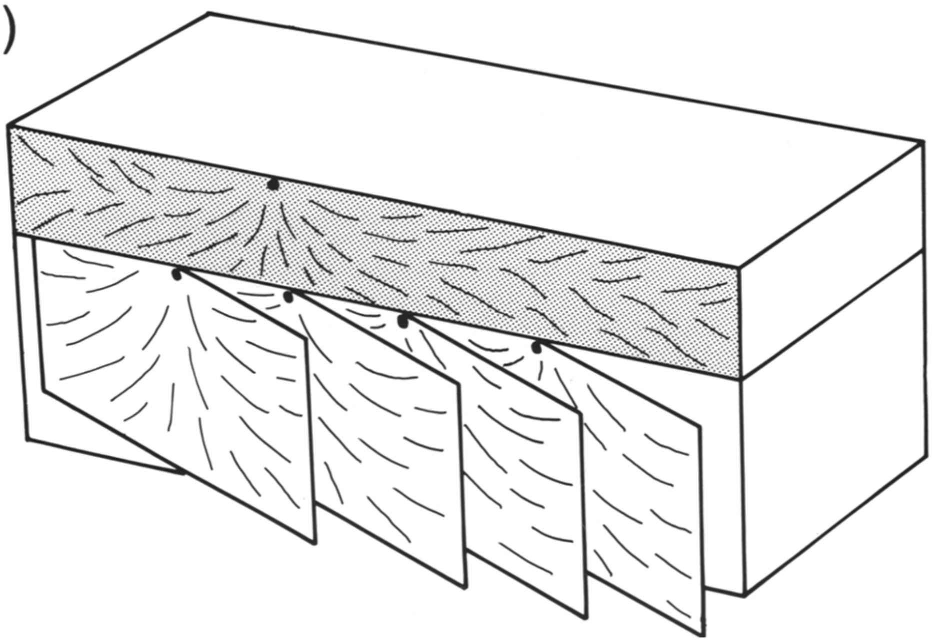


Fig. 6. Non-planar addition of new joints. (a) Photograph of a pre-existing joint in siltstone with many joints initiating at its lower tip in shale, each with a different strike. This angular difference is an important difference as compared to the previously described parallel cases. (b) Schematic drawing of the associated surface features. Joint propagation in siltstone (Ss) is predominantly horizontal, left to right, whereas all joints in shale (SH) show downward propagation.

detailed observations were made in the alternating siltstone and shale turbidite sequence within the Ithaca Formation of the Genesee Group. Although many joint sets exist in this region, the following observations are from the set of cross joints (Sheldon 1912a, Parker 1942, Nickelsen & Hough 1967, Engelder & Geiser 1980), which are N- to NW-striking and nearly perpendicular to the local fold axes. Since this joint set is the oldest set in the area, its formation is not influenced by other joint sets; i.e. the strike joint set.

Figure 3 shows several vertical joints in profile as they are manifest in the Watkins Glen State Park. This perspective view is parallel to the strike of the joints. The most remarkable feature of the vertical trace geometries is that they appear to be continuous in siltstone layers, whereas they are discontinuous across shale layers. That is, individual joints are confined to siltstone layers and are inhibited by thin shale layers. In spite of the discontinuities along vertical joint traces, however, they are well aligned in a vertical sense. Thus, the vertically stacked collection of distinct joint segments, forming an overall composite joint, implies a communicative mechanism for the formation of these adjacent segments of joints in layered rocks having dissimilar properties.

In order to understand more fully the process of formation of the large composite joints and the mechanical communication between joint segments in adjacent layers, it is necessary to document the surface features associated with composite joints. With this information, it is possible to establish a relationship between the kinematics of joint propagation in layered rocks and the resultant vertical trace geometry. We will now present specific examples of composite joint surface features with patterns that range from the simple to more complex, in terms of joint discontinuity and lithologic variation.

Figure 4(a) shows a simple case of a composite joint in a stack of siltstone layers of similar mechanical properties. The layers are partitioned by thin interfaces, most likely thin shale films. The vertical trace, shown by the three-dimensional block perspective (Fig. 4b), is well aligned in a vertical sense, suggesting a mechanical communication between discrete joint segments during propagation. This communication becomes remarkably clear, but only after detailed mapping of the joint surface features. Joint segments confined to each siltstone layer have their own initiation points and associated hackle (Fig. 4b), indicating that each layer fractured separately. Furthermore, the initiation points are positioned at the top of the respective siltstone layers and are well aligned vertically, suggesting sequential initiation and propagation. Reconstructing joint fronts (Fig. 4b) clearly shows why the initiation points are so systematically arranged. The origin of each joint segment is located at a point in the adjacent siltstone just across from the point of first contact between the upper joint and a thin inhibiting interface. Joint propagation in the upper layer is inhibited by the interface and, consequently, a new joint segment initiates across the interface. Hence, for this particular case, it can be concluded that the overall propagation direction is from top to bottom, and that the first formed joint determines the position of the subsequent increments, thus providing a rationale for the consistent alignment of the observed traces in profile view.

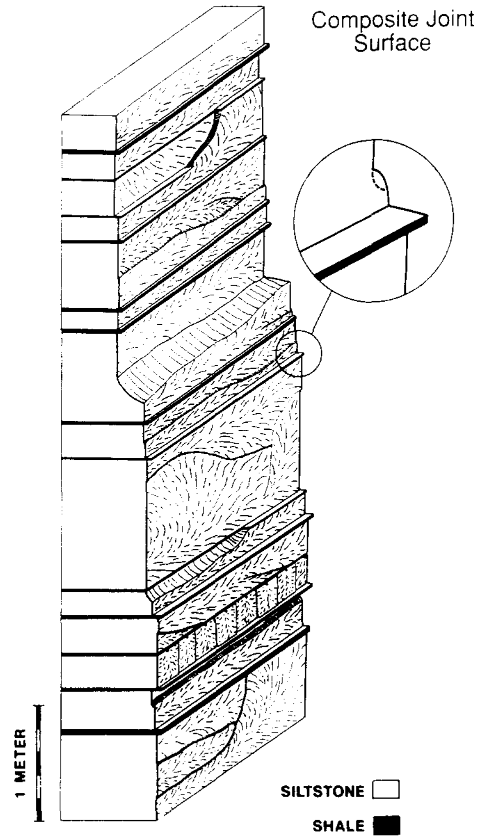


Fig. 7. Large composite joint surface where the inhibiting shale layers are thicker than in Figs. 4 and 5. The siltstone layers are individually jointed, as indicated by each layer having its own plumose structure. Note that the joints in adjacent siltstones are out of plane with each other, giving the overall vertical joint trace a discontinuous character. Compare this trace to those traces shown in Fig. 3(a), whose surface features would be expected to be similar to this case.

To illustrate the influence that an observable shale unit has on joint propagation in siltstone, Fig. 5 shows the hackle pattern in siltstone around a discontinuous shale lens. Here, joint propagation is continuous in the siltstone at the right past a projected extension of the lens from the left to the right. At the left, joint propagation is discontinuous across the shale lens above and below. The joint approached the shale lens from the top and terminated against it. Several new joints below the shale lens initiated in the next siltstone. As the shale lens pinched out, vertical propagation proceeded without interruption. Eventually, all joint segments in the siltstone layers truncate at the bottommost shale layer. It is interesting to note that joint propagation is not only kinematically discontinuous across the shale lens, but also that the segments above and below the lens are not in plane; the joints in the lower siltstone are oriented slightly clockwise from those above.

Figures 6–9 show larger scale examples where both the shale thickness and lateral offset of the vertical trace geometry have increased. Figure 7 was produced by mapping the surface features within individual siltstone

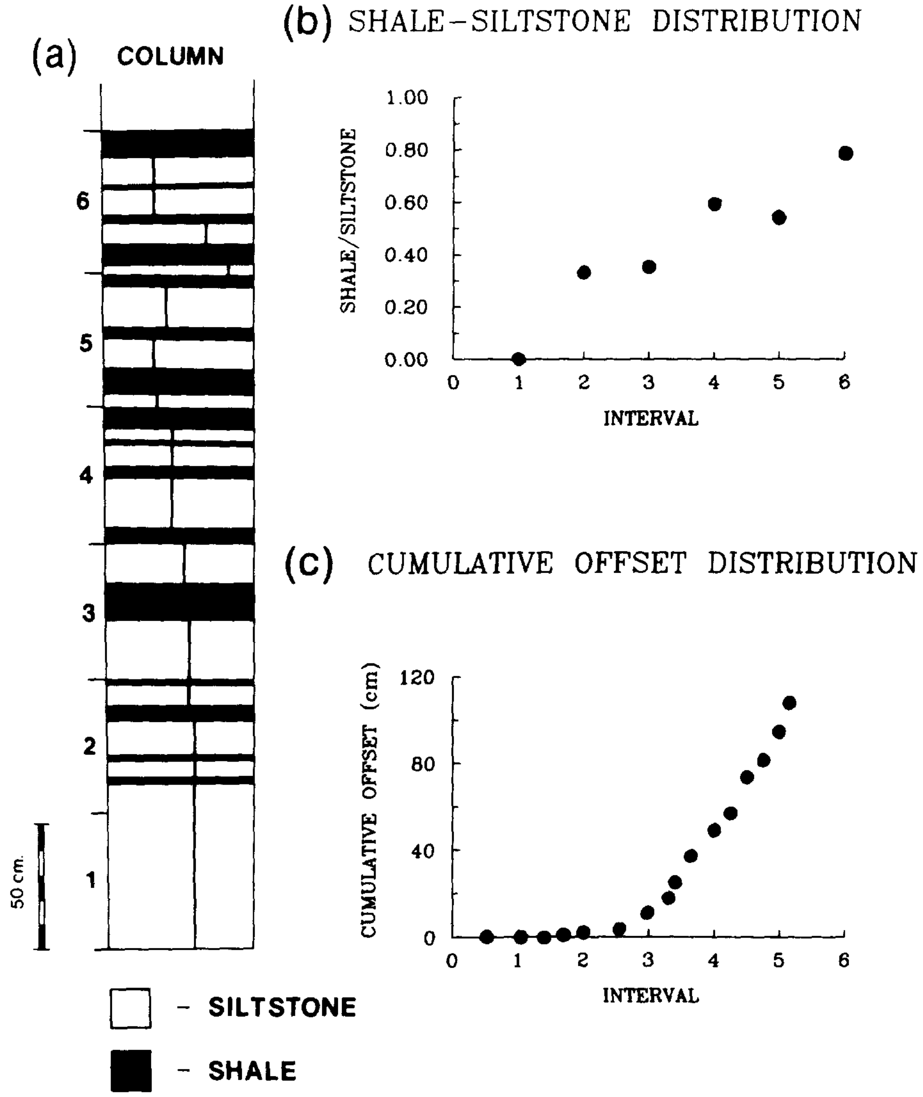


Fig. 8. Relationship between shale thickness and joint offset. (a) Column showing a joint trace measured through a section of siltstone and shale. (b) Plot showing ratio of shale to siltstone in six arbitrary sections making up the column. (c) Graph showing the tendency for increased offset upward through the column, which corresponds to increased shale/siltstone ratio. Although the relationship is not exactly linear, a systematic trend is observable.

layers and measuring the thickness and trace offsets as they appear in the field. Again, each individual siltstone is separately jointed and the vertical alignment of all joint segments is still quite good. Lateral propagation of joints in siltstone is parallel to the interfaces and proceeds from left to right. The overall vertical propagation direction of this composite joint is undetermined due to the physical dimensions of the outcrop, but the individual siltstone layer positioned third from the bottom contains several joints with initiation points consistently placed at the top, which suggests downward propagation. This, together with the notion of a consistent overall propagation direction for a composite joint, many provide evidence for overall downward propagation of this entire composite surface.

Another characteristic, illustrated in Fig. 7, is that the joint traces are not particularly well aligned in a vertical sense, as was the case in Fig. 4. That is, the joints in siltstone are still remarkably well stacked in a vertical plane, but the out-of-plane offset between parallel joints in siltstone across shale is greater than that for the previously documented cases where the shales were lensoidal or very thin (Figs. 4 and 5). This implies that, as the thickness of inhibiting shale layers increases, the degree of the communication among joints across shale decreases, causing an overall deterioration of the composite joint. However, as shown in Fig. 8, there is not a consistent relationship between the thickness of the shale unit and the amount of offset. One of the reasons for the apparent lack of consistency is the fact that individual segments can further diverge from the plane of the previous segment during lateral propagation. Therefore, profiles away from the initiation points of the segments may show offsets that are different from those around the initiation points. In any case, offset of composite joints across shale layers deserves attention and will be the subject of a theoretical model and more in-depth discussion in a later section. Referring back to Fig. 3, the large joints that appear to be throughgoing should be expected to contain discontinuous surface features similar to those shown in Fig. 7.

As the inhibiting shale layers approach thicknesses to about equal or greater than that of siltstone, there does not seem to be any recognizable alignment among joints

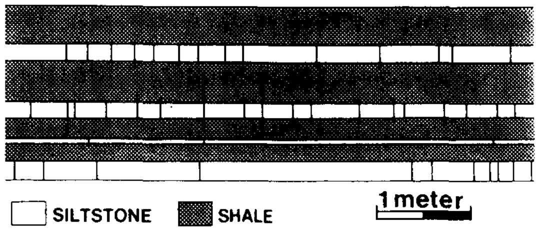


Fig. 9. Misaligned joint traces indicating no apparent communication between joints in siltstone across thick shales. Shown is a profile view of joints in several siltstone layers, separated by relatively thick shales. The composite nature of jointing is apparently lost, with joint alignment only random.

in siltstone. Figure 9 shows a profile view of a sequence containing relatively thick shale layers separating several siltstone layers. Here, alignment of joints in siltstone across shale is apparently only coincidental based on the density of the joints in thin siltstone layers. This suggests that joints in each layer formed independently, and that thick shale layers can entirely inhibit the formation of composite joints.

Thus far, we have described cases where the addition of new joint segments are approximately parallel with those previously formed. They may form parallel with in-plane addition or parallel with out-of-plane addition, depending on the geometry and the nature of the interface and the inhibiting layer. A case in which additional joint segments are not parallel to those in adjacent layers occurs frequently in the Finger Lakes region. Figure 6(a) shows that a joint in siltstone is connected to several joints in shale, which makes a small angle to the former. Detailed surface features show that the initiation points for those joints in shale are located by the lower edge of the joint in siltstone. Figure 6(b) shows a schematic drawing of this relationship. It should be noted that this geometry is distinctly different from border or fringe joints (Woodworth 1896, Bankwitz 1965, 1966), which are a continuous transition from a parent joint to a series of non-parallel smaller joint segments with a small angle difference. In the case shown in Fig. 6, the non-parallel joints confined to shale are independently initiated along the vertical extent of the joint confined to siltstone, indicating a discontinuous process. This relationship provides unambiguous evidence for the age of joints in shale as being younger structures, as well as for a local state of stress in shale different from that of the neighboring siltstone layer.

The field observations can be summarized to four points. (1) The propagation of an overall composite joint is an incremental process. (2) Joint segments are commonly confined to siltstone layers. (3) The trace geometry depends on inhibiting shale layer thickness; that is, the vertical trace is well aligned when the shale layers are absent or thin, and deteriorates as the thickness of shale layers increase until finally there is no longer a communication among joints in siltstone. (4) If the thicker shale units are jointed, the joints within the shale initiate at the tip of pre-existing joints in siltstone, commonly with a different orientation from those in the adjacent siltstone.

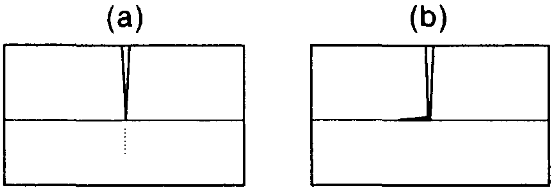
THEORETICAL ANALYSES OF JOINT PROPAGATION ACROSS INTERFACES

The foregoing account of the influence of interfaces on joint propagation in sedimentary rocks composed of siltstone and shale layers lends itself to several interesting problems that are analogous to those of fracture mechanics of composite materials. In this section, we attempt to highlight the pertinent concepts developed in fracture mechanics for composite materials, and to use these concepts for a better understanding of the kinematic models established from the field observations documented above. Basically, there are three elements that are crucial in fracturing across interfaces: (1) strength of the interface; (2) geometric and material properties of the layers on either side of the interface; and (3) loading.

A strongly bonded interface between similar layers is not likely to fail and, consequently, an approaching joint would continue in some form across the interface (Fig. 10a). However, a weak interface is prone to fracture along the interface (Fig. 10b). It is hard to evaluate the strength of interfaces between shale and siltstone. Although, at the present time, the interfaces appear to be less resistant to erosion, we have found no significant evidence that the interfaces failed by either jointing or faulting, with the exception of some horizontal hydrofractures, which are younger than the joint set considered in this paper.

Two parameters of material properties, Young's modulus and fracture toughness, can influence joint propagation. For strongly bonded interfaces, the role of differing Young's moduli of different layers on joint propagation should be considered in two stages that have markedly different results. The first stage covers the period prior to a joint tip reaching an interface, and the second is relevant to the case in which a joint tip resides at the interface. Figure 11 (after Erdogan & Biricikoglu 1973) shows that if the layer on the other side has a higher Young's modulus than that of the layer with the joint ($E_1 < E_2$), strain energy decreases as the joint tip approaches the interface, and, thus, propagation will be impeded: for the opposite ($E_1 > E_2$) it will be enhanced. If the moduli are the same ($E_1 = E_2$), there is no effect on joint propagation.

However, if one compares the stresses corresponding to the three cases, with the joint tip residing at the interface, the results are seemingly different, as shown in Fig. 12 (after Cook & Erdogan 1972). Here, the



Strong Interface **Weak Interface**

Fig. 10. Behavior of two types of interfaces between similar materials. (a) Strong interfaces; joint path is continuous. (b) Weak interface; joint path is deflected along an interface that failed.

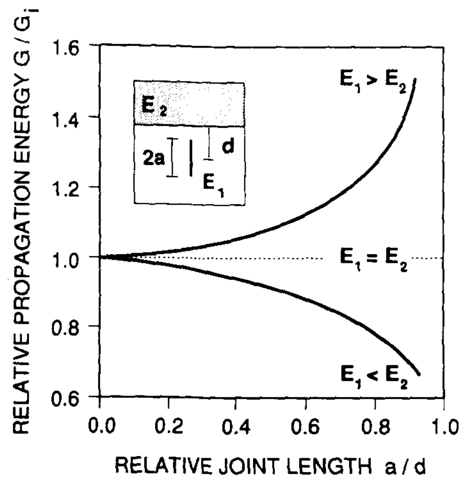


Fig. 11. Relationship between propagation energy of a joint and its proximity to a layer with different Young's modulus (as shown by inset). For a joint in a less stiff material approaching a more stiff material, the propagation is increasingly impeded, whereas the converse is evident for a joint in a more stiff material approaching a less stiff material. (Redrawn after Erdogan & Biricikoglu 1973.)

concentration of the angular component $(G_{\theta\theta})$ of the circumferential stress, $\tau_{\theta\theta}$, at the joint tip is higher in the adjacent layer with a higher modulus $(E_1 < E_2)$, and vice versa. Note also the maximum stress concentration occurs across a plane in the extension of the joint and perpendicular to the interface $(\theta = 0)$.

Combining these two sets of relationships, it can be concluded that strain energy associated with a joint approaching an interface with a layer with a higher modulus would decrease somewhat (see, for example, Abou-Sayed *et al.* 1977, Anderson *et al.* 1978). Additional energy is needed to drive the joint to the interface. As soon as the joint tip reaches the interface, the strain energy should increase proportional to the ratio of the moduli, the maximum corresponding to in-plane extension of the joint. The reverse scenario can be extracted for a case with a moduli ratio opposite to that considered above.

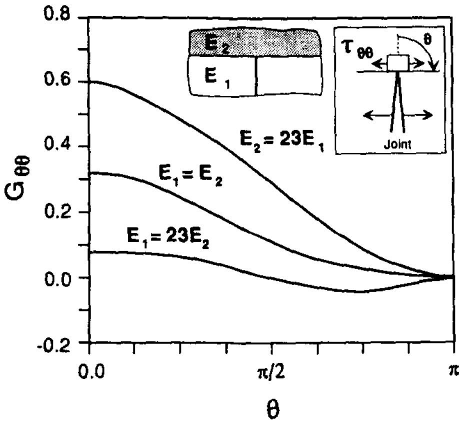


Fig. 12. Variation of angular component $(G_{\theta\theta})$ of circumferential stress $(\tau_{\theta\theta})$ around a joint tip residing at the interface (as shown by inset) for a plane strain case. For all cases of relative Young's moduli, the maximum circumferential stress is associated with a geometry perpendicular to the interface $(\theta = 0^\circ)$. Three curves corresponding to three arbitrary ratios of the moduli, $E_2/E_1 = 23$, 1 and 1/23 show that increasing ratios result in higher stress concentration. (Redrawn after Cook & Erdogan 1972.)

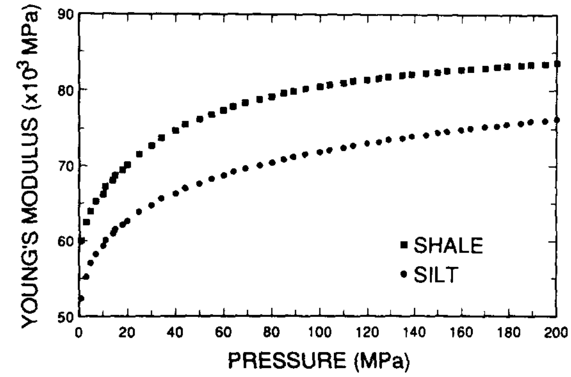


Fig. 13. Plot showing the calculated Young's modulus at changing confining pressures. Pressures reach 200 MPa, corresponding to 6 km depth, the greatest depth hypothesized for the Genesee Group.

As far as joint propagation is concerned, the most crucial material property is the fracture toughness of the layers in consideration. Obviously, higher fracture toughness offers higher resistance to jointing. Values of fracture toughness for the siltstone units of the Ithaca Formation are available in the literature (Engelder & Lacazette 1990), but unfortunately not for shale, partly because it is difficult to prepare intact samples from shale for laboratory testing. However, based on field observations that many joints in siltstone stop at shale interfaces and shale samples have higher Young's moduli than siltstone (Fig. 13), which would enhance joint propagation into shale, as discussed earlier, we may infer that the shale layers of the Ithaca Formation had a higher fracture toughness during jointing. If so, then joint terminations at shale interfaces are consistent with the basic premise of fracture mechanics.

We now turn to a follow up question as to why various fracture segments are aligned fairly well to form a composite joint. The field observations described above suggest the existence of some degree of communication between a segment on one side of a thin shale layer and another segment on the other side. It is also reasonable to hypothesize that the basis of this communication is probably some degree of transfer of stresses associated with the joint tip through the impeding shale layer. How much stress transfer takes place without dissipating in the interlayered shale probably depends on the strength of the interfaces, and the stiffness and thickness of the shale layer. This qualitative analysis, however, does not quite explain the offset geometry of sidestepping segments. An analysis of stress concentration in a second layer on the other side is required in order to test this hypothesis. We used a finite element method to determine the magnitude and distribution of the maximum principal stress due to the existence of a joint tip on the other side of an impeding shale layer.

Finite element model

The finite element model used is called STRIDYN (Doyle 1989), and is based on standard finite element techniques (Bathe 1981). The specific model geometry is shown in Fig. 14. The grid-patterned area represents the

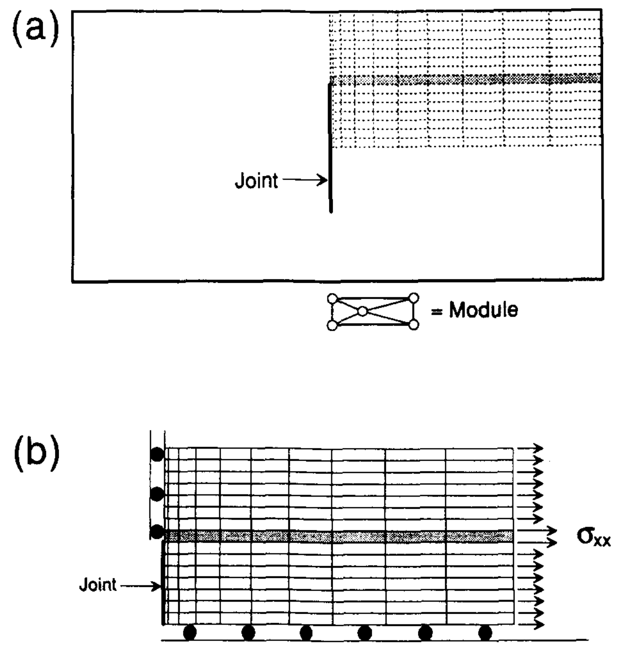


Fig. 14. Finite element model geometry. (a) Shown is a joint, whose upper limit is just at the bottom of a thin layer (shaded). The array of rectangles are the individual modules, which are divided into four triangles, in which a constant displacement is forced. At the nodal points, shown by open dots around the enlarged module, displacements are found, and thus all stress conditions. The overall border indicates the region in which symmetrical results can be assumed from the gridded area only. (b) Boundary and loading conditions applied. Applied stresses vary proportional to the Young's moduli, so as to ensure constant displacement across the layers. Boundary conditions are assigned to ensure the proper Mode-I (joint) symmetry. Solid circles are rollers representing free motion along specified planes.

area of calculation. Each rectangular module is composed of four triangular elements, formed by diagonals between the corners. Within each triangular element, stresses are calculated and translated to the nodal points, which are located at the vertices of adjacent triangles. The resultant pertinent values can then be processed.

Appropriate values for material properties, Young's modulus and Poisson's ratio, to assign to the layers, were obtained by analysis of longitudinal and shear wave velocities at changing confining pressures. We used Christensen's rock physics laboratory, thus for the procedure we refer the reader to Christensen 1985. Figure 13 shows the averaged Young's moduli for three cores from the siltstone and shale samples of the Ithaca Formation at increasing confining pressures, corresponding to 0–6 km depth. Comparing the two curves in the graph, it is easily concluded that the Young's modulus for the shale is 15% higher than that of the siltstone in the range of the experiment. The Poisson's ratios were basically the same for each sample, about 0.18. The properties used in the finite element model retain the measured differences in Young's moduli and equal Poisson's ratio. We should note that this is probably the lower end of the difference between the shale and siltstone members because the shale sample is probably not pure, and in fact, what is referred to as shale may actually be finer grained siltstones (Oertel *et al.* 1989).

Figure 15(a) shows contour diagrams of the magnitudes of the maximum principal stress, normalized by that of the background values (the stress values in layers without a joint), in the above unjointed layer at three different positions of the approaching joint with respect to the lower interface. If no joint were present in the lower layer, the normalized stresses everywhere in the above layer would be the same. Thus, the patterns that emerge in Fig. 15(a) are due solely to the presence of the joint in the lower layer.

The maximum principal stress is transmitted through the thin high modulus layer in such fashion as to produce two zones of high stress concentration, each symmetrically out of plane from that of the joint in the lower layer. It is within, or near, these two zones that new joints would most likely initiate, once the level of critical stress for that layer is reached. The actual initiation point would depend on the geometry of flaws along the interface as well as loading. That is, the flaw with the most favourable size, shape and orientation together with stress concentration due to an approaching joint, determines where the next joint segment initiates. STRIDYN can also be used to locate the point where the maximum principal stress is the greatest. These maxima positions, which are along the upper interface, are shown in Fig. 16 for some cases as the joint approaches the interface. Figure 16 shows that the position of the two symmetric maxima comes closer to the plane of the lower joint, but never lies directly above the joint. As shown in Fig. 15(b), the orientation of the maximum principal stress planes are nearly perpendicular to the interface, the largest divergence being about 7° nearest to the joint when the joint is closest to the interface.

The same basic concepts hold true for the case where the interlayer has a lower Young's modulus. There exist two symmetric regions of high stress concentration and as the joint approaches the interlayer, the high stress regions move inward toward the plane of the joint, but do not lie directly above the joint. The differences are that the intensity level of maximum principal stress is enhanced by the low modulus interlayer, the actual point of highest maximum principal stress is closer to the plane of the joint, and the orientation of the maximum principal stress deviates more from vertical than in the case with a higher modulus interlayer.

Thus, the main conclusion we derive from the modelling is that the highest stress first occurs out of the plane of the approaching joint at two symmetric regions in the layer ahead of the joint. Based on a maximum tensile stress criterion, a new joint would initiate when the maximum critical tensile stress is reached for the particular layer. Propagation of this newly formed joint in one of these two regions would continue upward in a direction nearly perpendicular to the layer as far as the next inhibiting layer. This incremental process would continue, layer after layer, until ultimately the conditions required for joint propagation no longer exist. This mechanical process, then, provides a sound basis for understanding the incremental and discontinuous nature of composite jointing as being related to the transfer of stresses through an interface or interlayer, as

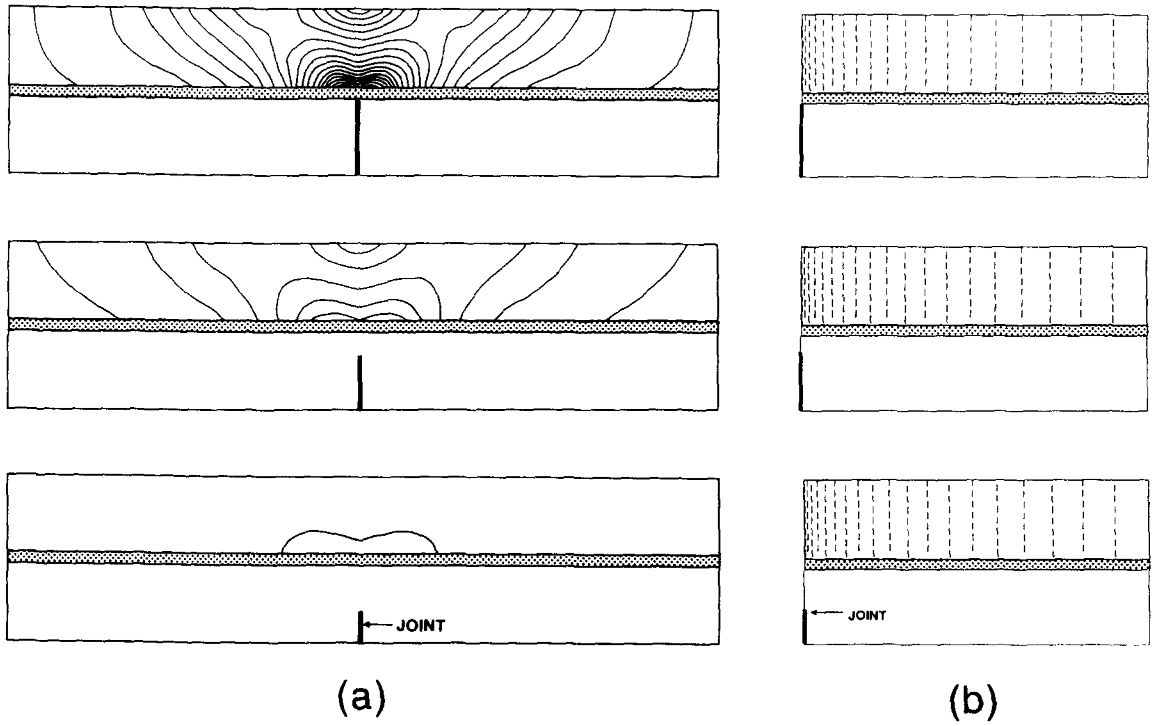


Fig. 15. (a) Patterns of the normalized maximum principal stress in the upper, unjointed layer due solely to a joint in lower layer for three differing joint configurations as shown. The contours are symmetrical about the plane of the lower joint. It is at one of these two maxima that new joints would likely initiate. (b) Orientation of the maximum principal stress planes at the nodal points. The tick marks represent the planes across which the maximum tensile stress acts, and these deviate from vertical by about 7° nearest to the joint.

well as the thickness and properties of the layers and interfaces.

DISCUSSION

It is suggested that the important parameters that control joint propagation in layered rocks are: (1) strength of interface; (2) Young's moduli and fracture toughnesses of the layers; (3) thickness of the layers; and (4) loading conditions. The mechanical character of layer interfaces in the siltstone and shale sequence of the Catskill delta is not clear. These rocks are known to be turbidite deposits; therefore, the transition from siltstone to shale is expected to be gradual in an upward direction within a given turbidite unit but quite sharp in downward direction between distinct turbidite events. In addition, a siltstone layer may be put above another siltstone layer either by pulses within a single turbidite or by the arrival of a new turbidite that washes away the fine-grained top of the previous sequence. The latter would then produce layers of similar materials with an average thickness of 10–20 cm, whereas the former results in siltstones interlayered by shales. In any case, these interfaces between similar and dissimilar lithologic layers appear to be bonded strongly enough to withstand the intensity level of deformation experienced in the study area.

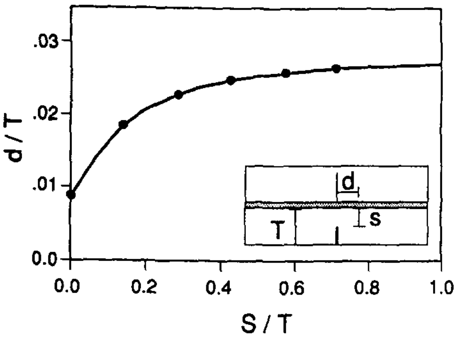


Fig. 16. Relationship between the position of the highest maximum principal stress, d, and the proximity of the joint to the interlayer, S, both normalized by the thickness of jointed layer, T. Note that as the joint approaches the interlayer (decreasing d/T), the point of highest maximum principal stress shifts closer to the plane of the joint (decreasing S/T), but never lies directly above the joint (zero d/T). It is near to these positions that a new joint would be most likely to initiate.

We have illustrated that jointing in one end-member, a stack of siltstone layers, causes a discontinuity in the growth of composite joints, but physically the segments are continuous. The parallel and in-plane growth of joints in this case is justified by the fact that the stress concentration associated with a joint tip at a strong interface between layers of comparable properties is similar in form to that in a homogeneous material. However, field observations suggest that joint propagation from siltstone to shale has not been continuous in time and in geometry. Joints in siltstone formed earlier. When later joints formed in shale, they were strongly influenced by existing joints in siltstone. This is obvious from the concentration of initiation points of joints in shale along the edge of the joints in a neighboring siltstone. The existence of a series of joints in siltstone and their interaction may be responsible in part for the out-of-plane growth of joints in shale. There also exist alternative hypotheses. For example, Engelder (1985)

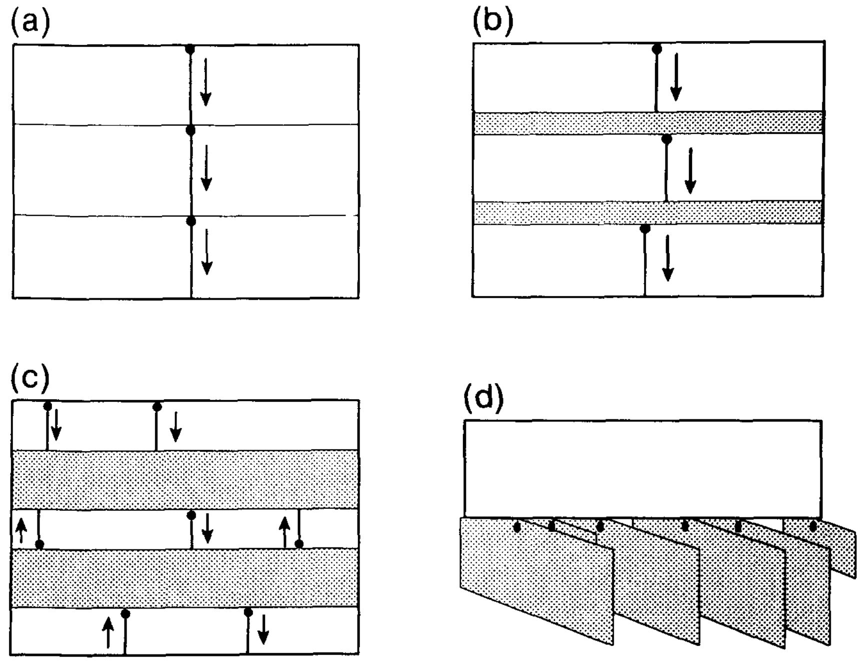


Fig. 17. Schematic summary of the observed characteristics of joint propagation in layerered sedimentary rocks as highlighted in this paper. (a) In-plane addition of sequential joint segments in siltstone layers. (b) Out-of-plane addition of sequential joint segments across shale lenses and thin shale layers. (c) Independently formed joints in siltstone layers separated by thick shale layers. (d) Non-planar addition of joint segments in shale (lower layer) around the periphery of a pre-existing joint in siltstone (upper layer). Note that the view is normal to a joint face in siltstone.

and Engelder & Oertel (1985) argued that joints in shale formed significantly later than joints in siltstone, possibly under a completely different state of stress. They associate the jointing of the shale units with uplifting and unloading of the rocks. These features will be discussed in more detail in a future manuscript.

Field observations provide evidence for termination of joints at the interfaces between siltstone and shale, and for initiation of jointing in siltstone on the other side of the unjointed shale, suggesting the existence of some kind of communication between the joint in one siltstone layer and the associated stresses in the siltstone layer on the other side of the shale. The nature of this communication has been analyzed by using a finite element model which shows that stresses in fact are transferred better through layers of relatively higher modulus. Stress concentration in the layer beyond the one that inhibits further vertical joint propagation has two maxima symmetric about the plane of the joint. Thus, fracture initiation in the next breakable layer will likely take place at these localities giving an apparent offset or sidestep trace geometry of the composite joint. Similar geometric results are obtained if the interlayer has a lower modulus.

Except for in-plane growth of composite joints in layered rocks with similar properties, all other joint growth mechanisms will result in geometries that will decrease the degree of connectivity among joint segments. Side stepping joint segments across shale lenses or thin layers are clearly disconnected and any oil, water, gas or contaminant waste going from one segment to the other has to go through the markedly less permeable shale. Initiation of joints at the edge of a single joint in an adjacent layer also has an important implication for vertical and horizontal fracture permeability. If the angle between the early joint and later ones is large, then horizontal permeability can change drastically from one unit to the next not only in magnitude but also in direction. This type of fracture geometry also limits vertical permeability. Because the fractures in the two adjacent units will be connected only at certain contact points (Fig. 6b), vertical fracture permeability will be markedly lower than that of a medium with continuous and well-connected fractures. Another implication for vertical permeability associated with these fracture systems is evident in the photograph in Fig. 6(a): the spacing of newly formed joints increases as they propagate away from the points of origin on the edge of the old joint by a systematic termination of some of the joints. This elimination process results in a decreasing joint density and, consequently, only a small number of joints may be able to propagate from one silt layer to another, thereby further limiting vertical permeability.

CONCLUSIONS

A coupled analysis of trace geometry and the associated surface features of joints in layered sedimentary rocks shows that interfaces between differing lithologies play a fundamental role on limiting the vertical extent of individual joints. Incremental propagation of a composite joint is accomplished by the sequential jointing of similar layers, whose joint segments are remarkably well aligned in a vertical sense. These segments are commonly (1) in-plane for layers of similar properties (Fig. 17a), and (2) out-of-plane across shale lenses and thin shale layers (Fig 17b). The amount of lateral out-of-plane offset is generally proportional to the thickness of the shale layer. If the shale layer thickness becomes relatively thick compared to siltstone, the overall nature of a communication between joints in siltstone layers may be absent (Fig. 17c). If a relatively thick shale is jointed by, for example, the introduction of additional energy into the system, the new joints initiate at the vertical extent of a pre-existing joint in siltstone and usually propagate at a small angle to the joint in siltstone (Fig. 17d).

An analysis of the pattern of maximum tensile principal stress due to a joint has shown that the maxima are split into two symmetric regions about the plane of the pre-existing joint slightly ahead of the joint tip. If the joint meets an impeding layer, the stresses may be transmitted through the inhibiting layer, with the two maxima situated in an adjacent layer. Since it is most likely that one of these maxima will initiate a new joint segment, the new segment will step aside. This provides a conceptual basis for understanding the out-of-plane growth of composite joints. However, as shown by the finite element analysis, the amount of side stepping of the highest stress concentration areas in a layer depends on how far the layer is from the terminated tip of the approaching joint. In reality, the distance of step will be determined by the mechanics of stress transfer and factors involved in joint initiation, such as the size and distribution of flaws near the interface.

Thus, it has been shown that joint propagation within a layered sequence of sedimentary rocks is controlled by changing lithologies and interface properties. Identification of these controlling layers and interfaces should improve field-based geometrical characterizations of fractured media. The physical continuity of joints and, consequently, fracture permeability are controlled by the distribution of the inhibiting layers and out-of-plane growth of fractures from one unit to another, all of which have practical and economic implications for oil and gas recovery, as well as waste migration predictions. For example, discontinuous composite joint segments resulting from out-of-plane growth of joints provide a less permeable path for fluids, gas, oil and contaminant waste than a continuous planar composite joint.

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