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PROPAGATION VELOCITY OF JOINTS: A DEBATE OVER STABLE VS. UNSTABLE GROWTH OF CRACKS IN THE EARTH

Terry Engelder
Department of Geosciences
334A Deike Building
The Pennsylvania State University
University Park, PA 16802

ABSTRACT

One of the hotly debated questions in the geoscience literature as of 2006 concerns the velocity of joint (i.e., a mesoscopic crack in rock) propagation in the crust of the Earth. Earthquake rupture loads rocks at stress rates of many MPa/sec, whereas plate tectonic deformation yields long-term loading rates as much as ten orders magnitude slower. This large range in loading rates leaves open the possibility of joint propagation in rocks anywhere from subcritical (i.e., stable growth) to critical and post-critical (i.e., unstable growth). Several facts are relevant during adjudication of the propagation-velocity debate: 1.) joints are inherently planar but may propagate as gradually curving single surfaces on scales > 10 m, 2.) hackle fringes are relatively rare, and thus, the exception to the planar surface (i.e., << 1% of all joint surface area in the crust of the earth consists of hackle fringe), 3.) fixed-grips loading is the normal configuration for propagation of joints in the brittle crust of the Earth if there is a fatigue limit, 4.) plume morphology on planar surfaces of joints is consistent with a velocity = $f(K_I)$ relationship, 5.) fracture under fixed-grips loading is inherently stable for several reasons, mainly, 5A.) developing elastic properties of a bulk rock with fractures favors stable propagation, 5B.) fluid-drive mechanisms in the earth favor stable propagation. The fractography of rock can demonstrate facts 1, 2, and 4 directly, and facts 3, 5A, and 5B indirectly. In summary, these facts point to a large role for subcritical propagation (i.e., stable growth) in the crust of the Earth whereas critical and post-critical propagation (i.e., unstable growth) in natural rock is exceptionally rare.

INTRODUCTION

Geoscientists use the term "joint" when referring to a macroscopic crack cutting rock as viewed on foot, within a mine, within core, or in a borehole image. A joint is a single discontinuity in rock that propagated from some smaller crack or flaw when its tip was subject to opening mode displacement.[1,2] Rupture to generate a brittle discontinuity is complex and leads to the rich textures found on the surfaces of both joints and cracks in ceramics and other materials. Larger-scale discontinuities are common in the Earth, but these consist of faults or joint zones growing from a more complex rupture sequence.[3,4] One of the earliest attempts to describe the texture of brittle rupture focused on the morphology of joint surfaces in the Cambridge slate quarries of Somerville, Massachusetts.[5] Observations elsewhere more or less reaffirmed that the surface morphology of joints in the Cambridge slate is representative of most joints.[6,7,8,9,10,11,12]

Joints are the product of prehistoric brittle fracture. This means that the rate of propagation of these ancient cracks cannot be measured by direct observation. Therefore, in situ propagation velocity must be inferred using models and experiments. Small samples are tested in the laboratory to measure fracture toughness, but joints are so large that 1:1 scale testing is not possible. Because joints and cracks in glasses, ceramics and metals have similar surface morphology, it is reasonable to draw upon cracks in the latter materials as analogs when it comes to inferring the velocity of ancient joints in rock.

The use of surface morphology on cracks in the engineering and ceramics realm as analogs for the surface morphology on rock joints is not as straightforward as it may seem for two reasons. First, in the case of joints, it is difficult to distinguish between surface morphology that is a product of single rupture moving through a change in orientation of the Earth's stress field in space, and morphology that is a product of a rupture that arrests and reinitiates after a change in the orientation of Earth stress with time. In the ceramics and engineering realm, rupture morphology may reflect a change in stress orientation in space as a consequence of odd boundary conditions, but rarely, if ever, is the rupture a product of arrest and reinitiation after boundary conditions change to cause a reorientation of stress. Second, it is difficult to gauge the velocity of joint propagation in the Earth, whereas in the ceramics and engineering realm, the velocity of the brittle rupture is often the product of unstable crack propagation.

BACKGROUND

One general conclusion arising from the analyses of joints in the Cambridge slate is that after more or less planar growth, the rupture often departed from the original plane of growth to form a fringe of multiple cracks.[5] These fringe cracks commonly consist of a set of parallel, en echelon planes that are systematically misoriented from the plane of the parent joint. When viewed normal to the parent joint, the en echelon cracks appear as river lines.[13,14] Engineering mechanics offers a theory for the departure from planar growth based on a stress-induced displacement of the crack tip.[15,16,17] As long as the crack tip is subject to pure opening mode displacement, propagation remains in its plane. Tearing or sliding mode displacements induce out-of-plane propagation and the generation of fringe cracks. In early studies of rock joints, there was no sense of whether the tearing and sliding mode displacements were the manifestation of a continuous rupture passing through a non-rectilinear stress field with curving stress trajectories or whether these latter displacements were the manifestation of a rupture that arrested and reinitiated after shifting in the Earth changed the orientation of the stress field.[18] In summary, fringe cracks on joints reflect either a spatial or temporal change in orientation of the stress field responsible for joint growth. Drawing a distinction between these two cases is difficult when using surface morphology alone.

Difficulty in the interpretation of joint surface morphology goes beyond the debate concerning a spatial vs. temporal stress reorientation. Without any direct observation of growth rate, connection between joint surface morphology and the velocity of rupture must be inferred. The first success in making a correlation between fracture surface markings and rupture velocity came in engineering fractography where rupture velocity could be controlled experimentally.[19,20] Glass was particularly suitable for producing a diagnostic set of surface features during high-speed propagation.[21] Later, a distinction was drawn between high-speed rupture at critical stress intensity, K_{Ic}, and chemically-aided low-speed rupture.[22] A complication arose because the glass literature adapted terms first used to describe the surface morphology of joints in the Cambridge slate where rupture velocity was unknown. For example, the original use of the term, 'hackle', was purely descriptive. Only later did hackle become linked to high-speed fracture in glass at or above K_{Ic} where it was used to describe the gradual roughening of fractures from a mirror to mist and beyond.

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rocks was not lost on 20th Century fractographers working with rock.[23] One of the earliest attempts to match joint surfaces and propagation velocity was a study of blast-induced fractures that display a much different morphology than found on the surface of natural joints.[24] Other attempts to understand the velocity of natural joints were based on a possible link between the mirror-mist-hackle morphology of high-speed rupture in glass and analogs on the surfaces of joints assumed to be growing during the high-speed rupture of rocks.[25,26] This analog is valid only if joints are the product of high-speed or critical rupture.

In comparing joint propagation in the Earth and crack propagation in engineering materials, a number of general statements apply. Joints propagate in rocks, a natural polycrystalline ceramic, that consists of relatively large grain size with some notable exceptions.[27] In the case of sedimentary rocks, the 'ceramic' is a layered composite.[28] Failure is commonly a low stress event and generally not transgranular.[29] Extrapolating the morphological features on the surface of glass to polycrystalline aggregates including rock is not easy because rupture involves a combination of intergranular and transgranular fracture that inevitably roughened the fracture surface regardless of rupture velocity. From these general statements it seems prudent to use caution before drawing an analogy between the morphology induced by high-speed rupture in glass and the morphology seen on rock joints, particularly when data on the velocity of joint propagation are not available.

OBJECTIVES

Despite the link between hackle and high-speed rupture in engineering materials, mainly glass, it is not clear that there is an immediate connection between surface roughness and high-speed fracture at or above K_{Ic} in rocks.[30] There are aspects to rupture and joint growth in the Earth aside from roughening that guide an interpretation of rupture velocity. The purpose of this paper is to briefly describe several critical aspects of rock fracture and its concomitant surface morphology that make joint propagation different from the high-speed rupture of glass and other ceramics. In brief, current theory points to a subcritical growth rate for propagation of an overwhelming majority of rock joints. With this current understanding, the fractography of glass is not a particularly useful analog for joint propagation in rocks.

Comparatively little attention has focused on the morphology of surfaces that are produced during low-speed, subcritical rupture in engineering materials. In this regard, it may be appropriate for the engineer to refer to geological experience in searching for analogs to slow rupture, particularly in polycrystalline materials. This paper attempts to summarize the geological literature regarding the fractography of slow crack growth in the Earth as a means of introducing that literature to the engineering community. Some of the best evidence supporting inferences about rupture velocity during joint propagation comes from the sandstone, siltstone and shale of the Devonian Catskill Delta Complex in a swath of New York State that includes the towns of Alfred, Corning, Watkins Glen, and Ithaca and this review focuses on that swath. Finally, this paper draws on an interpretation of joints in the Borsov Granite of the Czech Republic to illustrate pitfalls associated with making inferences about joint rupture velocity based on glass as an analog.

LOAD SYSTEM FOR FAILURE IN ROCKS VS. ENGINEERING MATERIALS

Placement of the fractography of joints in the proper context requires an understanding of Earth stress and how this stress ultimately leads to crack propagation. This understanding is best achieved with a model that expresses the nature of the Earth's loading system.

The Earth is a self-gravitating body which means that both horizontal principal stresses (i.e., S_H – the maximum horizontal principal stress and S_h – the minimum horizontal principal stress) are tied to the vertical principal stress, S_v.[31] Gravitational stresses are compressive and become even more compressive with depth, z, in the Earth. The coupling between the principal stresses [i.e, $S_h = f(S_v)$] is governed by constitutive equations for rock. On a short time-scale these are the equations of elasticity that can be solved to show that $S_h < S_v$ unless tectonic stresses are present. At first glance it is a paradox that the Earth contains any cracks because its interior is in a highly compressive state. However, thermoelastic contraction and generation of high fluid pressures are two mechanisms by which the Earth can relieve gravitationally induced compressive stresses and fail by crack propagation.

Time scales for Earth processes are orders of magnitude longer than those found in engineering applications. Thermally activated processes generally govern the rates of Earth deformation with mantle convection driving the deformation at strain rates $< 10^{-13}$ sec^{-1}. Some brittle processes such as long-term slip across major lithosphere bounding fault zones like the San Andreas are consistent with this mantle deformation rate.[32] However, little is known about crack propagation at rates less than 10^{-12} m/sec.[33] While experiments on both granite and silica glass leave open the possibility for slower crack growth, other materials appear to have a fatigue limit.[34,35] Some have suggested that under slow growth conditions, crack tips are blunted by dissolution and thus prevent crack velocity less than 10^{-11} m/sec.[36]

Although the reality is unknown, hallway discussion among Earth Scientists at national meetings admits the possibility of a fatigue limit so that crack propagation in the Earth is always faster than the Earth's innate loading rate of 10^{-13} sec^{-1}. Loading systems for crack propagation are distinguished by whether the loading rate is fast enough to maintain a load during crack propagation.[17] The dead-weight loading system can maintain a load during crack propagation whereas the fixed-grips loading system is incapable of maintaining a load (Fig. 1). The distinction between these loading systems is important because dead-weight loading drives many fracture toughness experiments and other types of engineering failures which tend to be unstable. Assuming joint propagation is faster than the Earth's innate loading rate, failures within the Earth are driven by fixed-grips loading which produced stable crack growth. If there is no fatigue limit, crack propagation can slow to the point that the Earth's innate loading rate of 10^{-13} sec^{-1} maintains a load. In this latter case, dead-weight loading drives joint propagation but such propagation is in a subcritical or stable regime.

According to the Griffith energy balance for crack propagation the two loading systems provide energy for crack propagation assuming that the total energy within the loading system and test specimen does not change during crack propagation.[37,38] The energy to drive most engineering failures comes from work by external boundaries in dead-weight loading systems. A stress-strain curve shows that the dead-weight system loses potential energy, $-U_w$, whereas the host rock gains strain energy, U_E (Fig 2a). If there is a fatigue limit to subcritical propagation, the immediate energy for crack propagation comes from the internal strain energy, U_E, within the rocks and not the work at the external boundaries. A stress-strain curve shows that the fixed-grips system does not give up potential energy at its boundary, but that the host rock loses strain energy, $-U_E$ (Fig. 2b). This point is important because fixed-grips loading leads to stable (i.e., low-speed) crack propagation in the Earth, whereas dead-weight loading of glass rods, for

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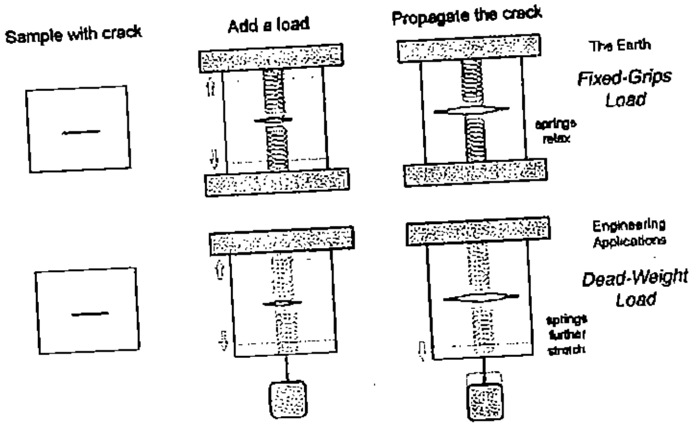

Figure 1. Basic elements of fixed-grips and dead-weight loading systems.[38] The sample material is elastic (represented by springs). Prior to loading a small crack is placed within the elastic medium. Loading the sample has the effect of stretching the sample and opening the crack regardless of the loading configuration. In fixed-grips loading surface energy for crack propagation comes from the elastic relaxation of the rock whereas in dead-weight loading the surface energy for crack propagation comes from the potential energy given up by the falling dead weight.

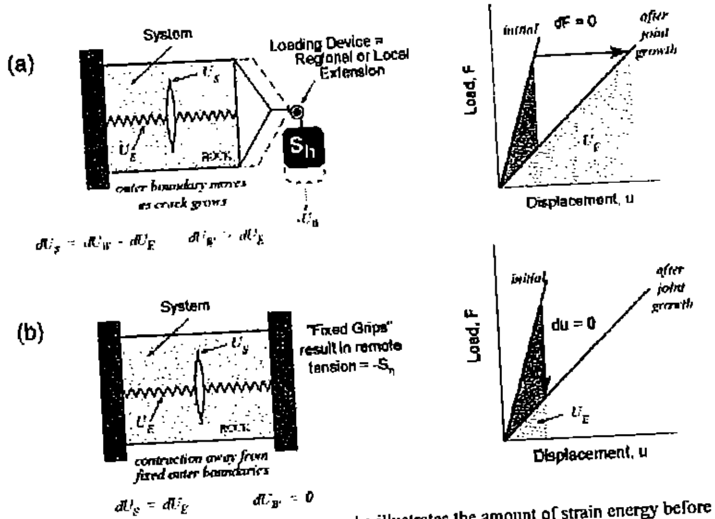

Figure 2. Loading systems and force-displacement graphs illustrates the amount of strain energy before (dark shade) and after (light shade) joint propagation under each loading system.[38] Rock modulus is the slope of the force-displacement curve. (a) Thermodynamic energy balance diagram for dead-weight loading. During joint propagation the strain energy (light shade) increases. (b) Thermodynamic energy balance diagram for the joint-driving mechanism under a fixed-grips loading system. During joint propagation the strain energy (light shade) decreases.

example, leads to unstable (i.e., high-speed) crack propagation.[39] We can anticipate that there are distinct and predictable differences in the fractography of stable and unstable propagation. Rock joints provide a natural laboratory (although not quite controllable) for establishing the differences in fractography between stable and unstable crack propagation.

THE FRACTOGRAPHY OF JOINTS DURING IN-PLANE PROPAGATION

A fine roughness appears on fracture surfaces during initial growth of joints. The fine roughness of the surface of joints during larger-scale in-plane propagation depends on the lithology of the host rock. Ironically, siltstone and sandstone of intermediate grain size carry some of the best-developed examples of the 'feather' or 'plumose' morphology first described on the surfaces of the Cambridge slate.[5] Plumose surfaces on siltstone beds have an rms height of about 10 μm for a profile length of 10 cm.[40] Cooling joints in diabase, an igneous rock, can have an rms height of an order of magnitude higher over the same profile length, whereas joints in shale have a smaller rms height. Joints cutting interlayered shale beds in the Catskill Delta Complex appear smooth to the unaided eye. The plume morphology on siltstones and sandstones allows mapping of the rupture history by tracing 10 μm ridges left by the rupture process back to the initiation point (Fig. 3).

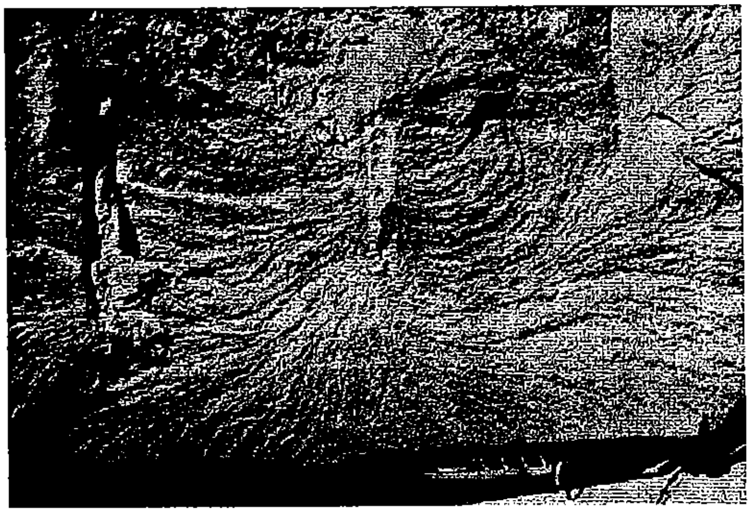

Figure 3. Joint initiation at a stress concentration (worm borrow) inside a siltstone bed, in the Devonian Ithaca Formation exposed along Highway I-81 near Marathon, NY. For scale, the edge of a Swiss army knife is seen below the bed.

Despite the fine roughness, joints in Cambridge slate remain inherently planar during initial growth.[5] Larger-scale planarity is common during the initial stages of joint propagation in the Earth. Modern fracture mechanics explains the tendency for in-plane propagation based on shape of the crack-tip stress field through theories such as the maximum circumferential stress

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criterion,[41] the maximum strain energy release rate criterion,[42] and minimum strain-energy density criterion.[43]

In mapping rupture back to initiation points, it is seen that in natural layered composites of shale, siltstone, and sandstone beds of the Catskill Delta Complex, joint initiation takes place at a variety of locations both inside and at the bottom of layers a few cm to > m thick. One feature that initiation points in rocks possess is a dimension on the order of one to ten cm.[44] Initiation points internal to bedding include fossils, worm burrows, concretions, and sedimentary structures such as ball-and-pillow structures (Fig. 3). Regarding joint initiation, one important characteristic of a bedded composite is that the bottom of siltstone beds makes a sharp contact with underlying shale whereas the top contact between siltstone and overlying shale is gradual. Flute casts and gutter casts mark initiation points at the bottom of siltstone beds. Joint growth commonly emerges upward from these structures on the underside of siltstone beds (Fig. 4).

Like any layered composite, joints in sedimentary rocks commonly cut the stiffer layer with the interlayered, less-stiff shale remaining intact (Fig. 5). Preferential joint growth is found in the siltstone layers because these are the stiffer member relative to the shale which tends to stretch without early failure.[45,46] The spacing of joints in the siltstone beds is approximately equal to the thickness of the beds.[47,48] This behavior is explained by the shear-lag model for layered composites.[49,50,51]

Not all siltstone beds display initiation points at cm-scale structures or inclusions. Invariably, these beds fracture by joints crossing shale interfaces from beds where initiation points are found. Joint propagation across shale interfaces leads to extensive vertical growth of joints.[28]

In engineering applications, tensile stress may exceed 100 MPa and under these circumstances pores and other flaws on the order of 10 µm are sufficient to initiate crack propagation. The Earth is so completely broken that it has no large-scale tensile strength and, hence, has no gripping mechanism that permits the generation of such large tensile stress. Rupture in the Earth starts from macroscopic stress concentration points that are several cm in size and 3-4 orders of magnitude larger than internal pores.[44] In the Earth macroscopic stress concentration points superimposed on microscopic porosity in rocks enable failure events at low tensile stress (Fig. 6).

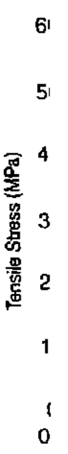
THE FRACTOGRAPHY OF JOINTS DURING OUT-OF-PLANE PROPAGATION

The question of what morphological features constitute out-of-plane propagation is scale dependent. Clearly the fine mist on glass rods is a manifestation of out-of-plane propagation at a microscopic scale. The plume structures on joints are also out-of-plane features at a scale large enough to be visible to the unaided eye (i.e., rms height = 10 µm at profile length of 10 cm). Yet, in the case of joints, the out-of-plane rupture to generate plume structures returns to the parent plane within a few grain diameters of the twist or tilt that generated the local out-of-plane propagation. The rupture growing from true out-of-plane propagation never returns to the plane of the parent joint.

Out-of-plane propagation is common in the sandstone, siltstone and shale of the Devonian Catskill Delta Complex in the vicinity of Corning, Watkins Glen, and Ithaca, New York.[18] This is largely a consequence of the shift in tectonic stress during the period of 50 million years or so when, according to plate tectonic theory,[52,53] Africa collided with North America. The vast majority of joints exhibiting out-of-plane propagation are a manifestation of reinitiation of propagation from parent joints after a shift in the tectonic stress field. There are,

Figure 4. Joint initiation at an asymmetrical stress concentration (flute cast) at the base of a bed. The outcrop is the Devonian Ithaca Formation exposed along Highway 14 between Montour Falls and Watkins Glen, NY. For scale, the coin above the bed is an American quarter dollar.

Figure 5. An interbedded composite of siltstone (the thicker layers) and shale (the thin layers) beds. Systematic joints occur in the siltstone beds with a spacing approximately that of the bed. This outcrop is the Devonian Braillier Formation near Huntington, PA.[54]



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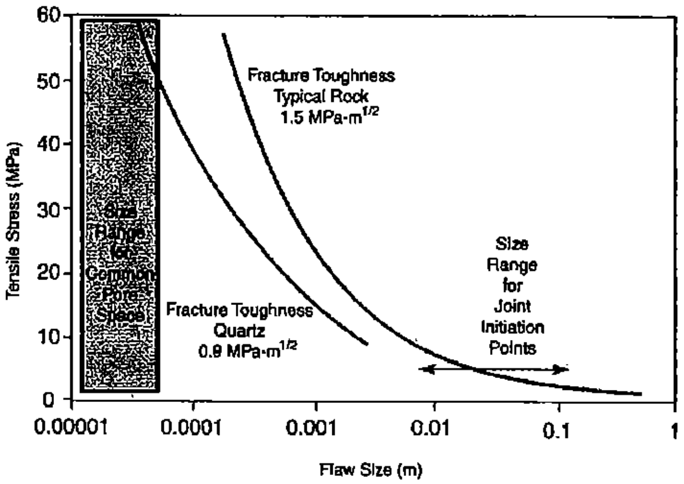

Figure 6. Failure curves for typical rocks and quartz plotted as tensile stress vs. flaw size.

however, joints that exhibit out-of-plane propagation because neighboring joints gave rise to an asymmetric crack-tip stress field.

Twist Hackles

Early descriptions of joint surfaces divided them into a planar portion and a rim of fringe cracks. With the evolution of terminology over time, these two parts of a joint surface are now described as the main joint face, or parent joint, with its characteristic plumose structure and the fringe, with its en echelon fringe cracks. The boundary between the main joint face and its fringe cracks may be either an abrupt transition, known as a shoulder, or a smoothly curving transition. Some descriptions of fringe cracks implicitly recognized the genetic similarity between the abrupt and smooth transitions by referring to both types of en echelon cracks as twist hackles.[10] The fringe is called a gradual twist hackle (Fig. 7) if individual cracks emerge from the tip line of the parent joint face in a smooth, uninterrupted manner, whereas the fringe is known as an abrupt twist hackle (Fig. 8) if a series of planar en echelon cracks abut the joint tip line. The former are known as river lines in the ceramics literature.[13] Other names for these structures include hackle zone, hackle marks, dilatant fringe cracks, fingers, and fracture lances.[55] Unlike its counterpart on glass fractures, hackle in joint fringe zones is usually not diagnostic of fracture velocity.

Gradual twist hackles result from a continuous breakdown of the parent joint, whereas abrupt twist hackles stem from a discontinuous breakdown. The twist angle is a function of change in remote stress orientation, stress magnitude, and elastic properties.[56] Presently, there is

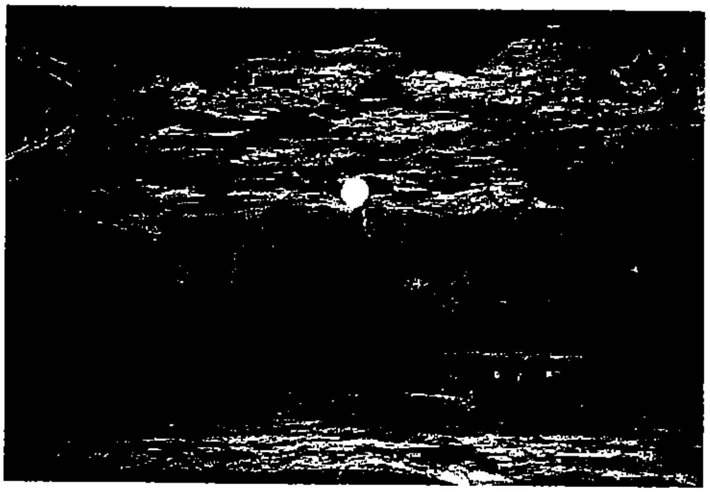

Figure 7. Gradual twist hackles. A parent joint and a twist hackle are carried within a single bed of siltstone of the Ithaca Formation at Taughannock Falls State Park, New York. Propagation direction for the twist hackle is upward. The sense of stress field rotation in this example is clockwise. The scale is an American quarter.

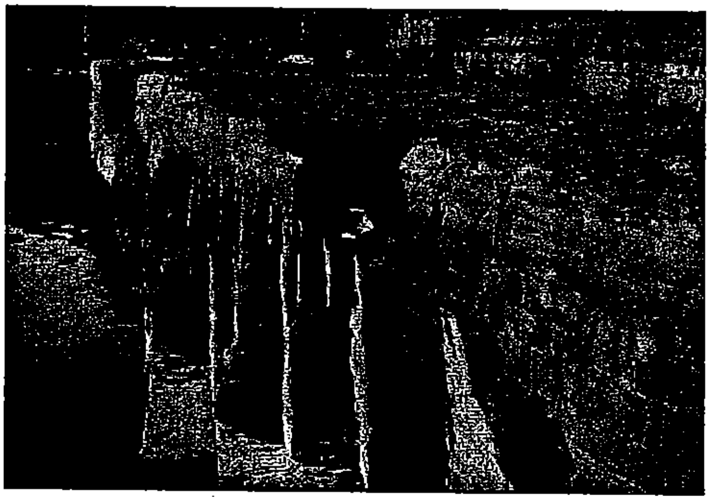

Figure 8. Abrupt twist hackles. This set of fringe cracks propagated downward into a thick shale bed from a thinner siltstone bed hosting the parent joint at Taughannock Falls State Park, New York. These rocks are part of the Ithaca Formation. The sense of stress field rotation in this example is clockwise. The scale is a geologic compass with an 8 cm base.

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general agreement that the breakdown of the parent joint into fringe cracks is a consequence of a stress field with principal components that are neither orthogonal nor parallel to the tip line of the parent joint.

Kinks

The tip line of the parent joint can be decorated with a single fringe crack known as a tilt or kink (Fig. 9). A kink is a planar crack that propagates laterally at some angle from the edge of a parent joint.[57] Often, kinks form after parent joints have arrested. If the parent joint had not arrested prior to kink formation, there would have been a smooth curving or hooking of the crack path (Olson and Pollard, 1989).[58]

The Complete Fringe

If a joint grows and then arrests in a homogeneous medium without the anisotropy that bedding introduces, its tipline may approximate a circle. Such macroscopic penny-shaped cracks are found in granite (Fig. 10). In some instances, crack propagation is reinitiated after the remote stress field has rotated. A fringe will develop that completely surrounds the joint but the nature of the fringe depends on the crack-tip displacement caused by this new stress field orientation. The fringe is a twist hackle where the crack tip is subject to mode III displacement and a kink where subject to mode II displacement (Figs. 11, 12).

"SELF-CORRECTING" JOINT GROWTH AND THE VELOCITY = f(K_I) RELATIONSHIP

Both joint growth in nature and crack growth in engineering materials are largely a function of the velocity of the crack tip-line, v_{ll}. If v_{ll} is equal in all directions at the onset of rupture, radial growth takes place with the expansion of a circular crack tip-line to create a macroscopic penny-shaped crack. Classic examples of fracture in glass rods are consistent with the growth of circular tip-lines even during unstable propagation.[59] Geological examples of a circular tip-line include isolated planar joints in granite where c is the radius of the joint (Fig. 10). Joints in the Mrákotín granite, Borsov, the Czech Republic, are remarkable examples of initial tip-line shapes in a homogeneous and relatively isotropic rock. While nature rarely provides a perfect circular tip-line, the best examples of tip-lines have long-to-short axes of no more than 1.37 on vertical joints with diameters in excess of two meters.[26]

The Earth contains fluids (mainly water with various salts) that are highly corrosive. When loads are applied slowly as is the case for the Earth, stress corrosion creep is an active deformation mechanism with static fatigue common.[60] During static fatigue, the magnitude and distribution of the stress intensity K_I along the crack tip-line is the most important parameter in dictating v_{ll}. Such a law was postulated for subcritical crack growth where n is the subcritical

$$v_{ll} = AK_I^n \tag{1}$$

fracture growth index and A is a constant of proportionality.[61,62,63] By Eq. 1, circular ruptures grow only if the instantaneous K_I and dK_I/dc have constant values at all points along the tip-line.

Joint growth in the Earth is often very complicated because both K_I and dK_I/dc are not equal along joint tip-lines. Stress gradients or crack geometry effects can alter dK_I/dc at different points on a joint front periphery. For example, in clastic, interbedded sedimentary sequences, differences in the elastic properties of adjacent siltstone and shale layers, weak bedding planes, or the interaction with nearby crack tip stress concentrations introduce a mechanical

Figure 9. Kink in a siltstone bed near Whitney Point, New York. Parent joint is on the left and the kink tilts away from the viewer on the right.

Figure 10. Penny-shaped joint in the Mrákotín granite of the Borsov Quarry, Czech Republic. This is close-up view of the J5 joint with an initiation point at o (see Fig 9. in Bahat et al.[26])

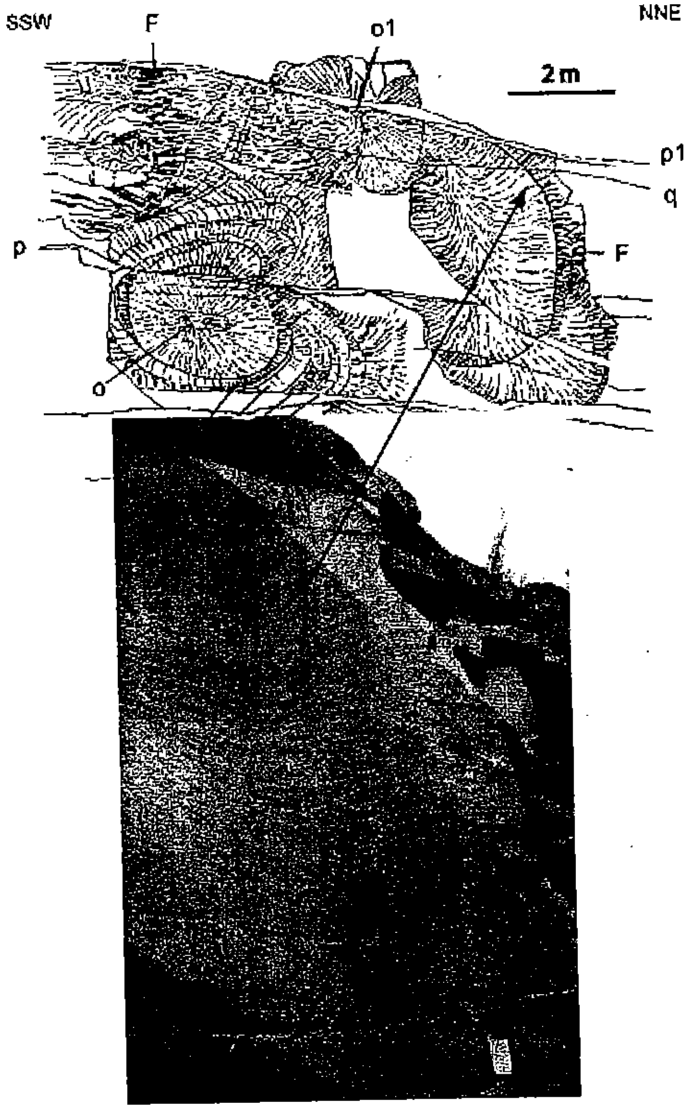

Figure 11. Fringe cracks on a joint in the Mrákotín granite of the Borsov Quarry, Czech Republic with the transition from a kink on the fringe to a mixed mode kink-twist fringe. Kink angle is consistent with the sense of twist. The picture is a close-up view of the fringe on the right side of J5[26] with an initiation point at o1. The line drawing is taken from Fig 9. in Bahat et al.[26]

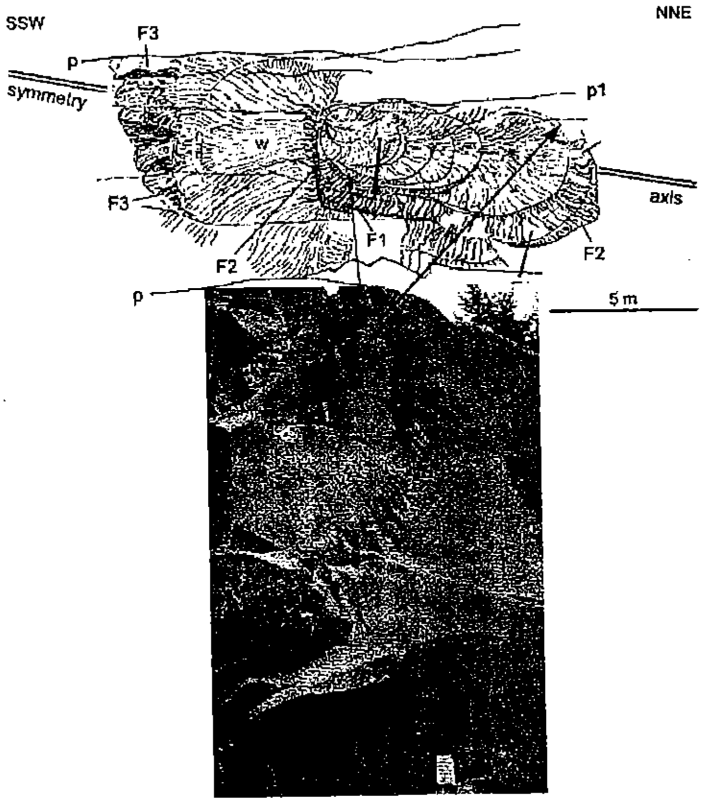

Figure 12. Fringe cracks on a joint in the Mrákotín granite of the Borsov Quarry, Czech Republic with the transition from a kink on the fringe to a mixed mode kink-twist fringe. Kink angle is consistent with the sense of twist. The picture is a close-up view of the fringe on the right side of J6.[26] The line drawing is taken from Fig 10. in Bahat et al.[26]

heterogeneity that modifies K_I along the crack tip-line. During subcritical propagation variation in K_I brings about differential or non-uniform instantaneous v_{II} that causes ruptures to evolve from circular to elliptical and then to irregular shapes. However, there is also a tendency to for an elliptical shape to redistribute K_I in a manner that returns the rupture to its stable, circular shape.[16] This leads to the phenomenon of a self-correcting rupture and the concomitant cycling of rupture shapes.[30] Hence, the circular or penny-shaped rupture is the stable shape from which more complex ruptures evolve providing rupture is subcritical. Eventually, the rupture will become irrevocably complicated at bed boundaries where the moving portion of the tip-line may

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Evidence for self-correcting rupture is found when stress concentration points in bedded sedimentary rocks force an odd-shaped initial rupture.[30] Occasionally primary growth involves an initial growth spurt producing an elliptical shape followed by a decrease in ellipticity in the central portion of a bed. This happens because v_{ll} becomes faster in the direction of the short axis. The short axis catches up in length to the long axis, thereby returning the rupture to a circular shape (Fig. 13). In some instances the rupture continues to grow in what was the direction of the short axis. The higher velocity portion of the crack tip does not decelerate instantaneously so the former short axis continues propagating and becomes the long axis. The effect is that an elliptical rupture seems to turn at right angles to itself in the interior of a bed (Fig. 13). In these cases, the rupture evolves seamlessly from elliptical to circular and back to elliptical. While circular crack growth occurs during unstable rupture, self-correction does not because in the critical realm there is no correlation between v_{ll} and K_{Ic}. Self-correction requires that $v_{ll} = f(K_{Ic})$.

INCREMENTAL JOINT PROPAGATION BY THE THERMOELASTIC CONTRACTION AND FLUID-DRIVE MECHANISMS

Joint propagation is commonly periodic. In the Catskill Delta Complex this is periodicity is manifest by cycles of gradual roughening of joint surfaces before an abrupt hesitation or complete arrest (Fig. 14). During cooling of basalt that flows onto the Earth's surface, columnar jointing takes place in a series of cycles as a cooling front moves from the edge of the basalt flow to its interior (Fig. 15). Joints in granite can grow cycle by cycle in a series of increasingly larger radius fringe cracks (Figs. 11, 12).

A self-gravitating Earth generates large compressive stresses in its interior. Nevertheless, there are a number of mechanisms by which tensile stresses superimpose on gravitationally generated stress. Joint growth requires the superposition of large enough tensile stresses to create a net tension that is called a tensile effective stress in the geoscience literature.[64] Two of the most common mechanisms for producing a net tension are thermoelastic contraction and fluid pressure generation.[38] The former also produces an absolute tension.

Thermoelastic Contraction

Thermoelastic contraction is strongest following the emplacement of magma into plutons in the Earth's interior or flow lava onto the surface of the Earth. Cooling causes a contraction. Because rocks, including freshly intruded magma or extruded lava, are fixed to external boundaries, the surrounding Earth prevents such contraction and a thermoelastic tensile stress is generated instead. Basalt flows on the Earth's surface are famous for their columnar jointing which is a manifestation of thermoelastic contraction. Early microcracking is very common in

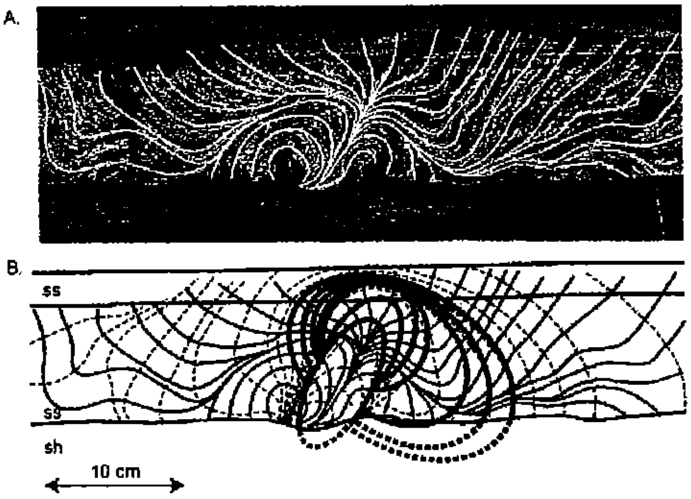

Figure 13. (a) Joint surface exposed along Highway 14 between Watkins Glen and Montour Falls, NY. (b) Interpretation of the joint surface (rupture shapes and tip-lines indicated).

Figure 14. Arrest lines in the Ithaca Formation along Route 414, Watkins Glen, New York. These arrests are part of a joint that propagated in 68 discrete increments.[68]

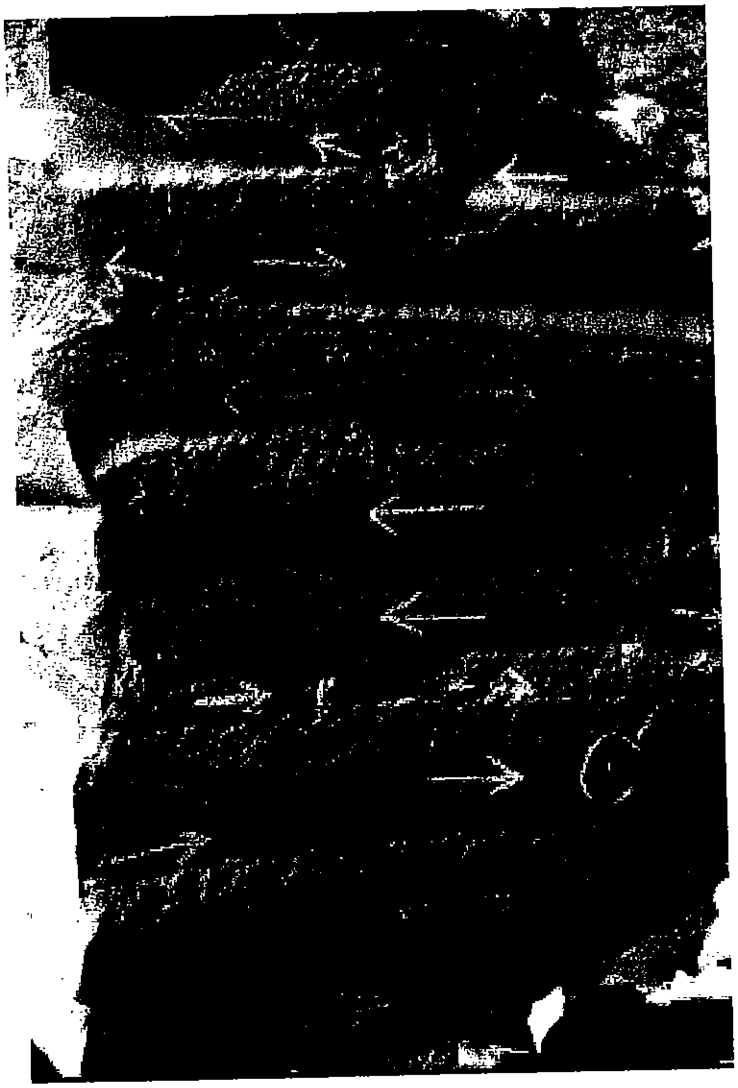

Figure 15. Arrest lines on cooling joints of the Snake River Basalt flow along the Boise River at Lucky Peak Dam, Idaho.[65]

granite intrusions and these microscopic fractures are also a manifestation of thermoelastic contraction. In both instances, the energy for crack propagation comes from a decrease of the internal strain energy within the body (Fig. 2b).

Thermoelastic contraction promotes stable crack propagation because the elastic properties of the rock change during crack propagation. The stiffness of the host rock is a function of joint length with the stiffness decreasing upon joint growth.[66] A changing modulus causes a load drop and concomitant drop in K_I at the crack tip (Fig 2b.). K_I rapidly drops and will become insufficient to drive joint propagation on the time scale of the fracture process. For cooling basalts, fracture growth stops until further cooling reloads the crack tip and fracture is again initiated.

Fluid Decompression

Fluids within pore space is pressurized by a number of mechanisms. One of interest in the Catskill Delta Complex is the volume-increase reaction during the coversion of organic material to hydrocarbons in a process called maturation.[67] During maturation the microscopic pore space within the rock does not expand so that a volume increase reaction leads to a pressure increase. Pressures may increase to the extent that they become larger than the gravitationally-produced compressive stresses in the Earth, thus producing a net effective tensile. This effective tension will drive crack propagation in a process called natural hydraulic fracturing. The driving mechanism, fluid decompression, is similar to dead-weight loading with the pressure against the inside of the joint (Fig. 16). The question is whether such joint propagation is unstable like engineering failures under dead-weight loading.

The Catskill Delta Complex is characterized by joints with fractographic evidence for cyclic propagation which means they are stable despite that dead-weight-like loading system (Fig 14). Although cyclic propagation could result from periodic external forcing by for-field stress changes, the regularity and rhythmic nature of joints within the Delta Complex suggest that fluid-pressure pulsation is the cause.[68] A joint more than 30m long by 44cm high that propagated within a single bed near Watkins Glen, New York has a plumose morphology with multiple arrest lines indicating the cracking occurred in increments rather than in one smooth rupture. The crack increments increase in overall length in the propagation direction over the final 28m portion of the exposed end of the joint with the largest increments increasing in length from 0.6 m to 1.0 m (Fig. 14). This increase in size of each increment suggests that propagation is tied to the crack length at the beginning of each increment.

At least three conceptual models based on linear elastic fracture mechanics and fluid flow along joints can be imagined to explain incremental crack growth under conditions of constant stress (i.e., fixed-grips loading) and pore pressure: The compressibility-limited propagation model; the flow-limited propagation model; and the infiltration-limited propagation model.[66] This surface morphology of the study joint provides constraints on the propagation process so that the growth of the joint may be analyzed in terms of these three models. Based on quantitative evaluation of the cracking process, the compressibility-limited propagation is favored and the driving fluid is identified as a gas like CH_4 rather than a brine.

Fluid decompression is the joint-driving mechanism for natural hydraulic fracturing. Cyclic propagation takes place for the simple reason that the fluid volume driving joint growth from the inside of the crack increases during each increment of propagation. CH_4 is a highly compressible gas that will decompress as the volume of the crack increases with each cycle. Internal crack pressure as exerted by the CH_4 on the inside of the crack decreases upon

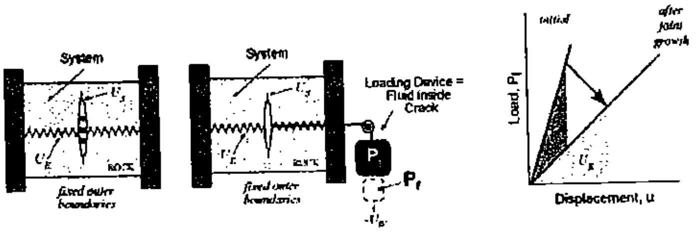

Figure 16. Thermodynamic energy balance diagram for the joint-driving mechanism, fluid decompression. The system is depicted in two ways. The first shows the load of pore pressure in the form of springs on the inside of the joint. As the joint grows, the springs (pore pressure) relax. The second shows the inside wall of the crack loaded by a dead-weight that is connected through the rock mass. The initial pore pressure is P_i and the final pore pressure is P_f. Displacement in this case is the displacement of the internal wall of the joint because the external boundaries are fixed. Schematic force-displacement graphs illustrate the amount of strain energy before (dark shade) and after (light shade) joint propagation. Rock modulus is the slope of the force-displacement curve.

decompression. Hence, the crack driving stress and concomitant K_I at the crack tip drop to stabilize the joint. The joint will recharge from rock porosity and gradually pressurize until K_I initiates propagation for another cycle.

THE MRAKOTIN GRANITE CONTROVERSY

The use of fractographic markings on glass (i.e., mirror, mist, and hackle) as analogs for the surface morphology of joints is controversial for two reasons. First is the question of whether or not it is possible to recognize fracture mirror and mist on joints (i.e., critical and post-critical rupture) when joint surfaces are overprinted by the plumose morphology first described in the Cambridge slates. Second is the question of whether well-organized, systematic fringe cracks are equivalent to the hackle that follows fracture acceleration through the mirror and mist stages of critical and post critical rupture. One interpretation of the fracture patterns in the Mrákotín granite, Borsov, Czech Republic is that joints in the Borsov quarry carry a mirror-hackle surface morphology indicative of unstable, critical and post-critical rupture.[26]

There are a number of facts that point to stable joint propagation in the Mrákotín granite. First, unstable rupture in glass and ceramics is achieved over very short distances within which there is an evolving surface morphology from mirror to mist to hackle. An increase in crack length under dead-weight loading causes unstable crack propagation because excess energy is available for crack propagation. Growth or the rupture under these conditions means that K_I becomes much larger than K_{Ic}. Glass and ceramics literature is replete with examples showing a gradual progression and increase in roughness as the crack radiates outward from the origin under dead-weight loading.[14,58,69] In contrast with glass, the surface morphology of the planar joints of the Mrákotin granite does not evolve until the fringe is reached (Figs. 10–12). The simplest explanation for a non-evolving surface morphology is that the crack-tip K_I does not undergo the radical change necessary for producing the evolving mirror-mist-hackle morphology. A non-evolving surface morphology is most likely to take place at $K_I \leq K_{Ic}$ where $K_I \approx const.$ This latter behavior requires that the load is reduced as the crack grows, a characteristic of local fixed-grips loading.

Second, the fringe cracks around several of the initial joint planes in the Mrákotin granite all have a consistent sense of twist or tilt (Figs. 11, 12). If the tilt on the fringe of one corner of the parent joint is forward, the tilt on the opposite corner is back (Fig. 10). Fringe at corners found at right angles to the tilt boundaries twist with the same sign. Furthermore, the twist angle is consistent with the tilt angle. This behavior is different from the morphology of joints that were generated by high-velocity fracturing associated with blasting at quarries or road cuts. In following around the rupture front of a high-speed fracture there is no consistent twist and tilt angle. The surface markings are formed by random and local deviations of the crack up and down out of the main propagation plane. During unstable rupture out-of-plane propagation along one portion of the fracture is inconsistent with out-of-plane propagation at other positions along the rupture front.

Third, a consistent sense of twist and tilt around the joint fringe, requires that joint propagation arrests so that the remote stress has time to reorganize and reorient itself to control the orientation of a consistent fringe. Such arrest is consistent with point #1 which is that the load comes off the joint during propagation in the Mrákotín granite. Load cycling is consistent with a low-stress, fixed-grips loading system that does not drive crack propagation to critical velocities.

Fourth, the majority of large fringe cracks in the Borsov quarry are systematically oriented clockwise from NNE-striking parent joints.[70] This is the pattern that exists throughout the Southern Bohemian pluton, an intrusive body more than 100 km long. Like the fringe cracks of the Catskill Delta complex, these are the manifestation of a regional rearrangement of Earth's stress.[18] Systematically oriented large fringe cracks are not part of a hackle fringe zone that is the manifestation of unstable joint growth. In a drawing of joint "J9" in the Borsov quarry, abrupt twist hackles of the regional set are mistakenly identified as rotating counter-clockwise from the parent joint.[26]

Fifth, growth of the joints beyond the initial planar joint is asymmetric. Forward progress is more efficient in the direction of the tilt boundaries than in the direction of the twist boundaries, and hence, the joint tip-lines evolve into elliptical shapes (Figs. 11, 12). This creates the impression that the joints are not self-correcting. However, all this means is that once arrested, resumed progress is more efficient when a single joint surface is initiated from a tilt boundary whereas further growth from numerous twist boundaries slows progress and exaggerates the tendency for elliptical growth. This is a pattern that is consistent with slow incremental growth with the slight adjustments in the Earth's stress field between increments.

Sixth, a thoroughly-cracked Earth cannot generate and maintain tensile stresses large enough to drive cracks unstably largely because unstable propagation requires a dead-weight load. A fractured Earth has no means of gripping smaller volumes of rock in tension. While these statements are subjective, they are supported by the fact that not even a small fraction of thousands of stress measurements in the Earth should have detected tensile stress of the type that would have driven joints in the Mrákotín granite to unstable velocities. In fact, tensile stress on the scale of the Borsov quarry has never been detected below the surface of the Earth.[31]

Joints in the Mrákotín granite, Borsov, Czech Republic are well documented in pictures.[26] It is left to the reader to test these six points of fact against the hypothesis that the surface morphology is indicative of unstable, critical and post-critical rupture.

CONCLUSIONS

This paper argues that stable, subcritical crack growth is the dominant mechanism for opening mode crack development in the brittle crust of the Earth.[71,62,72] To date, the majority of work on the subject is based primarily on the development of multi-joint growth patterns with minor input from joint surface morphology. Subcritical growth produces a distinct rupture pattern on joint surfaces and the presence of this rupture pattern is further evidence for stable growth within the subcritical regime. Six major characteristics of rupture in layered rocks support the stable growth hypothesis for propagation of joints in the Earth.

First, unstable, post-critical rupture leads to out-of-plane cracking that produces a surface topography that far exceeds the small-scale, local inhomogeneities seen on the plumose morphology of joints in layered rock. Wholesale out-of-plane cracking includes hackle fringe and branching, both of which result in very irregular joint surfaces.[25] Many joints in the Earth are planar and without a hackle fringe, thus devoid of any direct evidence for unstable rupture.[39]

Second, all evidence from joint surface morphology points to a self-correcting rupture shape in an isotropic, homogeneous rock. A K_I-dependent v_{II} is a necessary condition for self-correction. K_I-dependent v_{II} is one of the characteristics for rupture growth within region I of the subcritical regime but not a characteristic of post-critical propagation (Fig. 17).

Third, the whole notion of 'self-correcting' geometry is itself indicative of slow crack growth. Such a geometry is not consistent with unstable growth.

Fourth, the surface roughness of joints often does not increase with growth away from an initiation point. Post-critical propagation, as shown through experiments in glass and ceramics, is characterized by an increase in roughness with growth. A non-evolving surface morphology is indicative of a steady-state behavior consistent with stable growth.

Fifth, the surface roughness on a single joint may vary cyclically (Fig. 13). This behavior is consistent with alternating periods of propagation followed by hesitation or arrest.[66] Hesitation or arrest ($v_{II} \rightarrow 0$) occurs when the crack-tip K_I drops below a certain threshold in the subcritical regime. For incremental or cyclic growth to take place there must be a clear relationship between crack-tip K_I and v_{II}.

Sixth, joints with variable roughness are also likely candidates for the transition from region I to region II behavior ($v_{II} \approx 10^{-3} - 10^{-2}$ m/sec). In region II, K_I can increase a great deal as the joint grows while $\Delta v_{II} = 0$. Most clastic rocks make a transition to region II behavior at $v_{II} \approx 10^{-2}$ m/sec.[61] This leaves a broad range of K_I that must be crossed to reach critical behavior at K_{Ic} (Fig 17b). This plateau serves as a large 'barrier' separating stable and unstable behavior. Critical and post-critical behavior in the crust of the Earth is rare as a consequence of this 'barrier'.

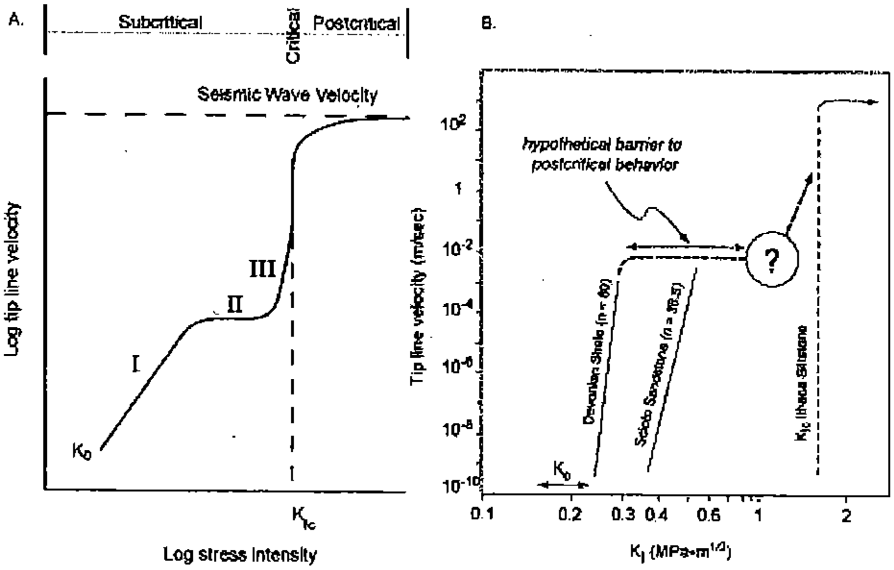

Figure 17. (a) Rate of crack growth as a function of stress intensity at the crack tip for subcritical (Regions I-III), critical, and post critical behavior. (b) Same plot with data from Devonian Shale,[73] Scioto Sandstone,[74] and Ithaca Siltstone.[29].

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The author (T.E.) grew up within 15 miles of the Alfred University campus. As a high school scholar he benefited from weekly science seminars at Alfred University and as a high school athlete, he competed against Van Fréchette's son.

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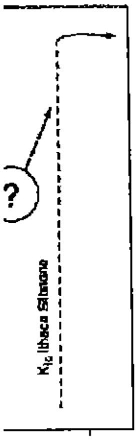

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