Skempton's poroelastic relaxation: The mechanism that accounts for the distribution of pore pressure and exhumation-related fractures in black shale of the Appalachian Basin

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EXPLANATIONS FOR TABLE 2: COMPARATIVE TERMINOLOGIES FROM SELECTED JOINT STUDIES IN THE APPALACHIAN BASIN

The first depictions of Appalachian Basin fractures were in wood block prints by Sarah Hall as they appear in her husband's paper from the geological survey of the fourth district of New York (Hall, 1843). A print of Taughannock Falls cascading over the Geneseo black shale a few kilometers north of Ithaca, New York, shows two major joint sets that are not quite orthogonal. The artist even captured a hint of lithological control of the black shale on joint development. Among other attributes, these joints crosscut in a streambed of black shale along Taughannock Falls gorge. The two joint sets depicted in Hall's block prints (Hall, 1843) were identified by their geometric relationship with gentle folds of the Appalachian Plateau as strike and dip joints (Sheldon, 1912). According to Sheldon (1912, p. 68), the lithological control was abundantly evident as "the strike joints (east-northeast) are better developed in the shales and the dip joints (J2) in the sandy beds." Sheldon (1912, p. 67) also states that the strike joints are "best developed in homogeneous shales, especially the Hamilton beds." The Marcellus gas shale is found at the base of the Hamilton beds. Sheldon (1912) was mapping mainly in the Geneseo black shale and the overlying Ithaca Formation, but her observations apply to other units constituting the mechanical stratigraphy of the Devonian Catskill Delta Complex (accompanying paper Figure 4). In sum, the effect of black shale on the development of joint patterns in the Appalachian Basin was recognized as far back as the geological survey of the fourth district of New York State by Hall (1843) in the late 1830s.

In an expansion of work by Sheldon (1912) on the Appalachian Plateau, east-northeast fractures were mapped across a region large enough to sample rocks through a 20° swing of the Appalachian oroclinal bend (Parker, 1942). Parker (1942) relabeled the strike joints in Sheldon (1912) as set III (accompanying paper Table 2 and in this Datashare). This was necessary because the azimuth of these set III joints (i.e., the east-northeast set) did not follow around the oroclinal bend as defined by fold axes. Parker (1942, p. 406) writes, "Their different character and constant strike over the whole region point definitely to an independent origin, perhaps simultaneous or perhaps much later." He was uncertain about the time of propagation by adding, "Possibly they formed early during the Acadian disturbance or perhaps much later during the post-Triassic Palisade movements" (Parker, 1942, p. 406). For more than 70 yr, geologists have known that east-northeast fractures did not form as a consequence of major Alleghanian folding and faulting, per se. The set III joints in Parker (1942) are J1 if they propagated before Alleghanian folding and J3 if they propagated afterward.

J1 JOINTS

At the Bear Valley strip mine in the anthracite district of Pennsylvania, the sequence of brittle fractures starts with the propagation of a pre-Alleghanian set of systematic joints in coal that strike between 050° (N50°E) and 070° (N70°E) (Nickelsen, 1979). Nickelsen (1979, p. 230) correlates the pre-Alleghanian joint set with other joints in the Appalachian Basin by stating, "Joints in coal are not symmetrical with any of the later structural stages recognized in the mine, but they do parallel the

Table 2. Comparative Terminologies within Selected Joint Studies in the Appalachian Basin

	Joint Sets (Chronology Implied Only at the Level of J1, J2, J3, Neotectonic, and Late Erosion)										
	Bed-Parallel	East-Northeast (J1)	Cross-Fold (J2)	Cross-Fold (J2)	Cross-Fold (J2)	Cross-Fold (J2)	Cross-Fold (J2)	Cross-Fold (J2)	Fold- Related	Neotectonic (J3)	Neotectonic	Late Erosion
		Approximate Orientation Range										
Author (Chronological)		40°–80°	280°–300°	295°–315°	310°–330°	325°–345°	340°–0°	355°–15°	Strike Joints	Northeast to East-Northeast	Horizontal	Cross Joints
Hall (1843)	–	–	–	–	–	–	Wood block print	–	–	Wood block print	–	–
Sheldon (1912)	–	–	–	–	–	–	Dip {GS and ST} (D)	–	–	Strike {BS} (D)	–	–
Parker (1942)	–	–	–	–	–	–	Set I {SS and ST} (D)	Set I {SS/ST} (D)	–	Set III (D)	–	Set II (D)
Ver Steeg (1942)	–	–	Dip {SS}	Dip {SS}	–	–	–	–	–	–	–	–
Nickelsen and Hough (1967)	–	Coal joints	Set C	Set B	Set A	Set A	Set D	Set E	–	–	–	–
Secor (1969)	–	–	–	–	–	–	Episodic joints	–	–	–	–	–
Nickelsen (1979)	–	Coal joints	–	–	–	–	–	–	–	–	–	–
Engelder and Geiser (1980)	–	–	–	–	Set Ib	Set Ib	Set Ia	Set Ia	–	–	–	Set II
Engelder (1982)	–	–	–	–	–	–	–	–	–	{BS} (neotectonic)	–	–
Bahat and Engelder (1984)	–	–	–	–	–	–	C-rhythmic	–	–	–	–	–
Hancock and Engelder (1989)	–	–	–	–	–	–	–	–	–	{Lst} (O)	–	–
Srivastava and Engelder (1990)	Veins (O)	–	–	–	–	–	Veins (O)	–	Veins (O)	–	–	–
Engelder and Gross (1993)	–	–	–	–	–	–	–	–	–	Curvy cross joints	–	–
Kulander and Dean (1993)	–	Domain 6 joints	–	–	–	–	–	–	–	–	–	–
M. A. Evans (1994)	–	–	Stage III CFJV3a	Stage II CFJV2b	Stage II CFJV2a	–	Stage 1 CFJV1	–	Stage IV SJV	Stage V CFJ4	–	–
Zhao and Jacobi (1997)	–	–	–	–	Northwest-striking	–	–	–	–	–	–	–
Ruf et al. (1998)	–	–	–	–	Partially filled	–	–	–	Joints (D)	–	–	Cross joints
Younes and Engelder (1999)	–	J1 {GS} (D)	–	–	–	–	J2	J2	–	–	–	–
G. G. Lash and Engelder (2005)	Bitumen (D)	–	–	–	–	–	–	–	–	–	–	–
Engelder and Whitaker (2006)	–	(D-M-P)	–	–	–	–	–	–	–	–	–	–
Engelder et al. (2009)	–	J1 {BS}	–	J2	J2	J2	J2	J2	–	J3	–	–
M. A. Evans (2010)	–	Pre-North Mtn.	–	–	North Mtn. Stg.	–	Pre-North Mtn.	–	–	–	–	–
Wilkins et al. (2014)	–	–	–	–	–	CSV {BS} (D)	CSV {BS} (D)	–	–	–	–	–
M. A. Evans et al. (2014)	Veins	–	Veins	–	Veins	–	–	–	Veins	–	–	–
Tan et al. (2014)	–	–	–	–	–	J1	J1	–	–	–	–	–
Lacazette and Morris (2015)	–	–	–	–	–	TFI {BS} (D)	TFI {BS} (D)	–	–	–	–	–
Hooker et al. (2017)	–	–	–	–	–	Veins	–	–	–	Veins	–	–
Engelder and Gross (2018)	–	–	–	–	–	–	–	–	–	–	Pancake	–
Present paper	–	J1	–	–	–	–	J2	J2	–	J3	–	–

Shown are joint and vein sets of the Appalachian Basin sorted by orientation from 29 different studies. Each column contains the names that likely apply to the same fracture set. The letter in parentheses is the geological period of the host rock (e.g., D is Devonian, etc.). The letter in brackets is the rock type (e.g., BS is black shale). A more detailed explanation of this table is found in the supplementary material available as AAPG Datashare 129 at www.aapg.org/datashare.

Abbreviations: – = not applicable; BS = black shale; CFJ4 = cross-fold joints; CFJV1 = cross-fold joints and veins; CFJV2a = cross-fold joints and veins; CFJV2b = cross-fold joints and veins; CFJV3a = cross-fold joints and veins; C-rhythmic = cross-fold joints; CSV = cross strike vein; D = Devonian; GS = gray shale; J1 = east-northeast joints (pre-cross-fold); J2 = cross-fold joints; J3 = east-northeast joints (post-cross-fold); M = Mississippian; Mtn. = Mountain; O = Ordovician; P = Pennsylvanian; SS = sandstone; ST = siltstone; Stg. = stage; SJV = strike joints and veins; TFI = tomographic fracture image.

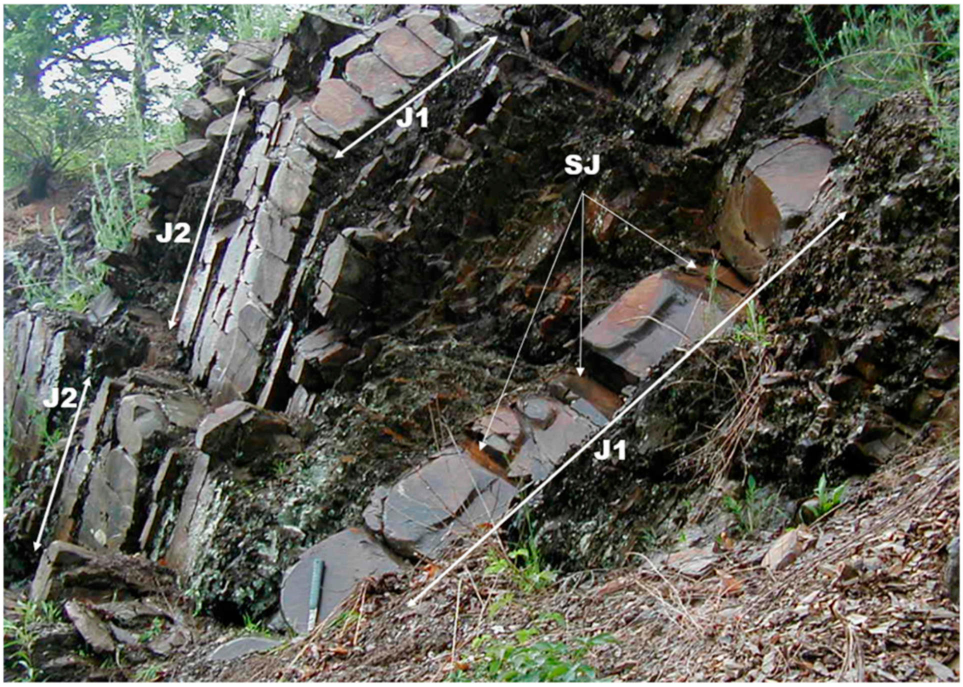

Figure S1. Joint development in the Devonian Brallier Formation along the Allegheny structural front, Pendleton County, West Virginia. The east-northeast joints (pre-cross-fold) (J1), cross-fold joints (J2), and strike joints (SJ) well developed in turbidite beds (Engelder, 2004).

systematic joints at the eastern end of the arc of set I [not set I by Parker, 1942] joints in coal described on the Appalachian Plateau, 60 km to the northwest (Nickelsen and Hough, 1967, plate 3, p. 619)." The Bear Valley paper was the first to unequivocally conclude that a fracture set in the east-northeast orientation was pre-Alleghanian and thus a bona fide early (J1) joint set. Evidence for timing was based on a geometric argument (Nickelsen, 1979). It seemed intuitive to Nickelsen (1979) that bed-normal joints propagated vertically and were later reoriented with folding. In fact, Parker (1942) used this same reasoning to date his set II joints as prefolding. The same argument applies as well to other places in the Appalachian Basin (Kulander and Dean, 1993; Engelder and Whitaker, 2006).

The Allegheny structural front near the Virginia–West Virginia border is one part of the central Appalachian Mountains where the nonorthogonality of east-northeast fractures and Alleghanian structures is well developed. There, east-northeast fractures are common in the Silurian through Devonian shale section of the Valley and Ridge where they propagated prior to the development of any Alleghanian structures (Evans, 2010). In the carbonates of this region, prefolding east-northeast veins were formed at depths of less than 4100 m, which was an overburden thickness involving just the Devonian–Carboniferous section, leaving open the possibility that east-northeast fractures in the region are Acadian rather than Alleghanian (Evans et al., 2012). One outcrop of fractures in the Brallier Formation of the Virginia–West Virginia region illustrates why both Engelder (2004) and Evans (2010) interpret east-northeast joints as prefolding (Figure S1). Here, the east-northeast joints remain normal to bedding while tilted at an odd angle relative to the dip of bedding and the axes of local folding. Early jointing is common in other mountain belts as well (Silliphant et al., 2002). Tilted, bed-normal east-northeast joints appear in several locations along the Allegheny structural front from Pennsylvania to Virginia, further reinforcing the perception that they predate Alleghanian folding (Engelder and Whitaker, 2006). However, it is puzzling that early joints show no evidence of either vein development or later slip despite the likelihood that they were subject to both deep fluid circulation and a significant shear traction during folding (Figure S1).

Although folding of east-northeast joints along the Allegheny Front near the Virginia–West Virginia border and the earliest coal cleat at Bear Valley both point to a pre-Alleghanian (J1) episode of east-northeast fracturing in the Appalachian Basin, other observations lead to the same conclusion including an east-northeast vein set in the Lockport Dolomite in western New York (Gross et al., 1992). At the Snook Quarry in Antis Fort, Pennsylvania, a bed-normal east-northeast set was rotated 110° as bedding was overturned by folding during the Alleghanian orogeny (Engelder et al., 2009). Offset of east-northeast joints by horizontal slip along J2 joints provides yet another datum consistent with the notion that east-northeast joints formed before the J2 set in Devonian gas shale of the Appalachian Plateau (Engelder et al., 2001). A statistical analysis of fracture-spacing data of east-northeast joints and veins in the Oatka Creek Member of the Marcellus at the Wolfe Quarry in Union Springs, New York, also fits the interpretation that east-northeast fractures propagated before being crosscut by J2 joints (Gale et al., 2013, 2014).

The early J1 set propagated in the direction of the maximum horizontal stress in a tectonic stress field dating from circa 320 to 290 Ma. By plate tectonics processes, the early J1 joint set was rotated into its present east-northeast orientation (see Engelder and Whitaker, 2006). It is important to emphasize that the maximum horizontal tectonic stress of circa 320 to 290 Ma was not in the east-northeast orientation. By coincidence, the maximum horizontal stress of the contemporary tectonic stress field rotated to the same east-northeast direction but much later than the rotation of the tectonic plates carrying the J1 joint set. After the contemporary tectonic stress field established itself, the J3 joint set propagated in the direction of the maximum compressive stress of the contemporary tectonic stress field.

A case has been made by at least six independent research groups that there is an early J1 joint set in the Appalachian Basin. The evidence seems compelling and, yet, there are alternative working hypotheses with the accompanying paper presenting one example.

J2 JOINTS

Up through and including the Bear Valley study by Nickelsen (1979), geologists noticed that fractures in the cross-fold orientation developed in multiple sets (Parker, 1942; Nickelsen and Hough, 1967). Sheldon (1912, p. 75) simply stated "dip joints do not belong to a single set." Parker (1942, p. 385) described set I joints as "double" and constituting a regional pattern that swings around the oroclinal bend. At Bear Valley, Nickelsen (1979, p. 232) recognized, "Two different sets of systematic joints formed as the principal stress axes rotated in the plane of the still horizontal bedding." Evidence at Bear Valley suggested that even cross-fold joints (i.e., the J2 set of Engelder et al., 2009) were early relative to folding. In other studies (see Table 2 in the main text of accompanying paper), fractures from multiple sets of cross-fold joints were labeled dip joints (Ver Steeg, 1942), sets A, D, and E (Nickelsen and Hough, 1967), sets Ia and Ib following terminology by Parker (1942), (Engelder and Geiser, 1980), stages I–III (Orkan and Voight, 1985), stages 1, 2a, and 2b (Evans, 1994), northwest striking (Zhao and Jacobi, 1997), parent joints and fringe cracks (Younes and Engelder, 1999), J2 joints (Gale et al., 2013), cross-strike veins (Wilkins et al., 2014), veins (Evans et al., 2014), J2 joints (Tan et al., 2014), and tomographic fracture images (Lacazette and Morris, 2015). Fluid inclusions in veins of the J2 sets indicate trapping conditions consistent with the deeper phases of burial accompanying the Alleghanian orogeny. Some later vein filling was emplaced during the early phases of exhumation of the Appalachian Basin (Evans et al., 2014; Wilkins et al., 2014). The multiple orientations for Alleghanian J2 joints and veins is evidence that the Alleghanian stress field did not remain in a fixed orientation in either space or time before folding or during fold amplification (Engelder and Geiser, 1980; Zhao and Jacobi, 1997; Younes and Engelder, 1999). This is consistent with the observation that joints and veins continue to propagate over extended periods of geological time (Becker et al., 2010).

In sum, because the central Appalachian Mountains constitute an oroclinal bend, the strike of folds varies by as much as 60° (Rodgers, 1970). Cross-fold fractures (i.e., J2 mode I cracks: both joints and veins) have various orientations around the oroclinal bend. The J2 fractures may encompass more than one joint set in a single outcrop and even in a single bed (Zhao and Jacobi, 1997; Younes and Engelder, 1999). The east-northeast sets (i.e., J1 and J3) are more difficult to interpret because they do not have a clear geometric relationship with the oroclinal bend but rather remain more consistent in orientation, striking between northeast-southwest and east-northeast–west-southwest, regardless of location (Parker, 1942; Evans, 1994; Engelder and Whitaker, 2006). In several instances, geological evidence points to east-northeast fractures predating Alleghanian folding, hence the label J1 (Nickelsen, 1979; Engelder et al., 2001; Gale et al., 2013). East-northeast fractures appear in rock outcrops on both the foreland and hinterland sides of Appalachian Plateau for which arguments support an early origin (Engelder et al., 2009). However, an interpretation of these observations is not straightforward as is demonstrated in the accompanying paper.

J3 JOINTS

During the mapping of the Bear Valley strip mine in the 1970s, the plate tectonics paradigm gave a context for the contemporary tectonic stress field with its maximum horizontal stress (S_{Hmax}) in the same orientation as east-northeast joints in the Appalachian Basin (Sbar and Sykes, 1973). The strike joints in Sheldon (1912), those to the right of Taughannock Falls in the print by Hall (1843), have an azimuth to the east-northeast; was this a coincidence or were east-northeast joints genetically related to the orientation of the contemporary tectonic stress field? East-northeast–striking joint sets are common in several geological settings with black shales, including the Michigan and Illinois Basins (Engelder, 1982). Such an abundance led Engelder (1982) to ask if the set III joints (Parker, 1942) in black shale were post-Alleghanian (i.e., J3 joints). If so, these qualified as neotectonic joints (Hancock and Engelder, 1989). A correlation in orientation between set III (Parker, 1942) and the orientation of S_{Hmax} of the contemporary tectonic stress field was a necessary condition for identifying neotectonic joints but not sufficient because its orientation relative to Alleghanian structures did not preclude a pre-Alleghanian age. This is particularly true when east-northeast and J2 joints crosscut in outcrops of different black shales (i.e., Marcellus, Geneseo, Middlesex, Rhinestreet, and Dunkirk–Huron) throughout the foreland (northwest) fringe of the Appalachian Basin (G. Lash et al., 2004) (accompanying paper Figure 4). However, in Hancock and Engelder (1989), the interpretation of J3 is based the observation that east-northeast joints cut vertically through Ordovician carbonates tilted during the Alleghanian orogeny.

Difficulties are encountered when drawing a distinction between early east-northeast joints in the Appalachian Basin (i.e., the J1 set) and late east-northeast joints that are candidates for a neotectonic set (i.e., the J3 set) (Hancock and Engelder, 1989). Sure indicators of neotectonic joints are curvy cross joints (Engelder and Gross, 1993) and joints cutting vertically through dipping beds (Hancock and Engelder, 1989). The premise of the (Hancock and Engelder, 1989) paper was that vertical neotectonic joints propagate in the near-surface environment. Yet the difficulty with the near-surface interpretation is that in the top 500–1000 m of sedimentary basins, the minimum horizontal stress is greater than the vertical stress, which should not permit the formation of vertical joints (Plumb, 1994; Nadan and Engelder, 2009). It became a challenge to explain the mechanism for propagation of late-formed vertical joints in an earth stress that favors horizontal propagation in the top half kilometer of sedimentary basins. This is also the zone populated by pancake joints in the Ordovician Utica black shale (Engelder and Gross, 2018) as well as sheet joints in granite (Nadan and Engelder, 2009).

Sheldon (1912) noted that east-northeast joints were common in rocks immediately above Devonian black shales in the Ithaca, New York, area. In keeping with our observations concerning fracture development in the Devonian section, we note that east-northeast lineaments are common in the Ordovician Lorraine and Queenston Shales above the Utica formation in the Niagara frontier between Buffalo and Rochester, New York (Figures S2, S3). Given the location of these shales just above the Ordovician Utica/Point Pleasant black shales, it seems possible that the same mechanism (i.e, the Skempton effect on exhumation in the contemporary tectonic stress field) might be responsible for natural hydraulic fracturing and the prominent fracture fabric in the Lorraine and Queenston Shales of western New York. This is at odds with the Gross et al. (1992) interpretation of east-northeast veins in the Lockport dolomite along the Niagara frontier.

Finally, it should be clear to anyone who has carefully studied the literature on jointing in the Appalachian Basin that we have struggled to reach a conclusion about the timing of east-northeast joints in black shale of the Appalachian Basin (G. G. Lash and Engelder, 2009). For example, Engelder et al.

Figure S2. Google Earth image of the Niagara frontier between Buffalo and Rochester, New York. East-northeast lineaments of up to 7 km in length are denoted with white arrows. The location of the four images presented in Figure S3 are indicated with dashed boxes labeled A, B, C, and D. The latitude (lat) and longitude (lon) indicate the approximate location of the center of the image.

(2001) interpret the displacement of east-northeast joints in Ithaca, New York, by slip on J2 joints as an indication that the east-northeast joints were early (i.e., J1 joints). We did entertain the possibility that such displacement was a consequence of glacial shove. Presently, we feel that the glacial shove hypothesis deserves further consideration.

Causal Stress and Stress Field Orientation

Although Sheldon (1912) recognized a geometric relationship between Appalachian Basin folding and fracturing, finding a causal stress proved more difficult (Bucher, 1921). The early literature had statements such as, "It is most likely that the (tectonic) stress which caused the folding also caused the various joint sets of the area…There appears to be no reason for believing otherwise" (Wedel, 1932, p. 33). Sheldon (1912) observed two (J2) joint sets in the dip direction and to explain this, later geologists drawing upon an image of laboratory conjugate shear fractures invoked shear failure as the mechanism for creating more than one joint set in an outcrop. Parker (1942, plate 1, figure 1) shows cross-cutting J2 joints with a later joint clearly abutting an early joint, an indication that these are not conjugate shear fractures. Confusion over the distinction between conjugate shear fractures and two joint sets persisted into the second half of the twentieth century (Muehlberger, 1961; Stearns, 1968). During early studies, geologists failed to understand that only one joint set could form at a time without unduly complex boundary conditions. This confusion should have ended with the introduction of the theory of linear elastic fracture mechanics (LEFM) with its rules for crack propagation in brittle solids (Lawn and Wilshaw, 1975; Pollard and Aydin, 1988). Once the rules of crack propagation were established by LEFM, the challenge was linking a particular joint set to one of four different driving mechanisms (Engelder and Fischer, 1996). Three mechanisms were tensile and the fourth was a fluid drive leading to natural hydraulic fractures (NHFs). Natural hydraulic fracturing is implicitly recognized when zero effective stress failure criteria are applied to identify tensile failure (English, 2012), extension fractures (Narr and Currie, 1982), or load-parallel extension fractures (Lorenz et al., 1991).

The distinction between the three tensile driving mechanisms and a fluid driving mechanism is important.

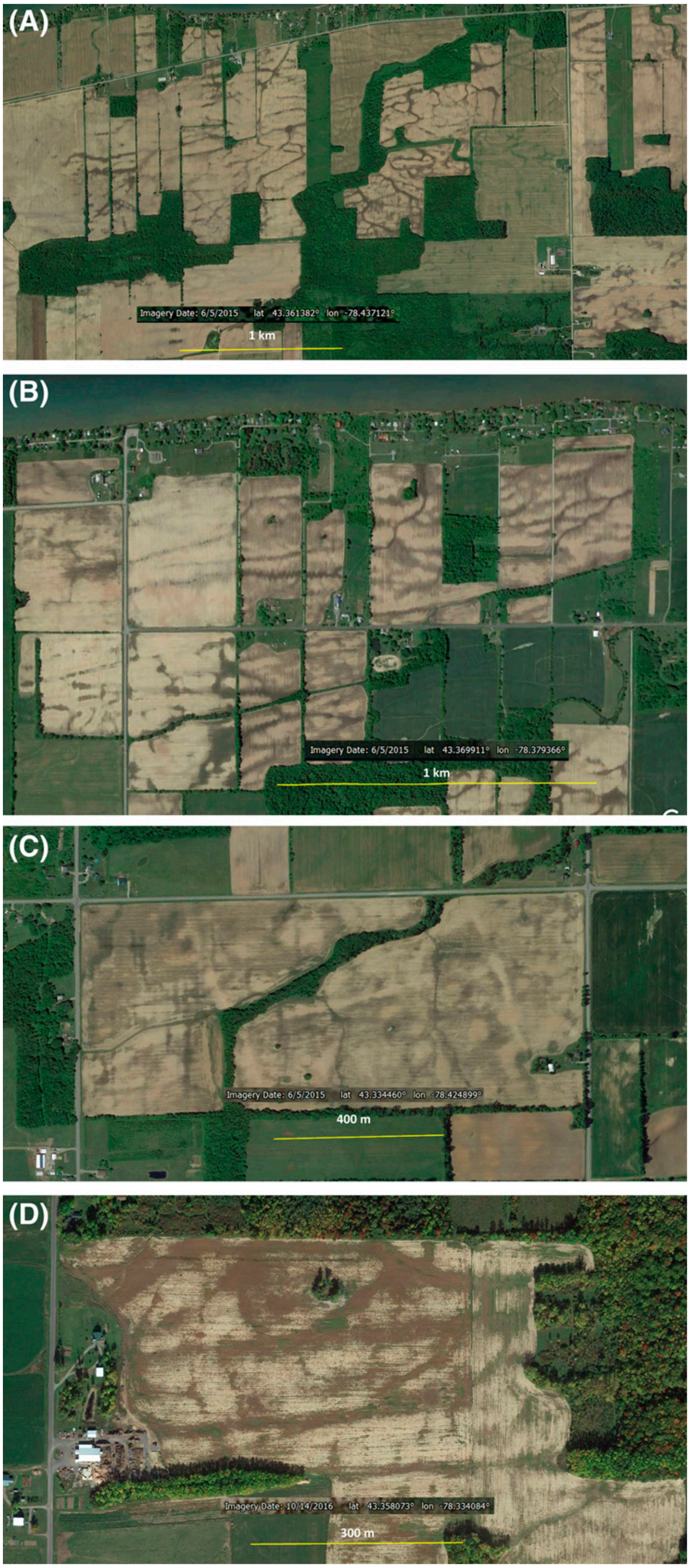

Figure S3. Four Google Earth images of east-northeast lineaments defined by soil moisture and vegetation along the Niagara frontier between Buffalo and Rochester, New York. The latitude (lat) and longitude (lon) in each figure indicate the approximate locations of the center of each image. Locations of figures (A)–(D) are shown in Figure S2.

The surface morphology of NHF evolves depending on the orientation and timing of propagation (Savalli and Engelder, 2005). One might interpret a difference in morphology, particularly when there are joints at high angles in the same bed and only one displays an evolving morphology, as the manifestation of the difference between true tension and fluid-driven propagation (Ruf et al., 1998; Engelder, 2004). The NHFs propagating at depth tend to crosscut because joint-normal stress is sufficient to allow the transmission of crack-tip stress concentrations across existing discontinuities including both thin beds and preexisting joints (Helgeson and Aydin, 1991). Crossing interfaces, particularly J2 joints, is a characteristic of east-northeast joints in black shales of the Appalachian Basin (G. G. Lash and Engelder, 2009).

Commonly, joint propagation in the Middle and Upper Devonian section of the Appalachian Basin evolves. It takes place during cyclic episodes at low effective stress (Bahat and Engelder, 1984). The idea of episodic propagation of joints in Devonian rocks inspired the first model for natural hydraulic fracturing (Secor, 1965, 1969). The interpretation of these cyclic episodes as evidence of NHF stood the test of time, but an understanding of their mechanical significance has evolved (Engelder, 2007; Raaen, 2013). An earlier interpretation was that the propagation episodes are a manifestation of gas as the driving fluid because of its higher compressibility (Lacazette and Engelder, 1992). A later interpretation pointed out that fracture compliance is the governing mechanical parameter leading to cyclic propagation (Raaen, 2013). Even if the latter interpretation proves correct, Raaen (2013) points out that episodic fracture growth is a manifestation of natural hydraulic fracturing. Furthermore, the presence of unmineralized joints points to gas rather than water as the primary driving mechanism for reducing effective stress, if not the primary cause for episodic growth. The episodic propagation reflects a recurring driving stress (actually a pressure), which is understood by applying the gas law (Lacazette and Engelder, 1992). During a propagation event, the crack volume increases, causing a pressure drop, which in turn causes a drop in stress intensity at the crack tip; that drop either slows propagation or stops it entirely (Savalli and Engelder, 2005; Engelder, 2007).

Remapping of the strike joints in Sheldon (1912) (i.e., the east-northeast set) throughout upstate New York demonstrated that these joints are best developed in black shales of Ordovician and Devonian age (G. Lash et al., 2004; G. G. Lash and Engelder, 2009; Engelder and Gross, 2018). The affinity between east-northeast joints and Devonian black shale in the Illinois and Michigan Basins is also unmistakable (Engelder, 1982). Aside from compaction disequilibrium, maturation of organic matter is another mechanism for generating pore pressure that is capable of reducing an effective normal stress to zero and driving NHFs (Meissner, 1978; Osborne and Swarbrick, 1997). Although gray shale exhibits compaction disequilibrium (Engelder and Oertel, 1985), maturation is much stronger in black shales, the host of the densest development of east-northeast joints in the Appalachian Basin (G. Lash et al., 2004; G. G. Lash and Engelder, 2009). The triad of black shale, maturation-related pore pressure, and east-northeast joints points toward a driving stress for east-northeast joints involving natural hydraulic fracturing in response to the maturation of organic-rich black shale. Furthermore, evidence for natural hydraulic fracturing in the Appalachian Basin is abundant (Lacazette and Engelder, 1992; McConaughy and Engelder, 1999). For example, high pore pressure is indicated by the abundance of bed-parallel slickensides in the Marcellus gas shale (Evans, 1994; Aydin and Engelder, 2014; Wilkins et al., 2014).

Nevertheless, the link between some joints and veins, mainly J2, and the orientation of Alleghanian-aged tectonic stress fields at the time of propagation is so firmly ingrained in modern interpretations that it is accepted as fact (Nickelsen and Hough, 1967; Engelder and Geiser, 1980; Zhao and Jacobi, 1997; Younes and Engelder, 1999; Hooker et al., 2017). Orientation of the stress field is important even if tectonic deformation did not generate the causal stress for joint propagation. If J3 and S_{Hmax} of the contemporary tectonic stress field are genetically related, that relationship controls the orientation of J3 but offers no information about the mechanism causing the propagation of J3 joints.

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