E&P NOTE

Joint sets that enhance production from Middle and Upper Devonian gas shales of the Appalachian Basin

Terry Engelder, Gary G. Lash, and Redescal S. Uzcátegui

ABSTRACT

The marine Middle and Upper Devonian section of the Appalachian Basin includes several black shale units that carry two regional joint sets (J_1 and J_2 sets) as observed in outcrop, core, and borehole images. These joints formed close to or at peak burial depth as natural hydraulic fractures induced by abnormal fluid pressures generated during thermal maturation of organic matter. When present together, earlier J_1 joints are crosscut by later J_2 joints. In outcrops of black shale on the foreland (northwest) side of the Appalachian Basin, the east-northeast–trending J_1 set is more closely spaced than the northwest-striking J_2 set. However, J_2 joints are far more pervasive throughout the exposed Devonian marine clastic section on both sides of the basin. By geological coincidence, the J_1 set is nearly parallel the maximum compressive normal stress of the contemporary tectonic stress field (S_{Hmax}). Because the contemporary tectonic stress field favors the propagation of hydraulic fracture completions to the east-northeast, fracture stimulation from vertical wells intersects and drains J_2 joints. Horizontal drilling and subsequent stimulation benefit from both joint sets. By drilling in the north-northwest–south-southeast directions, horizontal wells cross and drain J_1 joints, whenever present. Then, staged hydraulic fracture stimulations, if necessary, run east-northeast (i.e., parallel to the J_1 set) under the influence of the contemporary tectonic stress field thereby crosscutting and draining J_2 joints.

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INTRODUCTION

Devonian–Mississippian gas shale in the Appalachian Basin is particularly susceptible to joint growth, an observation dating from the early 19th century geological survey of New York state (Hall, 1843). By the early 20th century, geologists recognized that fracture by joint growth in black shale differs in orientation and density when compared with joint growth within gray shale and siltstones of the Appalachian Basin (Sheldon, 1912). Mapping of joints throughout the northern Appalachian Basin revealed that more than one black shale formation, including those of the Marcellus Formation (Ver Straeten and Brett, 2006), hosts the same east-northeast–striking joint set (Parker, 1942). Moreover, mapping of east-northeast joints in black shale of the Illinois Basin confirmed that the affinity between joint growth and Devonian black shale extends beyond the confines of the Appalachian Basin (Campbell, 1946). Viewed in hindsight, data collected through the mid-20th century point to a common post-Devonian growth mechanism that originated within black shale formations accumulating over more than 30 m.y. of the Middle to Late Devonian (Figure 1).

The timeline for industrial development of fractured Devonian shale in the Appalachian Basin starts with production from the Dunkirk Formation at Fredonia, New York, in 1821 and from the Marcellus Formation within the Naples field, New York, in 1880 (Van Tyne, 1983). Production began in the Huron (Dunkirk equivalent) black shale of the Big Sandy field, Kentucky, in 1914 (Hunter and Young, 1953). From 1821, it took industry more than a century to recognize the critical function that natural fractures have in economic gas production (Browning, 1935). Through 1953, natural-fracture-aided gas production from Devonian black shale in Kentucky, mainly from the Huron (Dunkirk equivalent) black shale of the Big Sandy field, had approached nearly 1 tcf (Hunter and Young, 1953). Indeed, some of the early wells in the fractured Huron and Rhinestreet formations produced for 50 yr (Vanorsdale, 1987). By the 1970s, however, matrix porosity was considered to exert the principal control on long-term production from black shale, thereby subordinating natural fractures to the function of high-permeability pathways (Smith et al., 1979). Initially, interconnectivity with natural fractures was achieved by shooting nitroglycerin in gas wells, but by the 1980s, this practice was supplanted by nitrogen, carbon dioxide, and foam-fracturing agents (Sweeney et al., 1986).

Horizontal drilling arrived in the Appalachian Basin in 1944 as a means of producing heavy crude oil from the Venango

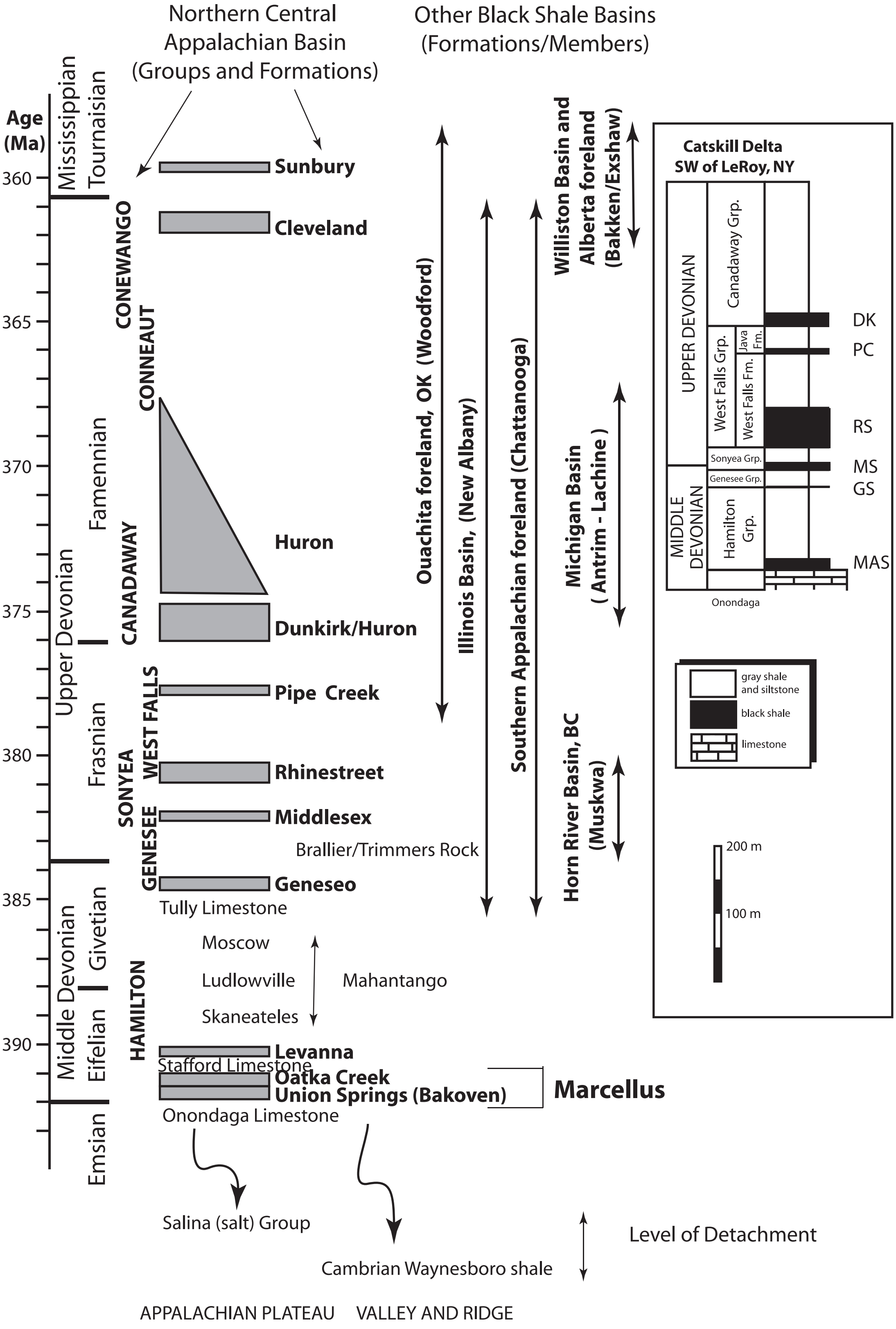


Figure 1. Stratigraphy of North American black shales with a focus on the northern central Appalachian Basin. Only the names of black shale units are given. The vertical scale for units outside the inset box is time and not thickness. The Devonian black shales are dated using conodonts and tied to absolute time with ash beds (Over, 2002, 2007; Stasiuk and Fowler, 2004; Kaufmann, 2006; Over et al., 2009). Many erosional surfaces punctuate the deposition of Devonian black shale so sections are mostly discontinuous. A stratigraphic section of the Catskill delta southwest of Leroy, New York, is scaled for thickness (inset box). The black shales of western New York include Dunkirk (DK), Pipe Creek (PC), Rhinestreet (RS), Middlesex (MS), Geneseo (GS) (found in central New York), and Marcellus (MAS).

sandstone following the depletion of its solution gas (Overby et al., 1988). Devonian black shale of West Virginia was tested with high-angle or slant drilling starting in 1972, and a horizontal test was completed in 1987 (Yost II et al., 1987a). The 1987 lateral was aimed S37°E because several subsurface data sets mostly from the U.S. Department of Energy Eastern Gas Shales Project (EGSP) showed that this orientation crossed the highest density of natural fractures, an east-northeast set (Cliffs Minerals, 1982; Yost II et al., 1987b). At about the same time, the Devonian Antrim gas shale was tested in the Michigan Basin with slant wells designed to crosscut natural fractures (Hopkins et al., 1998). Full-scale development of the Huron (Dunkirk equivalent) of the Big Sandy field, Kentucky, commenced in the 2000s where one in five horizontal wells (of 80 drilled to date) flows with enough volume to forgo stimulation, a clear indication of wellbores crossing east-northeast joints (Gerber, 2008). When stimulation is required, nitrogen and foam are commonly used as the fracturing medium in the underpressured Huron (Dunkirk equivalent) black shale.

Unlike the relatively shallow Huron (Dunkirk equivalent) black shale, every economic horizontal well in deeper Devonian–Mississippian gas shale requires stimulation with technological breakthroughs, including slickwater fractures and multistage fracturing (Fontaine et al., 2008). These stimulation techniques were perfected in the Cretaceous Cotton Valley of east Texas and Mississippian Barnett black shale of the Fort Worth Basin, Texas (Walker et al., 1998), and soon applied to other black shale plays, including the Woodford (Oklahoma), Fayetteville (Alaska), Marcellus (Maryland, New York, Pennsylvania, Ohio, West Virginia), and Haynesville (Louisiana) (Figure 2). The first horizontal wells in the Marcellus Shale of Pennsylvania date from 2006, and 47 horizontal wells have spud dates thru 2008 according to Pennsylvania Department of Environmental Protection records. As of early 2009, the most voluminous 24-hr flow test showed 24.5 mmcf/day in Washington County, Pennsylvania.

The Marcellus black shale of the Appalachian Basin constitutes one class of unconventional reservoir from which production is optimized if horizontal drilling penetrates a systematic fracture set (Curtis and Faure, 1997; Curtis, 2002; Law, 2002). In deeper, thermogenic black shale plays, the extent to which productivity is enhanced by stimulation of natural fractures remains a question. Here, stimulation is understood to mean the linking of natural, higher permeability pathways to horizontal wellbores. Citing experience gained from the Barnett Shale, some have questioned the paradigm that natural fractures are requisite for a successful play (Bowker, 2007). Indeed, questions remain regarding the nature of fracturing of the Marcellus Shale in the subsurface. The immediate purpose of this article is to present new outcrop data showing that the Marcellus gas shale, at least in places in the northern Appalachian Basin, has the same fracture pattern that makes for successful production from the Huron (Dunkirk equivalent) black shale, even in the absence of stimulation. These outcrop data are consistent with published data from the core that testify to the presence of unhealed fractures at depth. The economic importance of unhealed fractures in gas shales lends exigency to an extended discussion of the present understanding of the origin, orientation, and distribution of joints in the Marcellus and other black shales of the Appalachian Basin.

Marcellus and Its Tectonic Heritage

The Appalachian Basin contains eight major black shale units, most placed at or near the bottom of stratigraphic groups such as the Middle Devonian Hamilton (Ettensohn, 1985) (Figure 1). The lower part of the Hamilton Group comprises more than one black shale, including the Marcellus Formation whose basal unit, the Union Springs Member, contains greater than 10% total organic carbon (TOC) (Werne et al., 2002; Desantis et al., 2007). The prospective thickness of the Hamilton Group reaches 400–500 ft (122–152 m) where the overlying Oatka Creek Member of the Marcellus Formation and the Mahantango Formation are incorporated into completion strategies. The areal extent of the Marcellus Formation with at least 50 ft (15 m) of a high API gamma-ray signal exceeds 34×10^6 ac (Figure 2), which, given the typical porosity and adsorption properties of Devonian

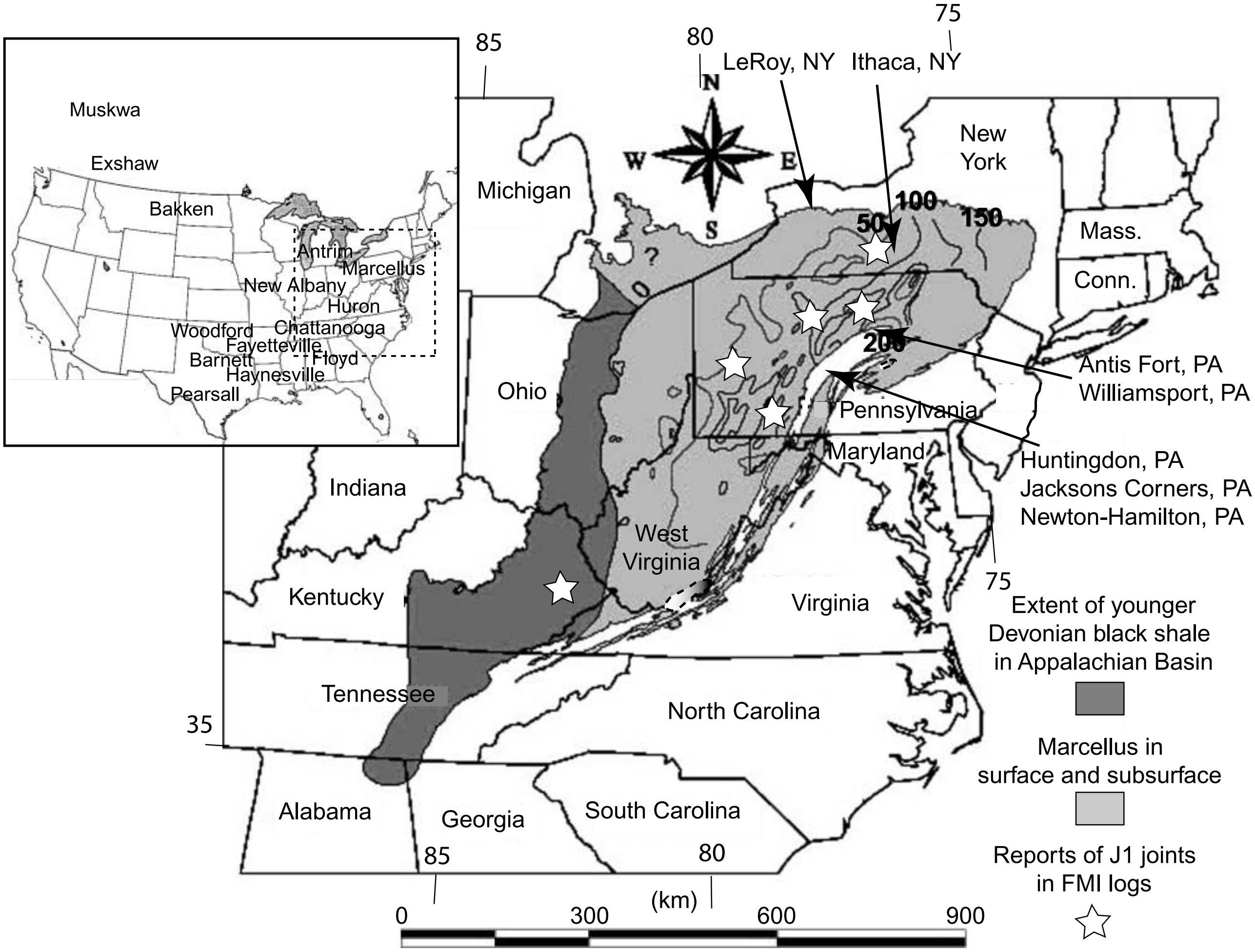


Figure 2. The areal extent of the Marcellus black shale in the Appalachian Basin (modified from Milici, 2005). Isopach contours on the Marcellus are 50-ft (15-m) intervals. Stars indicate the distribution of J_1 joints in the subsurface of the Appalachian Basin as reported to the authors by Marcellus Shale operators sharing proprietary data. The location of several North American Devonian black shales plus the Mississippian Barnett and Fayetteville and the Jurassic Haynesville is shown on the inset map.

black shale, translates to an excess of 1000 tcf and maybe as high as 3500 tcf of gas in place (Figure 2). All indications are that the Marcellus gas shale will develop into a super giant gas field.

The extent to which the Appalachian shales were incorporated into the deformation of a continent-continent collision, the Carboniferous–Permian Alleghany orogeny, separates the Marcellus and other Devonian gas shales of the Appalachian Basin from gas shales in several other North American basins (Rodgers, 1970; Hatcher et al., 1989). Although touched by Alleghanian tectonics, other Devonian gas shales linked to the Acadian foreland, including the New Albany and Antrim, were not subjected to the amount of layer-parallel shortening (LPS) seen by the Marcellus (Engelder and Engelder, 1977; Craddock and van der Pluijm, 1989). Layer-parallel shortening is a manifestation of detachment within the Silurian Salina salt and ancillary blind thrusts beneath the Marcellus (Wiltschko and Chapple, 1977; Davis and Engelder, 1985; Scanlin and Engelder, 2003) (Figure 3). The Devonian–Mississippian Woodford gas shale in the Ouachita foreland, Oklahoma, is structurally complex although the major Alleghanian detachment passes through the shallow Atoka, well above the Woodford (Durham, 2008). The Mississippian Barnett, Fayetteville, and Floyd gas shales in the Ouachita foreland were not subjected to large-scale LPS during the Alleghanian orogeny. The very eastern

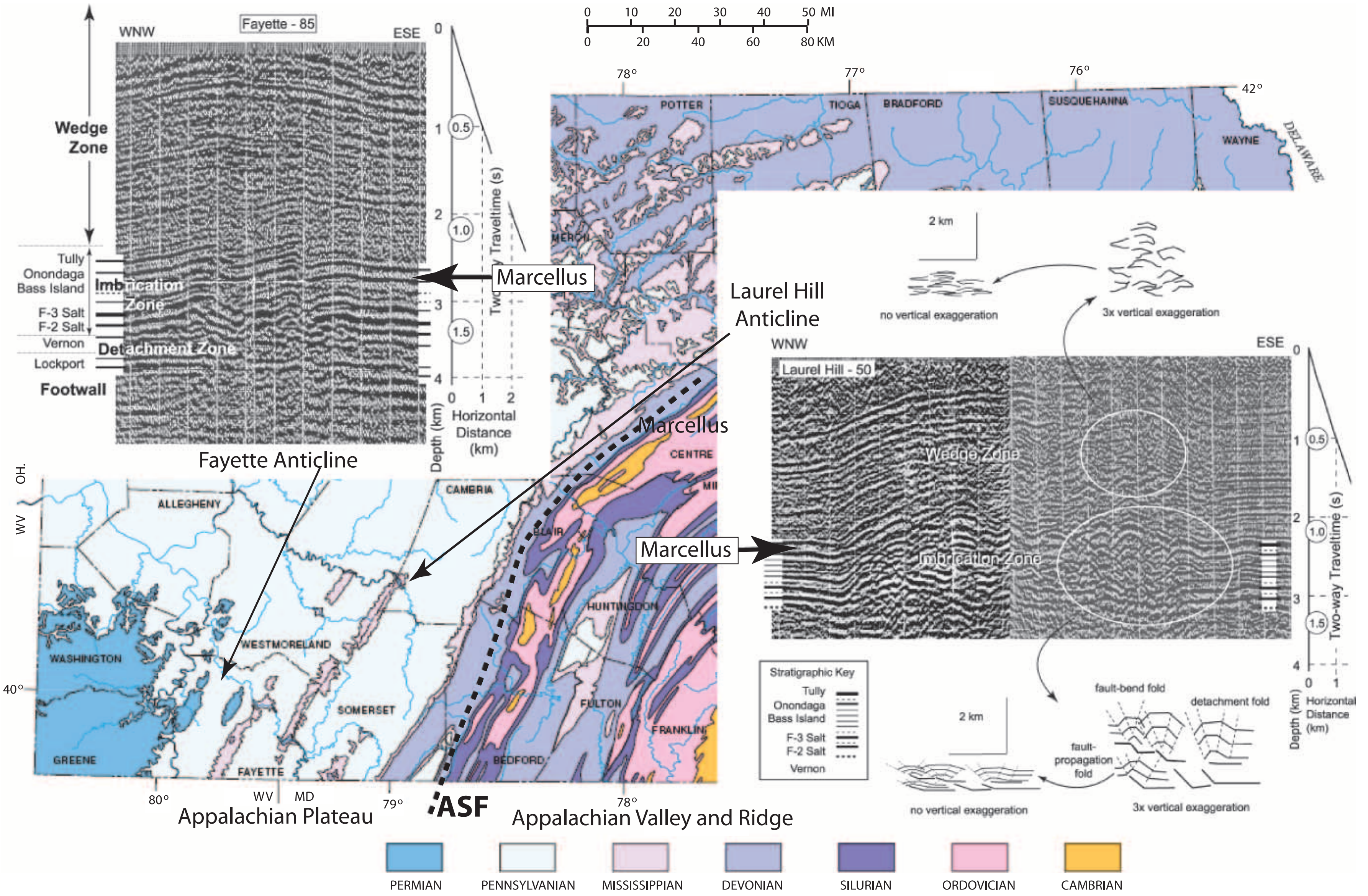


Figure 3. Two-dimensional seismic lines through the Laurel Hill and Fayette anticlines. The background is a geological map of the State of Pennsylvania showing the Allegheny structural front (ASF, dashed), which is the boundary between the Appalachian Plateau to the northwest and the Appalachian Valley and Ridge to the southeast. The stratigraphic position of the Marcellus is shown with heavy arrows. Seismic lines are modified from Scanlin and Engelder (2003). Refer to Figure 2 for the location of Pennsylvania.

part of the Floyd was incorporated in Alleghanian structures as a mushwad (Thomas, 2001). Such Mesozoic gas shales of the Gulf Coast region as the Haynesville-Bossier and the Pearsall were subjected to extensional tectonics with local salt movement forcing local but minor LPS.

Natural Fractures in the Appalachian Basin

Rock fracture occurs either by rupture in shear or rupture in tension. Rupture in shear yields faults (Handin and Hager, 1957), whereas rupture in tension leads to the propagation of joints (Pollard and Aydin, 1988). At depth in basins where stress is compressive, tension is an effective stress and joints are natural hydraulic fractures (Secor, 1965; Engelder and Lacazette, 1990). Faults are rarely systematic and are invariably concentrated in zones associated with a master fault or fold (Aydin and Johnson, 1978), whereas joints are frequently systematic and may be pervasive over large regions (Hodgson, 1961). Industry has established that joints of one systematic set in particular, the east-northeast set, are crucial to the success of horizontal completion techniques in the Appalachian Basin (Gerber, 2008). Systematic east-northeast joints have been observed in the core recovered from the Upper Devonian Huron (Dunkirk equivalent) black shale as part of the EGSP (Figure 4).

Outcrops of black shale within the Appalachian foreland commonly carry two systematic joint sets, herein referred to as the J_1 and J_2 sets (Sheldon, 1912; Parker, 1942; Engelder and Geiser, 1980; Lash et al., 2004; Lash and Engelder, 2007, 2009). The J_1 set is of particular interest because it strikes to the east-northeast and within a few degrees of the maximum horizontal compressive stress, S_{Hmax}, of the contemporary tectonic stress field (Sbar and Sykes, 1973; Engelder, 1982a; Zoback, 1992). The J_2 joints generally crosscut J_1 joints when the two sets are found in the same bed (Figure 5). In the Marcellus and other black shale units of the Appalachian Basin, the J_1 set is more closely spaced than the J_2 set (Figure 6). The affinity of J_1 joints for organic-rich shale was recognized a century ago (Sheldon, 1912); 30 yr lapsed before it was demonstrated that J_1 joints transect fold axes on the Appalachian Plateau at low angles and are unlikely to be fold related (Parker, 1942). Systematic J_1 joints were initially assigned a subordinate rank, set III, mostly because they are not well developed in the more abundant outcrops of gray shale and distal turbidites of the Catskill delta (Parker, 1942; Engelder and Geiser, 1980). Later still, J_1 joints were recognized in outcrops from Virginia to New York and interpreted to correlate with a strong east-northeast–trending coal cleat in Morrowan and Desmonian coal deposits scattered from Alabama to Pennsylvania (Engelder, 2004; Engelder and Whitaker, 2006).

The similar orientation of J_1 joints in black shales of the Appalachian Basin and the S_{Hmax} of the contemporary tectonic stress field lured many authors to the conclusion that all east-northeast–striking joints were de facto neotectonic and therefore related in some way to processes involving the contemporary tectonic stress field, including Tertiary exhumation or Pleistocene glaciation (Clark, 1982; Engelder, 1982a; Dean et al., 1984; Hancock and Engelder, 1989; Gross and Engelder, 1991; Engelder and Gross, 1993). These interpretations were challenged when it was noted that, in some places along the Appalachian Valley and Ridge, the early J_1 joints were folded along with bedding, a clear evidence of a pre- or early Alleghanian propagation history (Engelder, 2004). Finally, we understood that a pre- or early Alleghanian joint set, the J_1 set, occupies nearly the same orientation as Appalachian neotectonic joints and S_{Hmax} of the contemporary tectonic stress field (Pashin and Hinkle, 1997; Engelder, 2004; Engelder and Whitaker, 2006; Lash and Engelder, 2009).

The presence of early joints in black shale of the Appalachian Basin and their orientation, relative to, first, the Alleghany orogeny tectonic stress fields and then the contemporary ones, gives rise to three geological conundrums. The first conundrum involves the extrapolation of outcrop data for the purpose of predicting the orientation of unhealed joints within black shale at depth. Such extrapolation assumes that the geologist is able to distinguish between joints that formed in the near

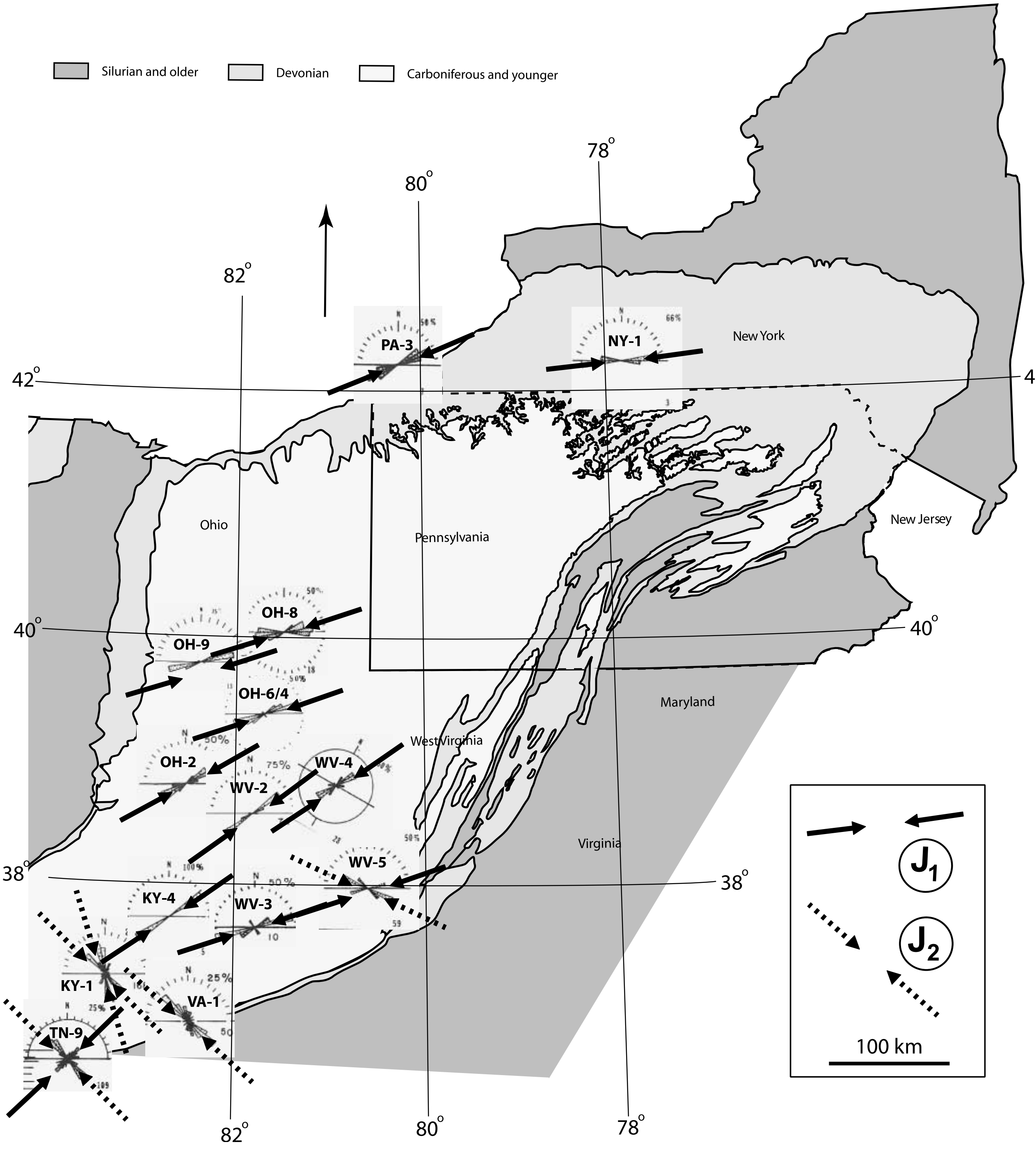


Figure 4. Rose plots showing the orientation of joints in the Dunkirk–middle Huron interval of cores recovered during the EGSP (modified from Cliffs Minerals, 1982). Well designations are those of the ESGP. Wells with less than three joints are omitted. Well WV-4 is corrected for misalignment as indicated by induced fractures.

surface as geomorphic phenomena and joints that formed close to or at maximum burial depth and persisted through exhumation. Drawing a distinction between early- and late-formed joints in the Appalachian Basin is complicated by the coincidence of the strike of J_1 joints and S_{Hmax} of the contemporary tectonic stress field. Neotectonic joints (J_3) whose east-northeast strike is controlled by the contemporary tectonic stress field have a mean orientation that falls within the same statistical

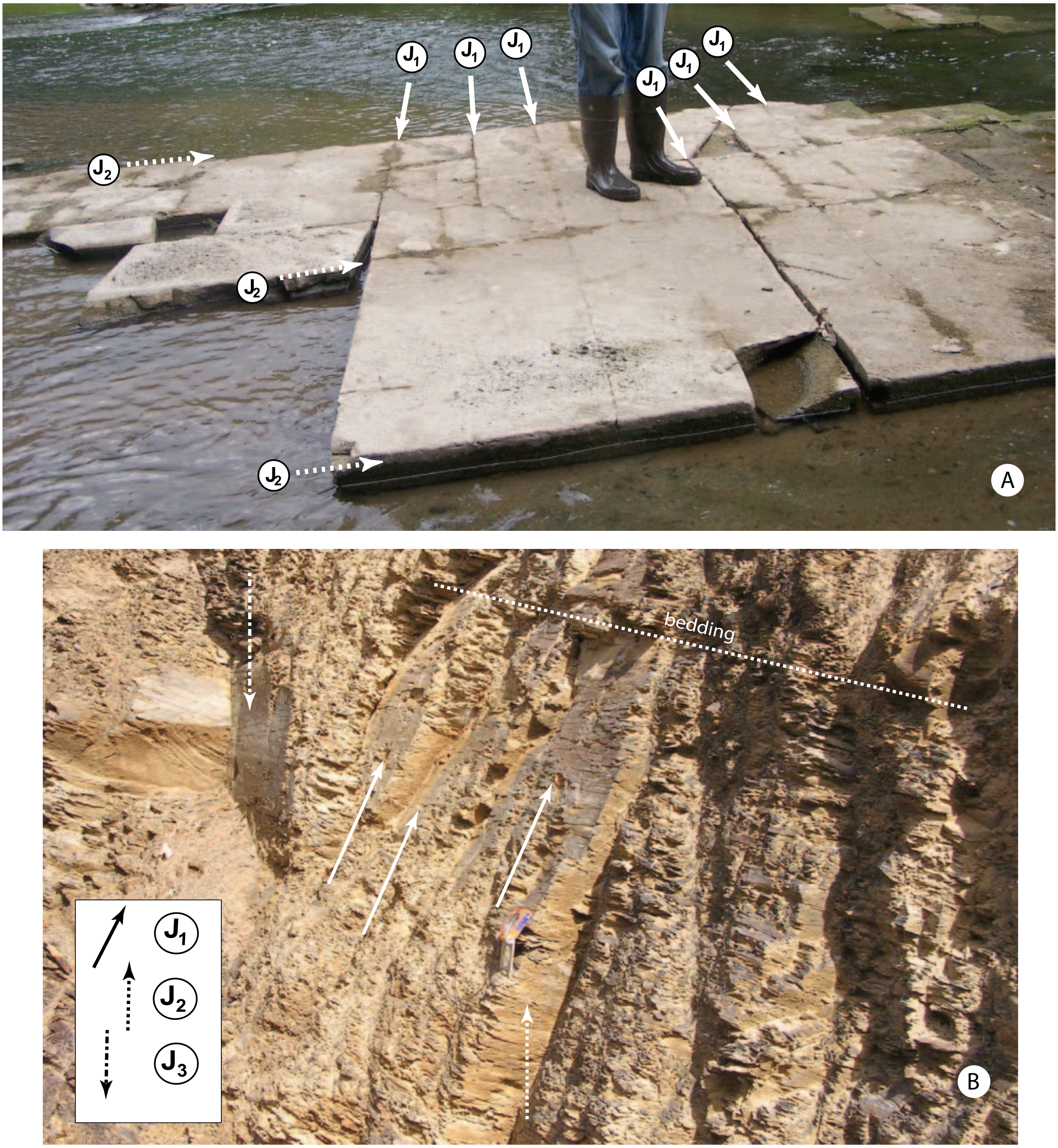


Figure 5. (A) Crosscutting J_1 and J_2 joints in the Marcellus black shale exposed in Oatka Creek, Le Roy, New York. View is to the east-northeast. (B) The J_1, J_2, and J_3 joints in the Marcellus black shale within folded beds just south of Jacksons Corner, Pennsylvania. The view is to the east-northeast showing south-dipping beds. Freiberger compass for scale. See Figure 2 for the locations.

range as the J_1 set (Hancock and Engelder, 1989; Lash and Engelder, 2009). The second conundrum stems from geological evidence that suggests that the J_1 set propagated before Alleghany-orogeny-induced folding and concomitant LPS (Pashin and Hinkle, 1997; Engelder, 2004). If the J_1 set predates Alleghanian LPS, then it survived this tectonic deformation in black shales as unhealed joints with little modification during penetrative strain despite being subnormal to the direction of

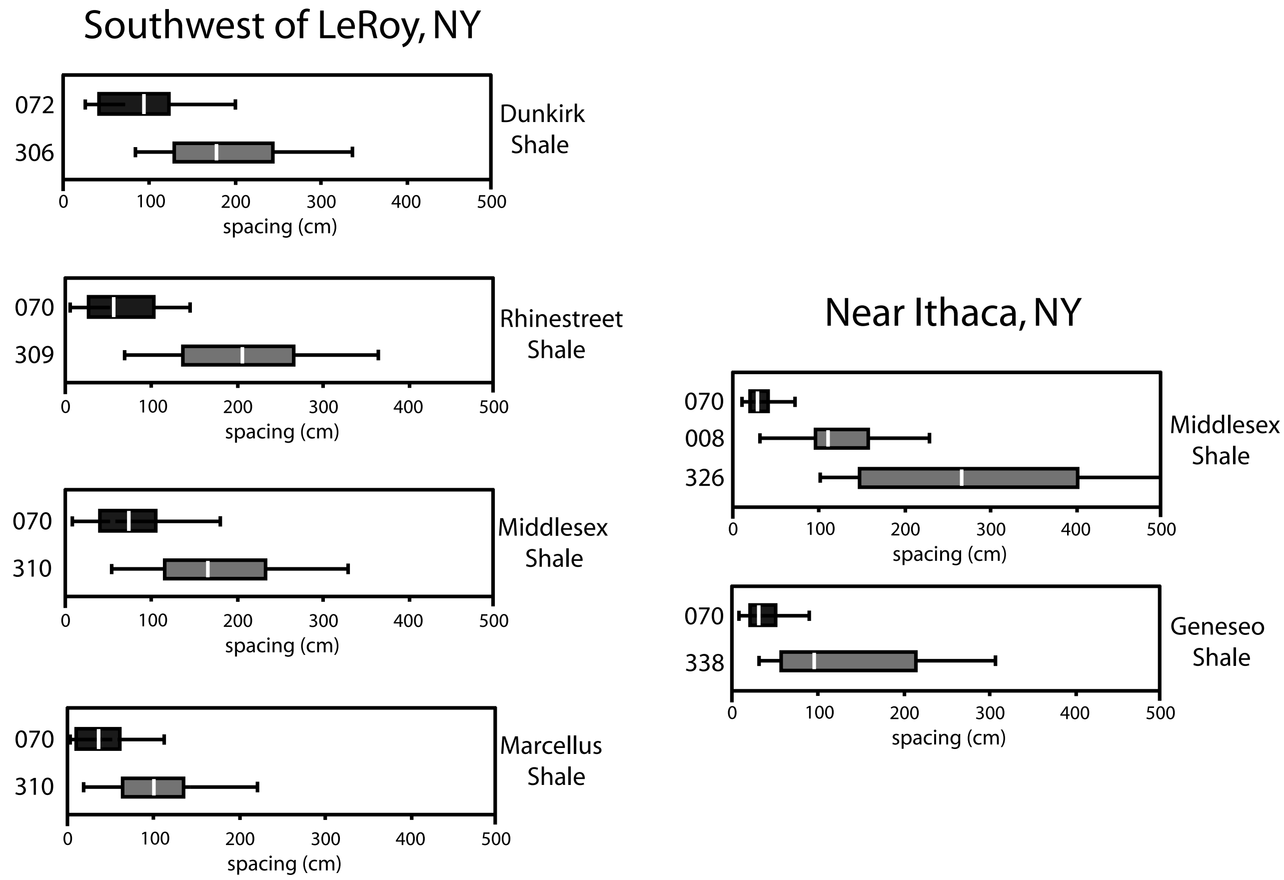


Figure 6. Representative box-and-whisker plots showing the joint density (orthogonal spacing) of J_1 (black boxes) and J_2 (gray boxes) joints at the base black shale units of the distal (southwest of LeRoy, New York) and more proximal (near Ithaca, New York) delta regions (see Figure 2 for the locations). Rocks of the proximal delta carry multiple J_2 joint sets. The average strike of each joint set is listed on the ordinate of each plot. The box encloses the interquartile range of the data set population; bounded on the left by the 25th percentile (lower quartile) and on the right by the 75th percentile (upper quartile). The vertical line through the box is the median value, and the whiskers represent the extremes of the sample range. In the distal scan lines, the spacing on east-northeast joints reflects the late-stage reactivation of those joints (modified from Lash and Engelder, 2009).

as much as 15% LPS (Engelder and Engelder, 1977; Geiser, 1988). Such a scenario presents a geological mystery that is difficult for some structural geologists to accept because it defies the more parsimonious interpretation that early joints can only survive as veins, whereas pristine joints with clean surfaces postdate penetrative deformation. The third conundrum arises from consideration of the origin of J_2 joints. There remains the matter of reconciling the Andersonian stress state for foreland fold and thrust belts (i.e., the thrust-fault regime where the least principal stress, σ_3, is vertical) with the observed spectrum of vertical syntectonic J_2 joints in the Appalachians and elsewhere (Anderson, 1951). Vertical joints imply that σ_3 was horizontal during fold and thrust tectonics. We present data that address each of these conundrums thereby permitting reasonable inferences regarding the extent to which the gas industry may expect unhealed joints in black shales such as the Marcellus.

FIELD OBSERVATIONS

Two simple experiments will enable us to further examine the aforementioned geological conundrums and to address other questions regarding the extent of joint development at depth in Devonian black shales of the Appalachian Basin. Each experiment involves documenting joints in the Marcellus Shale along two tracks directed at the

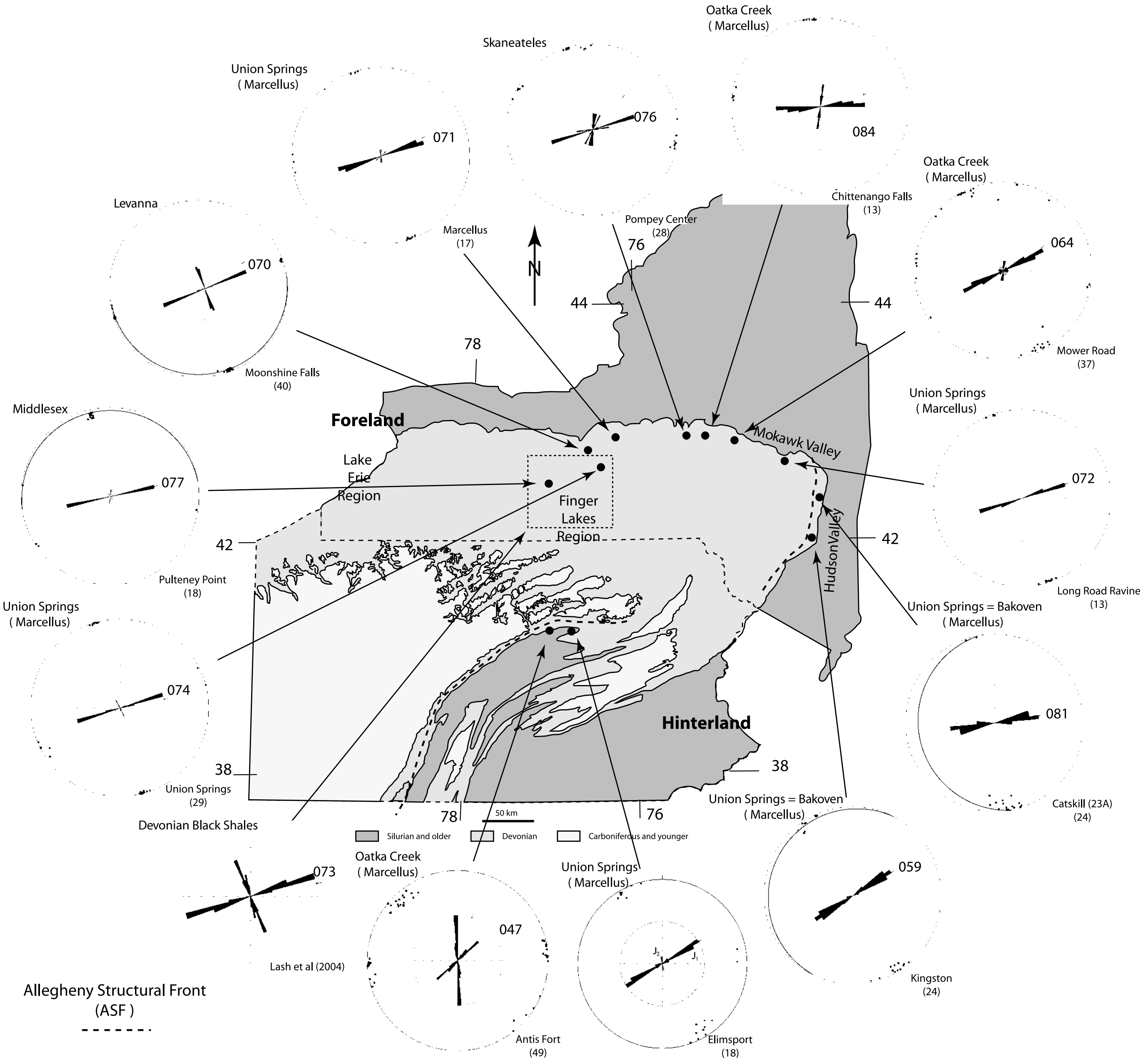


Figure 7. The orientation of joints in the Marcellus and other Devonian black shales of the Appalachian Basin. Poles to joints are shown in the lower hemisphere stereographic projection. The data from Antis Fort and Elimsport have been rotated back to their position relative to horizontal bedding.

hinterland of the Appalachian Mountains (Figure 7). Each track crosses the Allegheny structural front (ASF in Figures 3, 7), the boundary marking a fundamental change in structural style between the large amplitude folds that have a basal detachment on the Cambrian Waynesboro shale under the Valley and Ridge Appalachians (Gwinn, 1964) and the subtle folds that have a basal detachment on the Silurian Salina salts under the Appalachian Plateau (Rodgers, 1963; Davis and Engelder, 1985). Our experiments track the joint development across the ASF from a common starting point on the Appalachian Plateau and end along two different segments of the Valley and Ridge Appalachians. The common starting point is the Finger Lakes region of New York where the orientation of approximately 100 J_1 joints was measured at each of 22 outcrops of black shale (Lash et al., 2004). Our first track extends east to outcrops of the Marcellus Shale along the Mohawk Valley and crosses the ASF upon reaching the Hudson Valley (Figure 7). At each of these outcrops, as many as 50 joints were measured, depending on the outcrop quality. These data are plotted as poles on a lower hemisphere stereonet projection and then as rose diagrams. If a significant dip to bedding is observed, then the poles are rotated to return bedding to horizontal before constructing the rose diagram. Our second track points south crossing the ASF west of Williamsport, Pennsylvania. The Marcellus is not present along the southern track until the Valley and Ridge of Pennsylvania is reached.

Joint Characteristics that Carry across the Allegheny Structural Front

Several characteristics of joint development are common to both sides of the ASF. First, both J_1 and J_2 joints carry through the ASF as planar sets with uniform spacing (Figures 5, 8). Second, J_1 and J_2 joints propagated normal to bedding north of the ASF and remain normal to bedding when limb dips are modest (<10°) south of the ASF. Where limb dips exceed 15°, J_1 joints are subnormal to bedding as if rotated slightly less than bedding during folding. North of the ASF, beds dipping as little as 1°–2° carry joints dipping 89°–88° with the sense of dip on the joints congruent with the rotation of bedding during fold growth. Even where the Marcellus Shale immediately south of the ASF is overturned, dipping 75° to the south, J_1 joints are carried passively during folding to remain subnormal to bedding (Figure 8B). Although overturned bedding at Antis Fort, Pennsylvania, rotated through an angle of about 105°, the vector mean pole to J_1 joints overturned about 100° during the same folding event. Because of their cross-fold orientation, early J_2 joints remained vertical or subvertical as they spun through the same 105° rotation of bedding.

The third characteristic of joint development in the Appalachian Basin is its regional dependence on lithology. The J_1 joints predominate in black shale, and J_2 joints are predominant in gray shale and interlayered siltstone (Sheldon, 1912; Parker, 1942; Engelder and Geiser, 1980) (Figure 6). The J_2 joints strike across fold axes, thereby forming a radial pattern along the oroclinal bend of the central Appalachian Mountains (Nickelsen and Hough, 1967). This characteristic persists throughout the Valley and Ridge where J_2 joints are especially well developed in the Devonian Brallier and Trimmers Rock formations of the Genesee Group immediately above the Hamilton Group (Figures 1, 9). In general, the Devonian marine section of the Catskill delta carries a more pervasive J_2 fabric than overlying Devonian redbeds, and this rule holds for both sides of the ASF.

The fourth characteristic of J_1 joints common to both sides of the ASF is the interaction of J_1 and J_2 joints with carbonate concretions of the Marcellus and other black shales (Figure 10A). To the north of the ASF, joints of both sets pass completely around concretions without cutting them, a sign of natural hydraulic fracturing (McConaughy and Engelder, 1999). Similarly, to the south of the ASF, where joints and beds tilted during folding, neither J_1 nor J_2 joints penetrate and cleave congruently tilted concretions (Figure 10B). The fifth characteristic is that nonsystematic joints of two types are interspersed between systematic joints in some outcrops (Figure 11). In some instances, nonsystematic joints constitute curvilinear surfaces

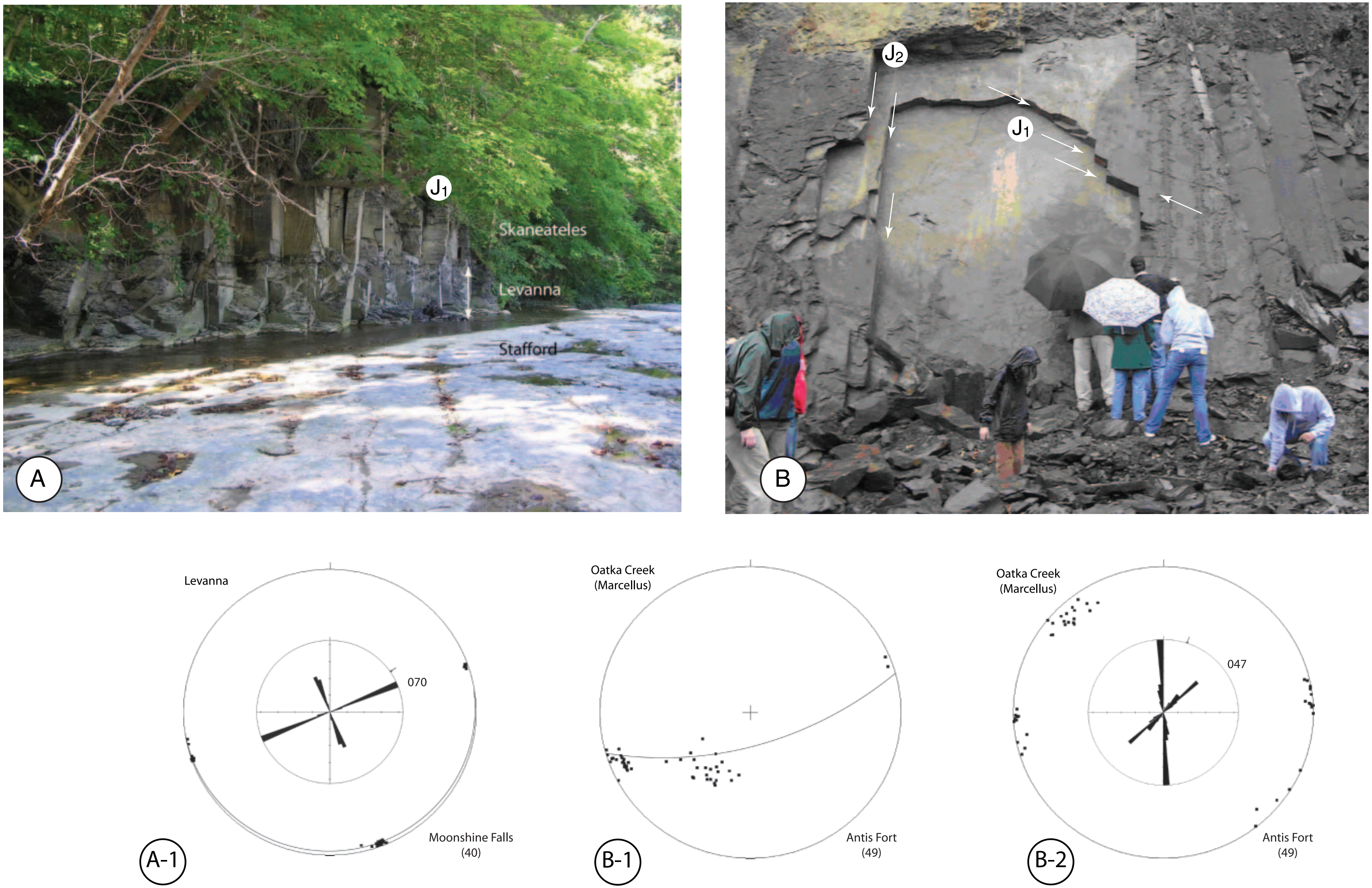


Figure 8. (A) Moonshine Falls east of Aurora, New York. Joints plotted in present coordinates in a lower hemisphere stereonet and rose diagram (A-1). (B) Examples of joint development in the Oatka Creek Member of the Marcellus Formation at the Ed Snook Quarry along Old Fort Road off Route 44 west of Antis Fort, Pennsylvania. Bedding is overturned at N82° E 75°SE. The view looking north at the underside of overturned Marcellus beds. Joints plotted in present coordinates (B-1) and rotated to their position with horizontal bedding using a fold axis plunging 05° toward 082°E with a rotation of 105° (B-2). Locations are on Figure 7.

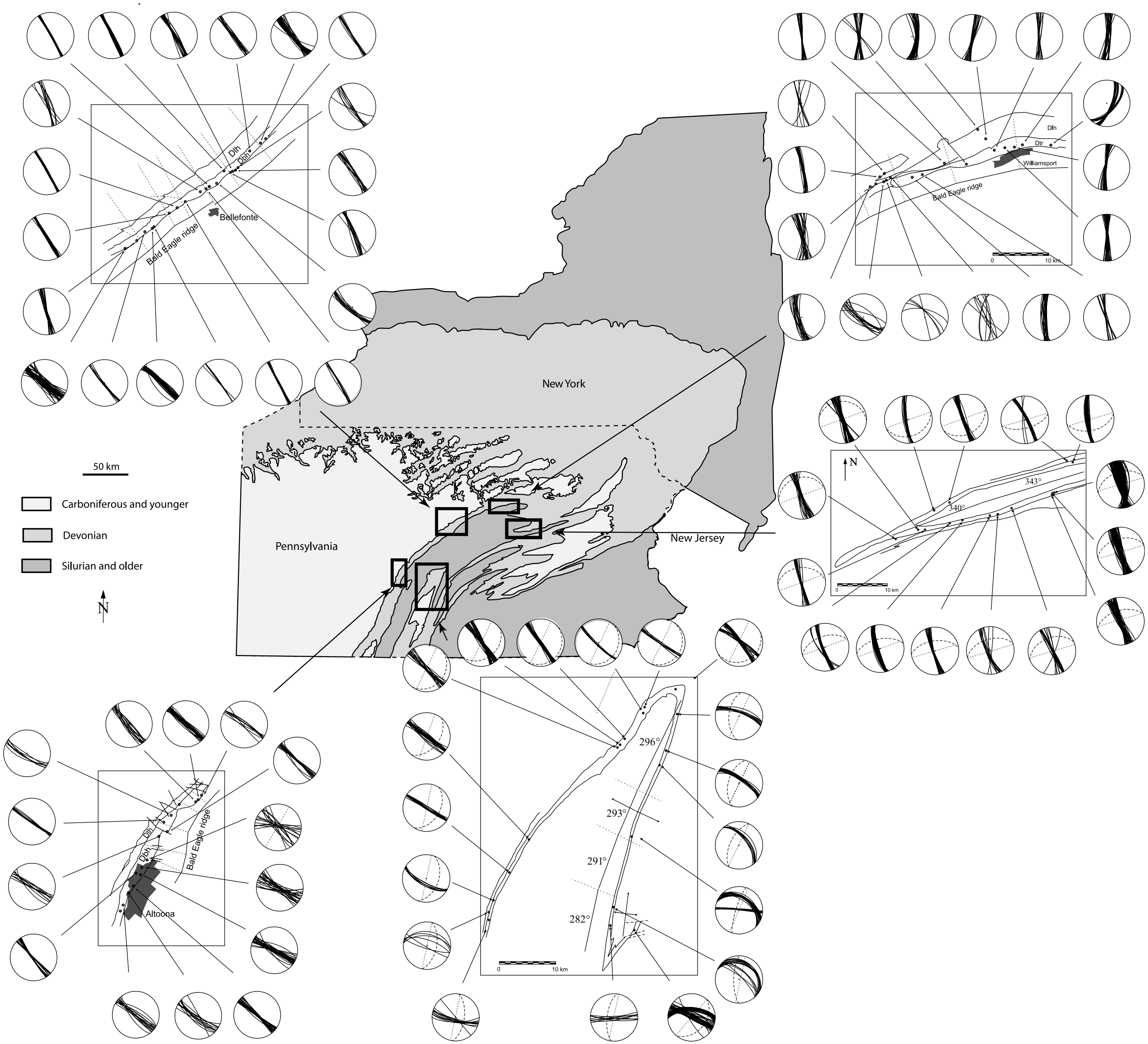


Figure 9. Regional map of J_2 joints in the Brallier and Trimmers Rock formations of the Valley and Ridge Appalachians, Pennsylvania. When present, the dashed line shows the orientation of bedding.

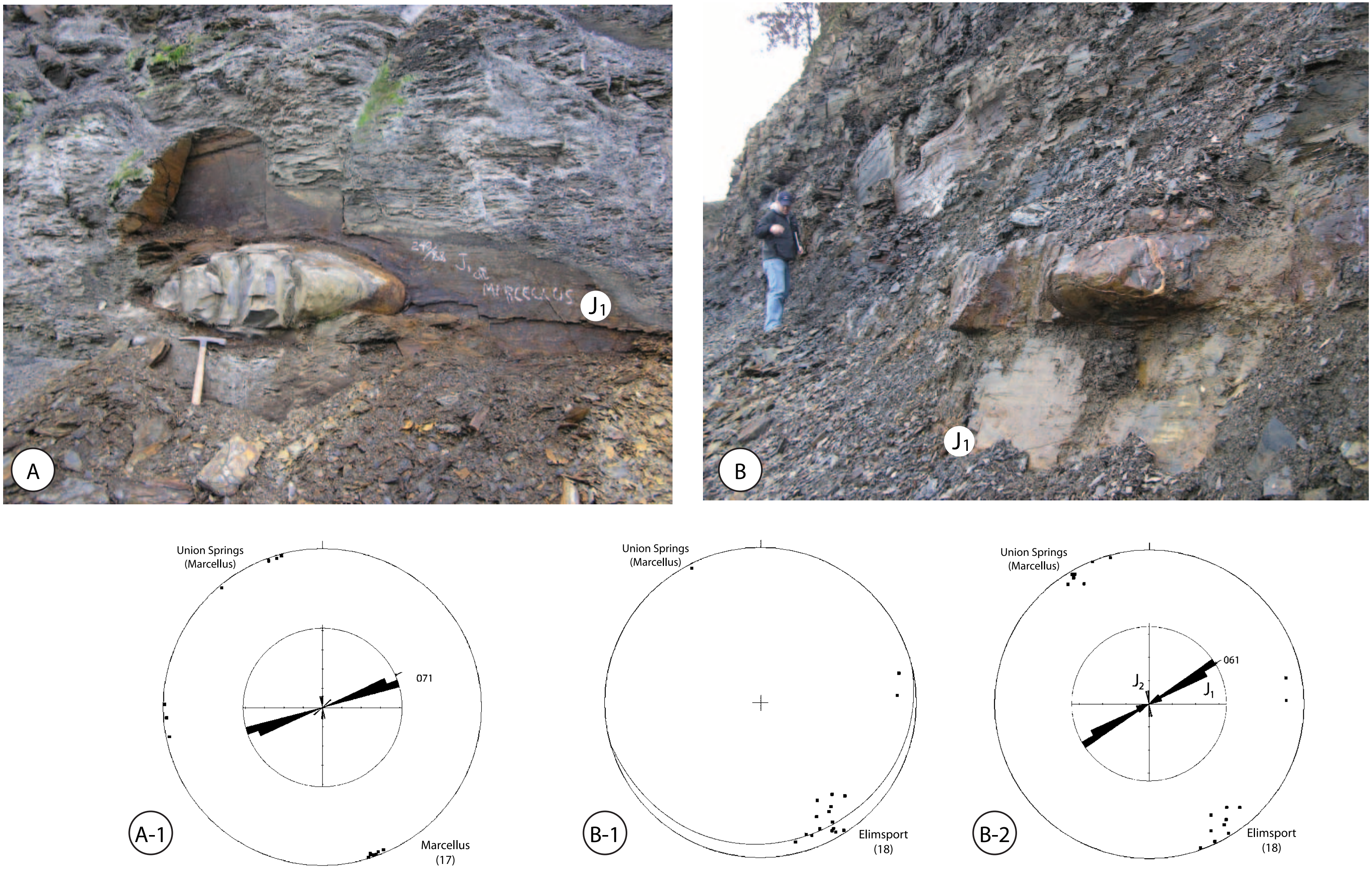


Figure 10. (A) Union Springs Member of the Marcellus Formation at Marcellus, New York. Here, J_1 joints propagate around but do not cleave concretions, a geological evidence for natural hydraulic fracturing. Joints plotted in present coordinates in a lower hemisphere stereonet and rose diagram (C). (B) Examples of joint development in the Union Springs Member at the Delmar Finck Quarry along Pikes Peak Road off of Route 44 east-northeast of Elimsport. Bedding is N75°E 10°SE. Joints plotted in present coordinates (D) and rotated to their position with horizontal bedding using a fold axis plunging 05° toward 075° with a rotation of 10° (E).

Figure 11. (A) Skaneateles Formation at Moonshine Falls east of Aurora, New York. Looking south-southeast parallel to J_2. (A-1, A-2) Neotectonic or exhumation joints parallel J_2. (B) Union Springs Member of the Marcellus Formation at Union Springs, New York, looking parallel to J_1 joints cutting vertically to the outcrop surface. (B-1) The J_2 joints curving toward the outcrop surface.

that flatten upward toward the top of bedrock (Figure 11B). These joints strike parallel to vertical joints that carry right up to the bedrock-soil contact. Elsewhere, interspersed nonsystematic joints curve to parallel planar neighbors (Figure 11A).

Finally, the plumose morphology that decorates the surfaces of joints hosted by siltstones of the Middle and Upper Devonian populates outcrops on both sides of the ASF (Figure 12). Plumose morphology is particularly valuable as a tool for assessing relative joint propagation direction, velocity, and points of arrest (Bahat and Engelder, 1984; Savalli and Engelder, 2005). Rupture acceleration and then arrest are indicated by surfaces with increasing roughness up to the point of arrest (Figure 12A). Smoother surfaces with irregular propagation directions indicate slower subcritical propagation (Figure 12B). Joint propagation extends over a long enough period that the regional stress orientation driving the deformation during the Alleghany orogeny realigns between propagation events as indicated by fringe cracks (Zhao and Jacobi, 1997; Younes and Engelder, 1999). Fringe cracks propagate both upward and downward from parent joints (Figure 13).

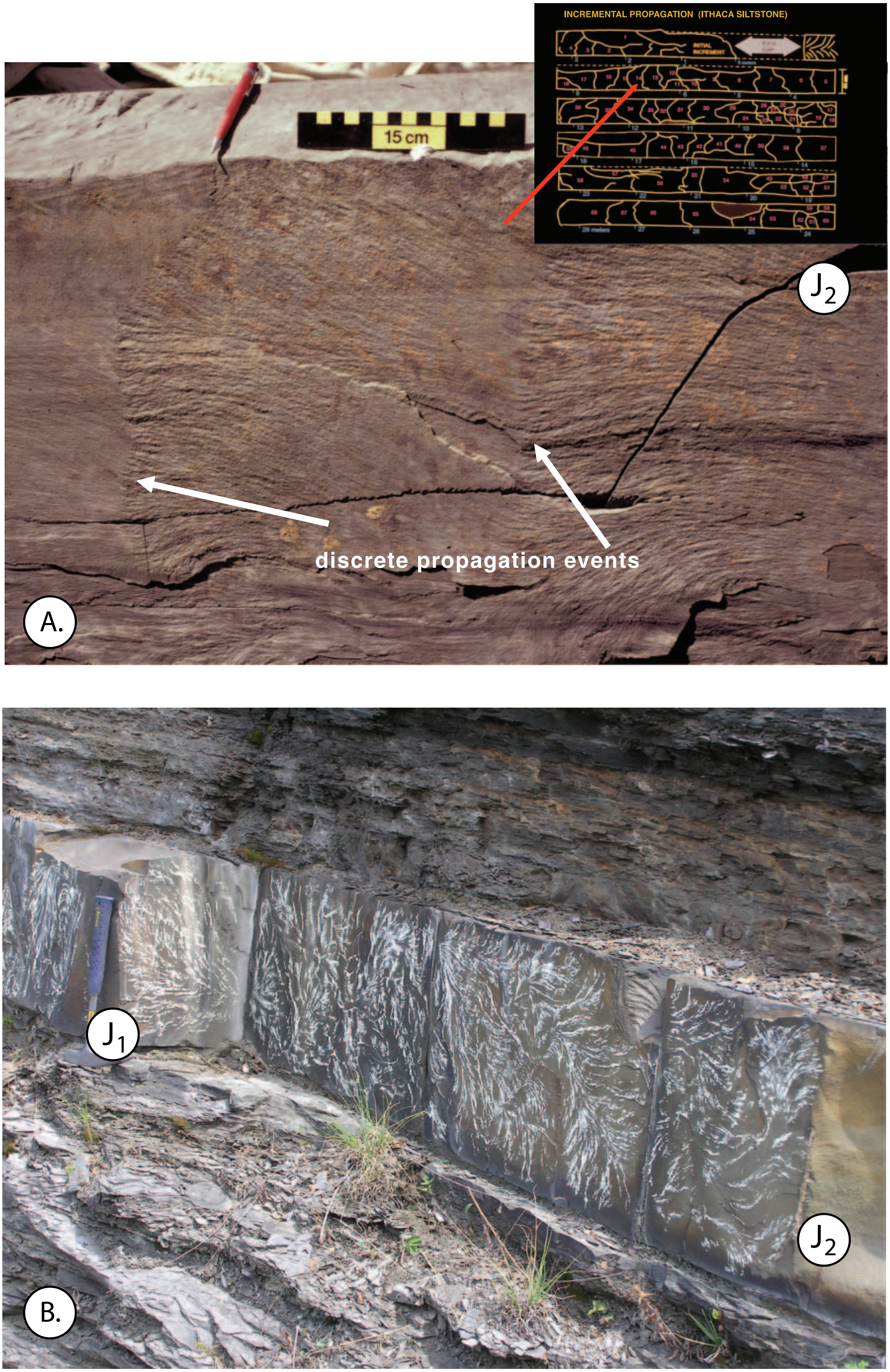
Joint Characteristics that Differ across the ASF

Three characteristics of joint development are not shared in common across the ASF. First, J_1 joints are present in every studied Marcellus, Geneseo, and Middlesex black shale outcrop in the Finger Lakes region as well as in other black formations in the Lake Erie region (Figure 7). To the south of the ASF in Pennsylvania, J_1 joints were identified with certainty in less that 50% of the studied Marcellus outcrops. The second characteristic that does not find its way across the ASF is the degree of clustering of poles of joints. On the foreland side of the ASF, J_1 joints cleave outcrops as if propagating in an isotropic homogeneous medium subjected to a homogeneous stress field (Figure 7). All J_1 joints in one outcrop are parallel to a first approximation. This behavior is recorded by the very tight cluster of poles to joints (Engelder and Whitaker, 2006). The cluster of poles to J_1 joints on the hinterland side of the ASF is far looser (Figure 7). Adjacent J_1 joints might be misaligned by 1 to 3° (Figure 5B). The third characteristic that differs from one side of the ASF to the other is the relationship between planar, neotectonic (J_3) joints and J_1 joints. Here, we presumed that nonsystematic joints are all exhumation-related neotectonic joints. Nonsystematic joints differ from the curving, systematic joints reported near faults (Rawnsley et al., 1992). South of the ASF where J_1 joints tilt with bedding on the limbs of first-order folds, a vertical east-northeast set, J_3, cuts bedding obliquely (Figure 5B). North of the ASF, J_3 joints are manifested by reactivated J_1 joints that abut J_2 joints (Lash and Engelder, 2009).

Layer-Parallel Shortening in the Marcellus

Four structures show the extent to which the Marcellus black shale was subjected to a penetrative strain indicative of LPS during Alleghanian deformation. Worm borrows in shale within the transition zone between the Marcellus and underlying Onondaga Limestone have an elliptical shape with their long axes parallel with fold axes of the Valley and Ridge in Pennsylvania (Figure 14A). Pencil cleavage with a lineation parallel to local fold axes is common in outcrops of the Marcellus in the Valley and Ridge of Pennsylvania (Figure 14B). Small-scale buckle folds are present in 2- to 3-mm-thick (0.07–0.11-in.-thick) silt layers within the Marcellus (Figure 14C). The axes of these buckle folds are parallel with first-order fold axes of the Pennsylvania Valley and Ridge. Finally, axial-planar stylolites are found in limestone layers at the Onondaga–Marcellus contact (Figure 14D).

Other structural elements common to the Marcellus include cleavage duplexes and small-scale faults that ramp toward the foreland. The duplexes are commonly parallel to bedding (Nickelsen, 1986). Bedding-parallel slip is also manifest by bedding-plane slickensides, which, in the Mahantango Formation, may be as closely spaced as 5–10 cm (1.9–3.9 in.) on the flanks of first-order folds in the Valley and Ridge. Other bedding-parallel slip is distributed within Marcellus gouge zones 2–3 cm (0.7–1.1 in.) thick (Figure 14D).


INCREMENTAL PROPAGATION (ITHACA SILTSTONE)
INITIAL INCREMENT
15 cm
J2
discrete propagation events
A.
J1
J2
B.

The sense of slip on bedding-plane slickensides in the Mahantango and the Marcellus gouge zones is top toward local anticlinal axes. Slip on the thicker cleavage duplexes of the Marcellus verges in the direction of the foreland regardless of position relative to local folding.

DISCUSSION

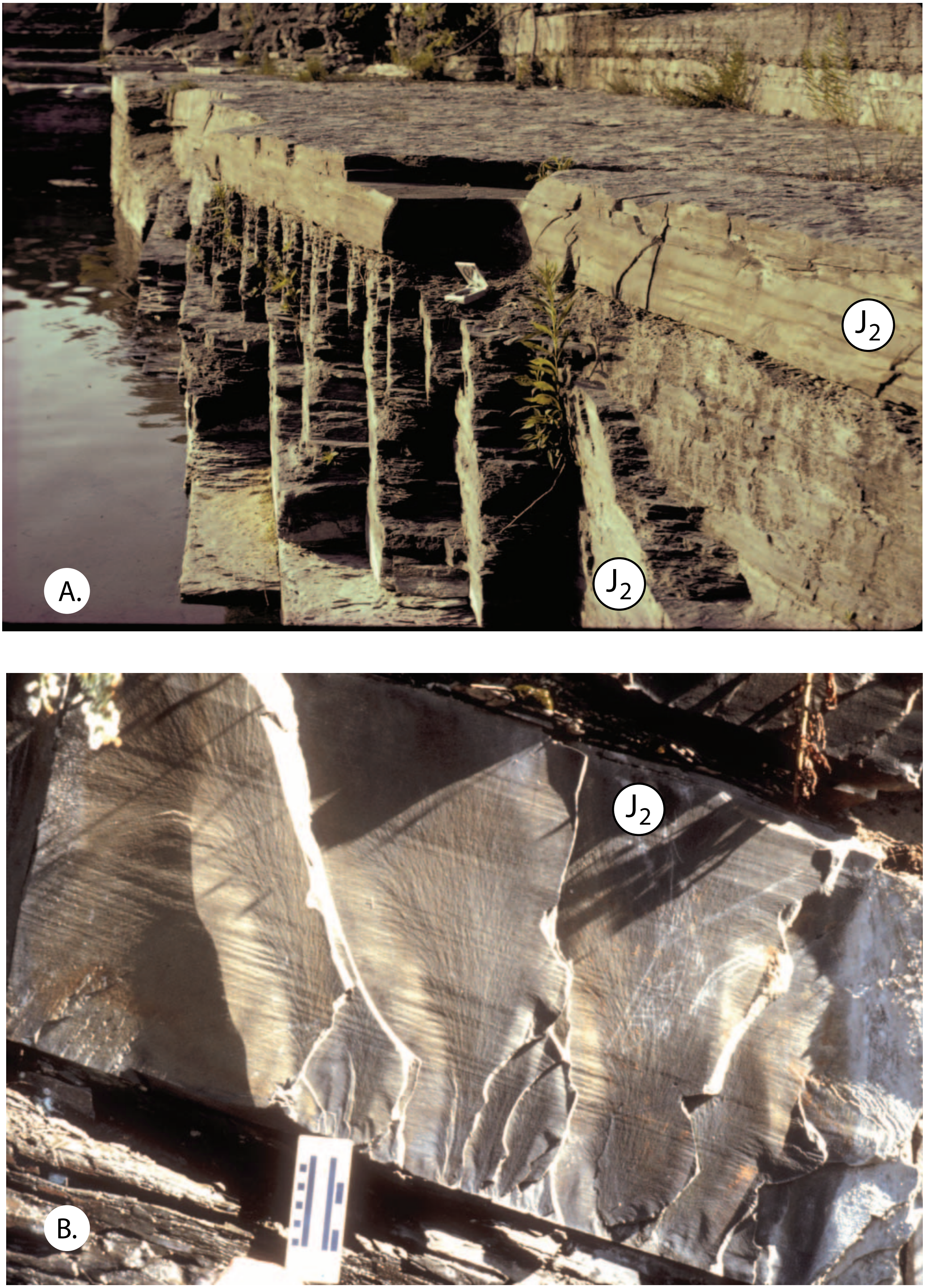
Conundrum 1: Recognition of Outcrop Joints that Formed at Depth

During the past half century, two important statements emerge from the observation of joints in outcrop. First, "it is unlikely … that all joints are the result of a single mechanism" (Price, 1966, p. 110). Second, "Fracture patterns are cumulative and persistent. Cumulative implies several episodes of fracturing … Persistent means not easily erased by later tectonic events" (Nickelsen, 1976, p. 193). From these statements, it follows that the effective tensile stress necessary for joint propagation is attained at the end of several loading paths involving stresses developed during burial, tectonic deformation, and/or later exhumation (Engelder, 1985). Furthermore, the energy necessary to sustain propagation of joints beyond initiation has at least four loading configurations (Engelder and Fischer, 1996). Given a complex matrix of loading paths and loading configurations, jumping from field observations to a unique genetic interpretation is difficult.

Of all the properties of joints, the most striking is their planarity. The mechanical explanation is that stress controls joint propagation and a rectilinear stress field serves to maintain in-plane joint growth (Pollard and Aydin, 1988; Lawn, 1993). The latter contributes to the development of parallel systematic joints. However, planarity in and of itself does not permit one to distinguish late-formed, near-surface joints from early-formed, deep joints that persist through one or more tectonic cycles. In this regard, the attitude of planar joints relative to bedding provides a clue. Vertical joints in a folded succession are interpreted as postfolding structures. In the Appalachian Basin, vertical east-northeast joints carried by tilted beds are candidates for shallow neotectonic joints (J_3) (Hancock and Engelder, 1989). Joints that propagated normal to bedding and remained in that position throughout subsequent folding are candidates for early, prefolding joints that formed at depth and persisted through exhumation to exposure at the Earth's surface (Figure 11). These are the J_1 joints of the Appalachian Basin (Engelder, 2004).

The upward growth of joints during exhumation was a popular explanation of vertical joints in outcrop (Nevin, 1931). The mechanical basis for this hypothesis was that horizontal compressive stress decreases upward in the Earth as a consequence of a reduction in both temperature and the gravitational component of the Earth's stress field (Price, 1966; Engelder, 1993). Fluid-driven fractures would naturally climb because the incremental decrease in density-related fluid pressure is less than the incremental decrease in the gravitational component of the horizontal stress (Nunn, 1996). However, the problem with the upward growth explanation is that if stress in a unit volume of rock is tracked during exhumation, the incremental decrease in horizontal stress in that unit cube does not keep up with the rate of vertical stress reduction (Brown and Hoek, 1978; Plumb, 1994). This behavior is reflected by a stress state in near-surface rocks in which S_{hmin} is greater than S_{v} (Nadan and Engelder, 2009). Indeed, some of the most common joints with a clear near-surface origin are subhorizontal sheet fractures and exfoliation joints (Holzhausen, 1989; Martel, 2006). Joints growing upward into a stress field where S_{hmin} is greater than S_{v} should tilt and eventually become horizontal as exemplified by the formation

Figure 12. (A) Discrete propagation events during the growth of a natural hydraulic fracture (J_2 joint) in the Ithaca siltstone cropping out along Route 414 southwest of Watkins Glen, New York (30 km [18.6 mi] west of Ithaca). The insert shows 68 increments of propagation mapped on this joint (modified from Lacazette and Engelder, 1992). (B) Joints in a bed of the Devonian Brallier Formation at Huntingdon, Pennsylvania. A plumose pattern decorates the surface of both a strike and J_2 joint sets (modified from Ruf et al., 1998).


J$_2$
A.
J$_2$
J$_2$
B.

of sheet fractures in exhumed granite bodies. Because this model requires the existence of near-surface horizontal compressive stress, the driving stress necessary for upward growth may require a modest tensile effective stress below the water table. Evidence of upward growth of late joints in black shale is seen in the tendency for late-formed joints to curve parallel to the Earth's surface under the influence of a stress state where S_h is greater than S_v (Figure 11). Alternatively, vertical joints that extend to the bedrock-soil contact in black shale outcrops were generated at depth and persisted during exhumation in their original orientation.

One common characteristic of joints in black shale along both transects is their close spacing relative to height (Figure 11). This observation is consistent with a deep-formed natural hydraulic fracture mechanism for driving vertical joints in black shale (Fischer et al., 1995). Even where black shale carries closely spaced joints in both J_1 and J_2 orientations (east-northeast and cross fold, respectively), late-formed joints are easily identified in cross section view as they curve parallel with the earlier, vertical planar joints (Figure 11). The same late-formed joints in plan view curve perpendicular to the systematic joints and abut them, hence the name curving cross joints (Engelder and Gross, 1993). The mechanical explanation for this behavior is that the crack-tip stress field of the late-formed joints is not transmitted across open joints, and without the benefit of a crack-tip stress field, late joints cannot jump across the earlier, open joint (Gross, 1993). Implicit in this explanation is the requirement that the older joint was open when the latter joint propagated. The persistence of remnant horizontal compression during exhumation means that curving cross joints are unique to beds in the upper few meters in the Appalachian Basin. The mechanism for curving parallel joints and curving perpendicular joints involves the distortion of an otherwise symmetrical crack-tip stress field (Olson and Pollard, 1989; Lash and Engelder, 2009).

Near-surface joint propagation has been attributed to glacial loading and unloading cycles (Clark, 1982; Evans, 1989) as well as to the presumed brittle nature of the deformed rocks. The thread that links both notions is the development of a flexural bulge accompanying glacial loading that may have generated a tensile stress in the elastically stiffest rocks entrained above the neutral fiber of the bulge. Although such joints have been described from the Appalachian Basin (Lash and Engelder, 2007), such an explanation is not consistent with the regional distribution of systematic J_1 and J_2 sets in Devonian black shales, which tend to be some of the most compliant, not stiffest, beds of the Appalachian Basin. The evidence that supports natural hydraulic fracturing for deep joints simultaneously speaks against both the stiffness hypothesis and the hypothesized function of glacial loading and unloading for the preferential jointing of the Marcellus and other Devonian black shale.

Geological Coincidence

The J_1 joint set and S_{Hmax} of the contemporary tectonic stress field are nearly parallel in eastern North America (Plumb and Hickman, 1985; Zoback, 1992). This correlation led to an early hypothesis that the orientation of the J_1 joints was controlled by the modern S_{Hmax} in the North American lithosphere (Engelder, 1982a). Indeed, J_1 joints in Devonian black shale have been explicitly called neotectonic joints (Hancock and Engelder, 1989). We now know that the parallelism of S_{Hmax} and the J_1 set is a geological coincidence (Engelder and Whitaker, 2006). In the late Paleozoic, the modern eastern edge of North America (Laurentia)

Figure 13. Abrupt twist hackles. (A) 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, which is 12 km (7.4 mi) north of Ithaca, 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 (31.-in.) base (modified from Younes and Engelder, 1999). (B) This set of fringe cracks propagated upward into a siltstone layer of the Brallier Formation at Huntingdon, Pennsylvania. Plumose morphology shows the upward direction of propagation from a parent joint in the layer below the scale marker.


A.
D.
B.
C.

Figure 14. Four different structures indicative of layer-parallel shortening within the Marcellus black shale near Newton-Hamilton, Pennsylvania. (A) Deformed worm tubes sampled at the Marcellus-Onondaga contact. (B) Pencil cleavage in the Union Springs Member of the Marcellus Formation. (C) Small-scale buckle folds in a silt layer within the Union Springs Member of the Marcellus Formation. The palm of a hand is seen behind the samples. (D) The core of the Marcellus-Onondaga contact (courtesy of Samson). The contact is an interlayered black shale and limestone (lighter unit). A stylolitic solution cleavage appears parallel to the axis of the core (vertical arrows). A small bedding plane detachment is seen in the upper part of the core (arrows indicate sense of shear).

was oriented about 45° clockwise from its present orientation such that this same edge of Laurentia faced south (modern coordinates). East-southeast– to west-northwest–directed convergence of Gondwana (Africa) against Laurentia (North America) generated a plate boundary system of dextral transform faults and concomitant S_{Hmax} that controlled the orientation of J_1 joint propagation. At the time of their propagation, J_1 joints were oriented east-southeast. However, post-Paleozoic continental drift carried these joints into their present orientation parallel to the east-northeast orientation for S_{Hmax} of the contemporary tectonic stress field. A geological coincidence is the interpretation of last resort and should be used sparingly, but this is one such time when an alternative, parsimonious interpretation of J_1 joints in black shale has failed to stand the test of time. We have presented examples of other joints that are neotectonic (Hancock and Engelder, 1989).

Fractures in Eastern Gas Shales Project Core

Our observations and conclusions must be consistent with observations and conclusions based on the EGSP core from the Appalachian Plateau of New York, Ohio, Pennsylvania, and West Virginia (Cliffs Minerals, 1982). Fractures in ESGP core include slickenside surfaces, coring-induced petal-centerline fractures, veins, and joints (Evans, 1994). Focusing just on joints and veins, the forelandward-most core (i.e., OH-4, OH-7, and PA-3) contains only unmineralized joints, whereas fractures in the deepest core (i.e., PA-2, PA-4, WV-6, WV-7, and WV-10) are nearly all mineralized veins. The core between these extremes is sparsely mineralized. Unmineralized joints in the foreland strike east-northeast and fall in either the J_1 or J_3 sets, whereas mineralized veins are more likely to belong to the J_2 set. The J_2 veins in the EGSP core were interpreted as Alleghanian, whereas the unmineralized fractures were interpreted as neotectonic (Evans, 1994). Our observations are consistent on two counts. Veins are virtually absent on the foreland side of the ASF and common on the hinterland side, particularly in the J_2 orientation. The J_1 joints populate all observed outcrops in the vicinity of the Finger Lakes region but are far less common on the hinterland side of the ASF. To an approximation, outcrops of the Valley and Ridge are a proxy for the deeper, hinterlandward EGSP core, whereas the outcrops in the Finger Lakes region are a proxy for the shallower, forelandward EGSP core. This would suggest that J_1 joints are less common to the Marcellus fairway than J_2 joints. At the same time, we doubt that any joints in EGSP core, however shallow, are neotectonic.

Conundrum 2: The Persistence of Open Joints during Greater than 10% Layer-Parallel Shortening

The Appalachian Plateau detachment sheet was subjected to greater than 10% LPS as indicated by deformed fossils in the marine section of the Catskill delta throughout western New York and south to the ASF (Nickelsen, 1966; Engelder and Engelder, 1977; Geiser, 1988). This pattern of LPS persists in sub-Marcellus rocks along the Helderburg Escarpment, which occurs north of the Marcellus Shale outcrop belt in western New York (Engelder, 1979b). There can be no doubt that gas production comes from a black shale that was part of an allochthonous thrust sheet that experienced greater than 10% LPS on the Appalachian Plateau and as much as 50% in the Valley and Ridge of Pennsylvania (Nickelsen, 1986). Evidence that the J_1 set was present in the Marcellus before it was subjected to LPS is abundant (Engelder and Whitaker, 2006). Still, surfaces of J_1 joints show little evidence of LPS, especially on the foreland side of the Appalachian Basin. At its core, conundrum 2 questions why a pervasive fabric produced by greater than 10% LPS does not manifest itself on the surfaces of J_1 joints as either vein filling, another form of healing, or a stylolitic surface. Furthermore, why do pervasively jointed Devonian gas shale outcrops carry so few veins? The preservation of unhealed joints is important to gas production because healed fractures and veins would otherwise serve as barriers to gas flow.

This second conundrum is addressed by analyzing the plumose structure on J_1 and J_2 joint surfaces (Bahat and Engelder, 1984; Savalli and Engelder, 2005). Joint surface morphology, which is a product of the rupture process, is irregular on a microscopic scale, whereas the overall surface of a joint remains planar. The depth of the irregularity varies with velocity of the rupture so that a continuous rupture may be distinguished from episodic joint propagation (Figure 12). Joints driven by internal pressure as natural hydraulic fractures leave a trail of incremental propagation and arrest events (Lacazette and Engelder, 1992). Gas production and concomitant pressure buildup during burial maturation of black shales is one of the mechanisms leading to natural hydraulic fracturing (Lash and Engelder, 2005).

Several lines of evidence point to the propagation of both J_1 and J_2 sets as natural hydraulic fractures. First, tensile joints cleave concretions, whereas the concretion acts as a barrier to natural hydraulic fractures (McConaughy and Engelder, 1999). A natural hydraulic fracture will propagate around the concretion leaving the concretion intact (Figure 10). Second, episodic joint propagation is best understood using Boyles Law for the behavior of an ideal gas: $P_1V_1 = P_2V_2$, where P is pressure and V is volume (Lacazette and Engelder, 1992). The sudden rupturing of a joint and the consequent increase in volume cause the pressure within the joint to decrease thereby halting further propagation. Evidence of incremental propagation indicates that pressure builds again until the rupture starts anew and that the source of fluid cannot feed fluid to the growing joint at a speed sufficient to maintain continuous joint propagation. Fluid is fed to the joint volume through an interconnected matrix pore space on either side of the joint. The decrease of pressure within the joint after each propagation cycle leads to an inward pressure gradient promoting flow from the rock matrix to the open joint. Renewed fluid flow into the joint causes pressure to increase, which again elevates the stress intensity at the joint tip until another cycle of rupture commences, a process that repeats cycle after cycle.

Role of Methane

In addition to episodic propagation, joints hosted by rocks of the Devonian Catskill delta sequence display progressively longer rupture increments

(Lacazette and Engelder, 1992). The rupture increment length scales with bed thickness, the initial increments being shorter than bed thickness. After several dozen propagation episodes, rupture length exceeds bed thickness. A gradual increase in increment length with joint growth is the manifestation of a compressible driving fluid, a property that water does not possess but methane does. The long-term presence of methane also explains why so many joints observed in outcrops of the Appalachian Plateau show no indication of mineralization. Methane within joints suppresses water filling and concomitant mineralization, thus preserving both J_1 and J_2 joints as unhealed, permeable pathways in a tight-gas shale.

The major mechanisms for penetrative strain during LPS include pressure solution and mechanical twinning of calcite (Engelder, 1979a, 1982b). Low-temperature, penetrative deformation is critically dependent on water films at grain-grain contacts to allow the diffusion-mass transfer that enables pressure solution (Durney, 1972; Rutter, 1983). Evidence for pressure solution within the Marcellus Shale of the Valley and Ridge is extensive, including pencil cleavage, deformed worm borrows, and stylolitic axial-planar cleavage (Figure 14). This deformation mechanism also likely enabled buckle folding within the Marcellus as well. Assuming the Marcellus entered the dry-gas window before or during early folding, modern water saturation (S_w = 10–20%) likely reflects S_w during folding. Such water saturation was apparently sufficient to allow pressure solution in the Marcellus Shale matrix during Alleghanian LPS. Equally, S_w along methane-filled, unhealed joints in the Marcellus was likely insufficient to allow appreciable pressure solution and concomitant vein development at the scale of macroscopic joints. However, well-developed examples of pressure-solved joints are observed in the Ordovician carbonates of the Valley and Ridge where S_w along joints must have been sufficient for the necessary diffusion mass transfer (Srivastava and Engelder, 1990). We conclude that the ability of a methane fill to protect unhealed J_1 joints from the ravages of diffusion mass transfer, including the deposition of vein material, should not be underestimated.

Alleghanian tectonics appears to have scattered joint planes on the hinterland side of the AFS, thereby affecting the tight cluster of poles to J_1 joints described from stereographic projections of data collected in the Finger Lakes region, New York (Figure 7). One possibility is that an LPS of 10–15% just to the south of the ASF was sufficient to disrupt the otherwise well-aligned J_1 joints (Nickelsen, 1983). The problem with this hypothesis is that J_1 joints on the Appalachian Plateau predate Alleghanian deformation without LPS having disrupted the tight cluster of poles to systematic joints (Figure 7). However, flexural folding may disrupt joint clustering in the Marcellus to a much greater extent than LPS alone (Donath and Parker, 1964). Evidence of the two end members of flexural folding, flexural-slip folding, and flexural-flow folding is found in Hamilton Group shales (Figure 14D). The Marcellus Shale coarsens upward into the Mahantango, which carries bedding-parallel slickenside surfaces spaced as closely as a few centimeters, a manifestation of flexural-slip folding. The Marcellus is more homogeneous and contains fewer discrete slip surfaces. However, axial-planar cleavage is evident in lime-rich beds within the Marcellus Shale (Figure 14D). The development of, and slip along, the axial-planar cleavage is used to explain passive folding (Alvarez et al., 1978), yet flexural-flow folding may also be an active mechanism during folding. Disruption of the early joint set and consequent scattering of poles to J_1 joints in the Valley and Ridge may have been a consequence of flexural-flow folding. Furthermore, the sense of rotation for poles to J_1 joints is consistent with flexural flow passively shearing bedding to rotate J_1 joints away from their original position normal to bedding, thereby leading to a joint population that has a steeper dip in upright bedding than would be the case if joints tilted as much as bedding during folding (Figure 8B).

Unhealed Joints versus Veins

The differences between J_2 fracture development in deep EGSP core (nearly all mineralized; Evans, 1994) and most of the unhealed joints in outcrop on the hinterland side of the ASF (see Figure 9) present difficulties in interpretation. An outcrop of Marcellus Shale along the Norfolk Southern Railway line at Newton-Hamilton, Pennsylvania, contains a well-developed J_2 joint set with less common J_2 veins. The same relative abundance of J_1 joints and veins has been observed at any number of outcrops of Middle and Upper Devonian marine rocks in the Valley and Ridge. This observation is common enough to suggest the possibility that unhealed (i.e., methane-filled) joints can co-exist at depth with water-filled fractures that end up as veins. Here, the implication is that water invasion fails to drive gas from early joints, governed by a physical process similar to the mechanism that allows the persistent water-over-gas contacts (Masters, 1984; Spencer, 1987).

The growth and preservation of unhealed J_1 joints are not consistent across the Appalachian Basin as indicated by comparison of their abundance in the Finger Lakes region relative to that of the Pennsylvania Valley and Ridge (Figure 7). Throughout the northern Appalachian Basin, the J_1 joints, where present, are mostly confined to black shale. Where methane-driven joints propagated out of the black shale in the northern part of the basin, they did so as J_2 joints, thus accounting for the latter's abundance in gray shale and siltstone on either side of the ASF. This situation differed along strike into the Virginia Valley and Ridge where J_1 joints appear in siltstone and fine sandstones upsection from the nearest black shale (Engelder, 2004). In the Virginia part of the basin, methane-driven joints appear to first break out from organic-rich sections as J_1 joints. This is also true to the east of the Finger Lakes region where J_1 joints populate the more coarsely clastic part of the Genesee Group in a section of the Catskill delta that is inherently thicker (Younes and Engelder, 1999).

Candidates for the early breakout of J_1 joints in the Pennsylvania Valley and Ridge have been described from an outcrop of the Brallier Formation of the Genesee Group at Huntingdon, Pennsylvania (Ruf et al., 1998). Here, the Brallier contains both mineralized and unhealed J_2 joints and unhealed strike joints that were originally interpreted as fold related. Both unhealed joint sets are mostly confined to the silter beds in this distal turbidite section. The original and classic interpretation is that mineralized J_2 joints formed first. However, abutting relationships suggest that the unhealed strike joints propagated before the unhealed J_2 set. The strike joints fall within the range of strikes for J_1 joints in the northern Appalachian Mountains. This raises the possibility that these strike joints correlate with the J_1 joints observed in coarser clastic rocks above black shale in Virginia. If so, the J_1 joints in the Brallier at Huntingdon, Pennsylvania, display the characteristic geometry of J_1 joints elsewhere in the Valley and Ridge where J_1 joints fail to tilt over the requisite amount during folding to remain normal to bedding, an indication of a small amount of flexural-flow folding (Ruf et al., 1998). One interpretation is that unhealed J_1 joints were methane filled thereby preventing the invasion of the water, a requisite for mineralization at the time of propagation and mineral filling of some J_2 joints. Again, this raises the possibility that water-filled joints can invade a methane-saturated rock without displacing methane from earlier methane-filled joints, a lesson that may apply to a slickwater fracture stimulation of the Marcellus. Clearly, the degree of structural growth correlates with vein development in Devonian gas shales (Evans, 1994). Structural growth may promote interformational fracturing that allows water invasion and concomitant vein filling, but such water invasion is incapable of displacing methane from early joints, a necessary condition for the persistence of joints through multiple tectonic cycles.

J_3(?) in the Hudson Valley

The orientation of east-northeast joints in the Hudson Valley does not mimic the behavior of J_1 joints in the Finger Lakes District (Figure 7). At Kingston, New York, where the lower part of the Bakoven (Union Springs equivalent) Shale of the Marcellus is exposed, the best developed joint set has a vector mean strike of 059°. This set exhibits four characteristics that may be more consistent with exhumation-related neotectonic joints of the Appalachian Plateau. First, those joints taller than a meter or two appear to have propagated out of plane. Second, the outcrop contains many short joints with vertical growth restricted to less than 0.5 m (1.6 ft). Third, these joints do not cluster like their counterparts in the Finger Lakes District of New York. Fourth, the vector mean strike of these joints falls within the range of the contemporary tectonic stress field in the eastern United States (058°–069°).

The pattern of east-northeast joints in the Bakoven Shale at Catskill is closer to that at Kingston than found in black shale of the Finger Lakes District. Although the outcrop gives the impression of a robust vertical growth of joints, most joints have visible top and/or bottom tips with vertical growth less than 2 m (6 ft). A weaker clustering of poles may be a manifestation of curving growth. Moreover, growth is not orthogonal to bedding, an indication that joints were not tilted during folding (Figure 7). In places, the Bakoven contains bed-parallel veins against which the joints abut, a sign that the joints postdate vein growth. Neither outcrop in the Hudson Valley displays a well-developed J_2 set, evidence that a gas drive from a source rock may never have been present. Coincidentally, TOC of the Bakoven Shale of the Marcellus Formation is lower than its lateral equivalent in the distal foreland, the Union Springs Member, perhaps reflecting a greater dilution by clastic detritus.

In summary, joints in the two best exposures of the Marcellus along the Hudson Valley foreland fold and thrust belt give the impression of belonging to the J_3 neotectonic set. If ever present, the J_1 set was overprinted by J_2 during the strong LPS produced by Hudson Valley foreland deformation (Marshak and Engelder, 1985). Alternatively, thermal maturation of the Marcellus during the Devonian Acadian orogeny in the Hudson Valley foreland fold and thrust belt predated J_1 jointing (Marshak and Tabor, 1989). Other outcrops of the Marcellus where J_1 and J_3 joints appear together serve as the strongest evidence that J_1 joints survive LPS in the Valley and Ridge of Pennsylvania, so we conclude that J_1 joints were never present in the organically leaner Marcellus of the Hudson Valley foreland (Figure 5B).

Conundrum 3: Generating Vertical Joints in a Thurst-Fault Stress Regime

Fold and thrust belts form mostly by the thrust stacking of detached sections. The major stiff layer in the Appalachian Valley and Ridge is a greater than 2-km-thick Cambrian–Ordovician carbonate section (Hatcher et al., 1989). Such thrust faulting is presumably characterized by a state of stress in which the least principal stress, σ_3, is vertical (Anderson, 1951). Such a stress regime is consistent with thrust ramp dips in the Appalachian Valley and Ridge of 20 to 25°. Yet, the major syntectonic joint set, J_2, is vertical and in the cross-fold orientation. One of the striking features concerning the orientation of joints described from core recovered during the EGSP is the radial pattern that follows the oroclinal bend of the central Appalachian fold and thrust belt (Evans, 1994). Likewise, outcrop mapping of the Devonian Brallier Formation along the Allegheny Front reveals a similar radial pattern of cross-strike joints (Figure 9). This joint set may be the primary target for a stimulation-driven fracture from horizontal wells within the Appalachian Plateau detachment sheet.

The horizontal σ_3 necessary to form vertical joints within a thrust-fault regime may be explained by the extension fracture hypothesis, which holds that joints are driven by the joint-parallel principal stress, S_{Hmax} (Lorenz et al., 1991). Extension fractures are the product of laboratory compression experiments at low confining pressure where samples split end to end in the direction of maximum compression even when all macroscopic principal stresses are compressive (Griggs, 1936). The paradox concerning extension fractures is that they propagate in the absence of macroscopic tensile stress. However, "there is convincing experimental evidence that the extension fracturing of a brittle material is due to a wedging action such that a local tensile stress is developed at the point of the wedge" (Griggs and Handin, 1960, p. 351). Tension also develops as a consequence of slip on internal cracks subjected to shear stress, and such tension produces wing cracks (Brace and Bombolakis, 1963; Cruikshank et al., 1991). For most geologists, the allure of extension fracturing does not serve as a model for vertical joints because "fractures originate in response to local tensile stresses around flaws or cracks on a microscopic scale" (Paterson, 1978, p. 19). Although the axial splitting mechanism is a perfectly adequate mechanism for the origin of sheet fractures in the near surface, it fails to explain regional, large-scale joint propagation at depth in a sedimentary basin.

Crosscutting relationships (Srivastava and Engelder, 1990) indicate that the final episode of crack propagation and cross-fold vein development in the carbonate thrust sheets of the Valley and Ridge Appalachians occurred after the Cambrian–Ordovician carbonates were emplaced onto the upper flat of thrust duplexes. The orientation of the veins indicates that σ_3 was parallel to the strike of the host rock and local fold axes. Such an orientation of σ_3 within the thrust-faulting state of stress may reflect the influence of horizontal contraction caused by cooling and removal of overburden during syntectonic erosion. Another mechanism for reducing strike-parallel stress is strike-parallel stretching to accommodate an increase in the radius of curvature around an oroclinal bend. Strike-parallel stretching is also required to accommodate lateral ramps in a foreland fold and thrust belt.

HORIZONTAL VERSUS VERTICAL WELLS

The presence of systematic J_1 joints in Marcellus outcrops on either side of the deep central region of the Appalachian Basin increases the probability that the J_1 joint set will be found in the Marcellus at depth. Reports of J_1 joints appearing in Formation MicroImager (FMI) images of recent wells penetrating the Marcellus confirm its presence at drilling depths (Figure 2). Furthermore, J_1 joints are abundant in Huron (Dunkirk equivalent) black shale EGSP cores (Figure 4). The presence of J_1 and J_2 joints in the EGSP cores assures that, in some parts of the Appalachian Basin, joints of both sets propagated at depths in excess of 2 km (Cliffs Minerals, 1982; Evans, 1994).

Perhaps one of the earliest hints that the Marcellus contains unhealed joints at depth came from blowouts as early wells penetrated the Marcellus to exploit the gas found in the deeper Devonian Oriskany Sandstone of the Appalachian Basin (Bradley and Pepper, 1938). A notable example is the April 3, 1940, Crandall Farm blowout near Independence, New York, where gas production reached 60 mmcf during the first eight days of uncontrolled flow from the upper part of the Marcellus formation at a depth of 4800 ft (1463 m) (Taylor, 2009). Because this production came from an unstimulated vertical well that lacked any evidence of faulting that could have tapped gas from the Oriskany some 120 ft (36 m) below, the interpretation is that the blowout was fed by self-sourced joints within the Marcellus Shale. Over the following half century, blowouts were a common consequence of drilling vertical wells penetrating the Marcellus. The low permeability of the Marcellus Shale suggests that many, if not all, blowouts must have tapped a reservoir of interconnected natural fractures. In fact, blowouts were one of the major attractions drawing Range resources to Washington County, Pennsylvania, where Range started targeting the Marcellus gas shale during 2004 (W. A. Zagorski, 2009, personal communication).

Although both J_1 and J_2 joints in black shale are natural hydraulic fractures and, consequently, virtually identical in terms of aperture and surface roughness, two important differences between these joint sets are observed relative to engineering and completion techniques necessary to maximize the production of natural gas. First, unmineralized joints subjected to lower normal stress will be more permeable (Kranz et al., 1979). The least horizontal normal stress, S_{hmin}, in the Appalachian Basin is nearly perpendicular to J_1 joints, meaning that, all other things being equal, stress-controlled permeability favors J_1 joints over J_2 joints. This may be the seminal characteristic for unstimulated production from horizontal wells in the Huron (Dunkirk equivalent) black shale of Kentucky. Second, J_1 joints are better developed and more closely spaced than J_2 joints in organic-rich rocks (Loewy, 1995; Lash et al., 2004). Thus, even if J_1 and J_2 joints have the same permeability, the host black shale will exhibit greater bulk permeability in the J_1 direction.

The completion of vertical wells may involve large hydraulic fracture treatments. Induced hydraulic fractures will propagate east-northeast–west-southwest, the direction of S_{Hmax} of the contemporary tectonic stress field (Evans et al., 1989). Hydraulic fractures propagating in this direction may travel along J_1 joints to intersect J_2 joints. In this case, the major drainage path to the well is first along J_2 joints and then along the east-northeast–trending hydraulic fracture, which may or may not have propagated along pre-folding J_1 joints. By intersecting J_2 joints, hydraulic fracture treatments in vertical wells are capable of taking advantage of neither the bulk permeability anisotropy of black shale nor the normal-stress induced permeability anisotropy of J_1 vs. J_2 joints. Still, the ability of J_2 joints to deliver natural gas to the plane of an artificial hydraulic fracture should not be underestimated for those operators wishing to use the conventional vertical completion techniques in the Marcellus Shale.

Given that the contemporary tectonic stress field controls the propagation direction of hydraulic fractures across J_2 joints, the only practical means of immediately communicating with the more permeable J_1 joint set is by horizontal drilling in a north-northwest or south-southeast direction. In this case, artificial hydraulic fractures generated in the horizontal part of the wellbore will propagate in the direction of S_{Hmax}, which is parallel to J_1 joints. The likely outcome of a hydraulic fracture treatment in a horizontal well drilled to the west-northwest, for example, is the reopening of J_1 instead of the fracturing of intact black shale. Hence, horizontal drilling in Devonian black shale should be directed to the north-northwest, perpendicular to S_{Hmax} of the contemporary tectonic stress field, to benefit from both the bulk permeability anisotropy from joint development and the normal-stress-induced permeability anisotropy of these rocks. This is the practice established by Marcellus Shale operators through early 2009.

CONCLUSIONS

Successful horizontal drilling of unconventional reservoirs may depend on the presence of systematic fractures. The J_1 joints formed preferentially in Devonian black shale throughout the Appalachian Basin early in the Alleghanian tectonic cycle as a consequence of burial-related thermal maturation of kerogen to hydrocarbons. This joint set, the most closely spaced in black shale, is now oriented parallel with S_{Hmax} of the contemporary stress field. Black shale also carries a less well-developed younger joint set (J_2) which, by virtue of its orientation, is subjected to higher normal stresses in the contemporary tectonic stress field. Hence, a higher joint density and stress-induced permeability anisotropy in Devonian black shale speak to the advisability of horizontal drilling toward the north-northwest or south-southeast to cross the more densely formed J_1 systematic joint set subjected to a lower normal stress in the contemporary tectonic stress field.

The presence of systematic J_1 joints in outcrops of the Marcellus Shale on either side of the deep central region of the Appalachian Basin increases the probability that the J_1 set will be found in the Marcellus at depth. A compilation of proprietary FMI images from recent wells penetrating the Marcellus Shale confirms the presence of the J_1 set at depth (Figure 2).

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