Pittsburgh Association of Petroleum Geologists Field Trip (Sept. 12-13, 2008)
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# Structural geology of the Marcellus and other Devonian gas shales:

The outcrop of a Middle Devonian black shale in Marcellus, NY from where the name of the famous gas shale comes.

# Geological conundrums involving joints, layer-parallel shortening strain, and the contemporary tectonic stress field

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*Field guidebook with David P. (Duff) Gold*

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## Introduction: Three geological conundrums for structural geologists

The similar orientation of ENE-striking joints in black shales of the Appalachian Basin and the $S_H$ of the contemporary tectonic stress field lured many authors to the conclusion that all ENE-striking joints were *de facto* neotectonic and therefore related in some way to processes involving the contemporary tectonic stress field such as Tertiary exhumation or Pleistocene glaciation (e.g., Clark, 1982; Engelder, 1982; Dean et al., 1984; Hancock and Engelder, 1989; Gross and Engelder, 1991; Engelder and Gross, 1993; Evans, 1994). Later work demonstrated that a pre- or early Alleghanian joint set, $J_1$, has approximately the same orientation as Appalachian neotectonic joints and the contemporary tectonic stress field (Pashin and Hinkle, 1997; Engelder, 2004; Engelder and Whitaker, 2006; Lash and Engelder, 2008). In some places in the Appalachian Valley and Ridge the early $J_1$ joints were folded along with bedding, clear evidence of a pre- or early Alleghanian propagation history (Engelder, 2004). These observations give rise to three geological conundrums that will have a great bearing on the Marcellus shale-gas play.

The first geological conundrum involves distinguishing joints of the $J_1$ set from neotectonic joints ($J_3$) when they look nearly indentical and their mean strikes fall within the statistical range of the other joint set. The second conundrum arises because geological evidence suggests that $J_1$ of the Appalachian Plateau propagated before Alleghanian folding and concomitant layer-parallel shortening (Pashin and Hinkle, 1997; Engelder, 2004). If $J_1$ predates Alleghanian layer-parallel shortening, it survived such tectonic deformation in black shales like the Marcellus without a scratch (no pun intended), particularly where layer-parallel shortening was less than 15%. This second possibility presents a geological conundrum that has been very difficult for a number of very good structural geologists to accept because it defies the more parsimonious interpretation that pristine joints with clean surfaces post-date penetrative deformation. The third conundrum is a matter of rectifying the Andersonian (1905) stress state for foreland fold-thrust belts (i.e., the thrust fault regime where least principal stress, $\sigma_3$ is vertical) and a spectrum of vertical syntectonic $J_2$ joints in the Appalachians and elsewhere. Vertical joints mean that $\sigma_3$ was horizontal during fold-thrust tectonics.

## Gas shales: A paradigm shift

2008 marked a paradigm shift in American's energy supply toward natural gas from unconventional gas shales. Public manifestations of this paradigm shift include the recent (i.e., September 2008) TV ads by T. Boone Pickens (Texas oil and gas executive) and Aubrey K McClendon (CEO of Chesapeake) pushing the conversion to CNG powered vehicles in North America. On the personal note, the shift was felt by the national attention given to the January 2008 Penn State press release announcing that the Devonian Marcellus black shale of the Appalachian Basin contained in excess of 50 Tcf of technically recoverable gas. Prior to this press release, Range Resources, a company leading the way in the Barnett black shale play of Texas, had successfully tested the Marcellus with a horizontal drilling program in Washington County PA. Other companies including Cabot, Chief, Equitable Resources, and Atlas had also realized early success in the Marcellus. Later in the spring of 2008, gas shales in Louisiana (the

Haynesville) and British Columbia (the Horn River Basin) also entered roster of prospective black shales with a potential for gas recovery comparable to the Barnett and Marcellus.

The success of horizontal drilling programs in the Marcellus has benefited from previous experience in the Barnett (Fort Worth Basin of Texas), the Woodford (Arkoma Basin of Oklahoma), the Fayetteville (Ouachita Foreland of Arkansas) and before these, the Antrim (Michigan Basin of Michigan). Each of these is a Devonian-Mississippian black shale deposited on continental seaways during the 60 m.y. leading up to the assembly of Pangea. Of these five including the Marcellus, only the Marcellus was subject to extensive foreland deformation during the Alleghanian Orogeny and only the Marcellus is exposed in outcrop on both the hinterland and foreland side of the shale-gas play. The objective of this fall PAPG/AAPG field trip is to examine tectonic overprint(s) on the Marcellus and other Devonian gas shales on the hinterland side of the Appalachian Basin. This trip is a companion to the spring 2008 PAPG/AAPG field trip to the foreland side of the Appalachian Basin in the Lake Erie District in western New York (Lash, 2008).

A ***tectonic overprint*** is any structure (macroscopic or mesoscopic) or fabric (mesoscopic or microscopic) carried in the rock of the Appalachian Basin beyond overburden compaction and initial lithification through diagenesis. Such structures and fabrics are the cumulative mechanical and chemical responses of the rock to either sudden or persistent differential stress arising in the lithosphere from plate tectonics processes. Post-lithification Devonian shale of the Appalachian Basin experienced four general tectonic stress fields associated with the four stages of a Wilson cycle during formation and breakup of Pangea. Simply put, the Wilson cycle is the successive occurrence of plate-spreading and convergence divided into four phases: convergence, continent-continent collision, rift, and drift (Marshak, 2005). In the Appalachian Mountains the most recent four phases include: 1.) the Pennsylvanian dextral stike-slip convergence of Laurentia and Gondwana during the Pennsylvanian and early Permian; 2.) the head-on continent-continent collision of Africa and North America during middle Permian (i.e., the Alleghanian Orogeny proper); 3.) the Triassic-Jurassic rifting of Pangea; 4.) the late-Tertiary drifting of North America with the further opening of the Atlantic Ocean following the last major realignment of tectonic plates. The contemporary tectonic stress field in the Appalachian Basin reflects the last of these phases which is presently the second phase of a post-Pangean Wilson cycle, the drift stage.

For the purpose of discussion during this PAPG/AAPG field trip, the tectonic overprint on the Marcellus and other Devonian black shale is arbitrarily divided into two general classes of outcrop structures: 1.) joints and 2.) structures associated with layer-parallel shortening. The latter includes faults, fault-related folds, cleavage duplexes, small-scale buckle folds, pencil cleavage, disjunctive cleavage, and strain markers. While these structures will be observed in the Appalachian Valley and Ridge, all are also seen on the north and northwest side of the Appalachian Basin where the Marcellus and other Devonian gas shales reappear in outcrop. In fact, the Marcellus is the only major gas shale that can be seen in outcrop on both the foreland and hinterland sides of the deep-basin play. Because all these structures are seen on both sides of the deep-basin play, it is logical to presume that they are present in reservoirs rocks throughout the extent of the

Marcellus shale-gas play as well. The best reservoir management of the Marcellus will take into account the possibility of the presence of one or more of these tectonic structures and fabrics. In fact, best practice will involve sorting out these structures and fabrics by age and responsible phase of the Pangean and post-Pangean Wilson cycles.

## The contemporary tectonic stress field

In an unconventional shale-gas play such as the Marcellus, reservoir management is all about horizontal drilling. Such drilling is often designed to cut across open joints, if present, as is the case of the Devonian Antrim shale-gas play of the upper Michigan Basin. When additional stimulation is necessary, common practice is to drill normal to the maximum horizontal stress of the contemporary stress field as is the case for the Mississippian Barnett shale-gas play of the Fort Worth Basin. So far, the most productive Marcellus wells have been drilled in a NNW-SSE pattern which is normal to the direction of the maximum horizontal stress, $S_H$, of the contemporary tectonic stress field in the Appalachian Basin as defined by the 'World Stress Map' (http://www-wsm.physik.uni-karlsruhe.de/pub/introduction/introduction_frame.html).

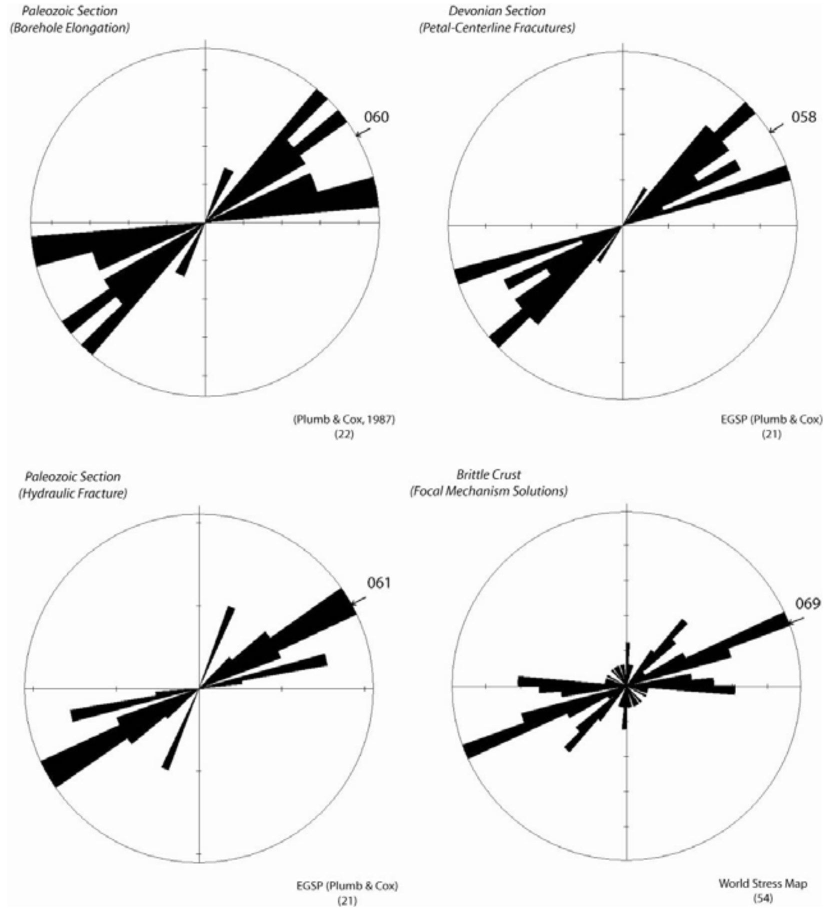


Figure 1. The orientation of the contemporary tectonic stress field in the northeastern United States. These data come from a latitude range between 35ºN and the Canadian border and a longitude range between the eastern seaboard of North America and 100ºW. The data are plotted as rose diagrams for the maximum horizontal stress, $S_H$, using GEOrient which calculates the mean resultant direction. As a general rule of thumb the contemporary tectonic stress field falls in the range of 058º and 069º.

The 'World Stress Map' demonstrates that the eastern 65% of the North American lithospheric plate is subject to a homogeneous tectonic stress field. Homogeneous means that the horizontal trajectories of the stress field are parallel at least to a first approximation. In the northeastern United States, the home of the Appalachian Basin and the recent Marcellus black shale gas play, the orientation of the contemporary tectonic stress field is measured using four stress indicators: hydraulic fractures, petal-centerline fractures, borehole breakouts, and earthquake focal mechanisms (e.g., Engelder, 1993). A compilation of data from the northeastern US constrain the maximum horizontal stress from contemporary tectonic stress field between 058º and 069º (Figure 1). This range of data both within and among data sets suggests that the contemporary tectonic stress field is not exactly homogeneous. Narrowing the data set to the northern Appalachian Basin and then to specific wells in the Appalachian Basin does not help to further resolve the problem other than to suggest that the measurement techniques themselves are inherently imprecise (Figure 2).

The question of relatively homogeneity becomes important when attempting to sort out the origin of joint sets within the black shales of the Appalachian Basin. There is strong evidence that some joints are neotectonic which means that their orientation was controlled by the contemporary tectonic stress field. The propagation of vertical joints is

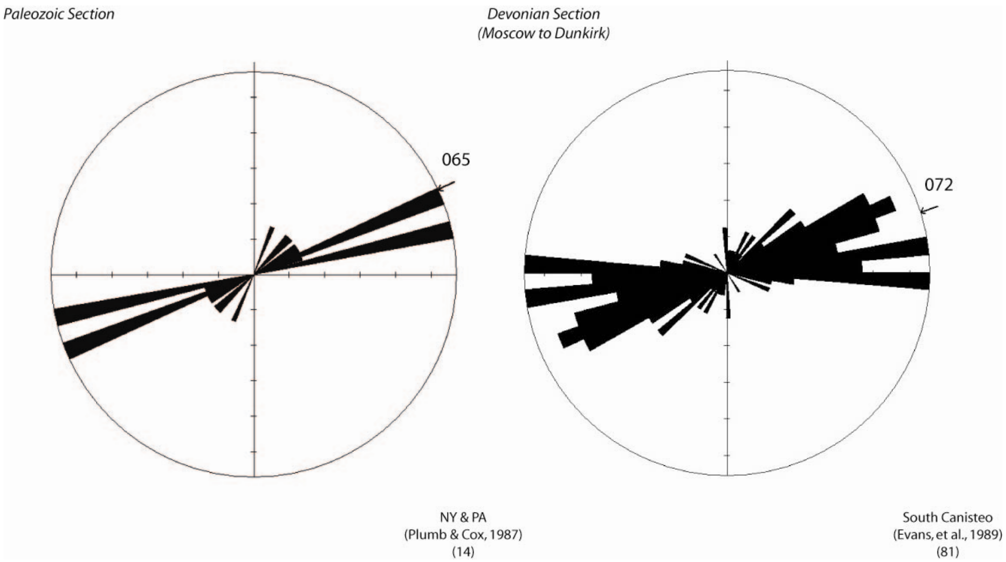


Figure 2. The orientation of the contemporary tectonic stress field in the states of New York and Pennsylvania. These data include borehole breakouts, petal-centerline fractures and hydraulic fractures. The data from South Canisteo come from two wells: The Wilkins and Appleton. The data are plotted as rose diagrams for the maximum horizontal stress, $S_H$, using GEOrient which calculates the mean resultant direction.

always parallel to the maximum horizontal tectonic stress, $S_H$. A set of joints whose mean strike (i.e., $S_H$ at propagation) falls outside the range of 058° and 069° may come from a source other than the contemporary tectonic stress field.

When considering the origin of joints in the contemporary tectonic stress field there is another element to earth stress that may have a great bearing on joint orientation. In the upper crust, the least compressive principal stress is overwhelming vertical, particularly in the top 500 m (Figure 3). This behavior is here called the Brown-Hoek stress profile

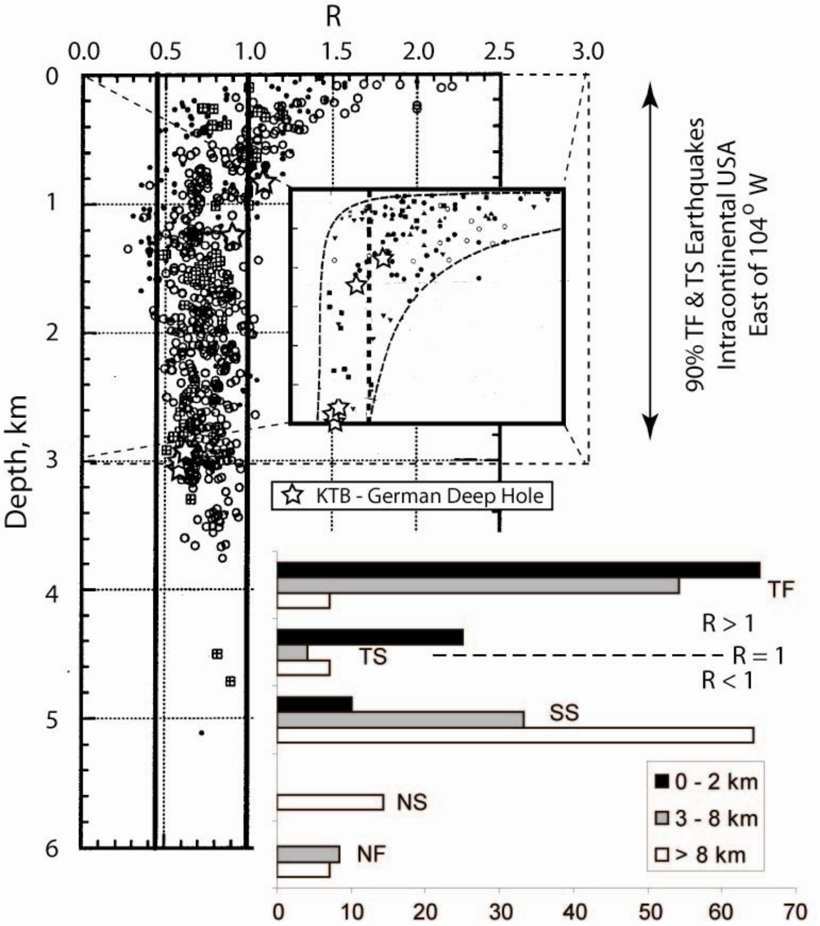


Figure 3. Global compilations of stress measurements show an upwardly increasing ratio, *R*, of least horizontal to vertical stress ($R = S_h/S_v$ with compressive stress positive) through the top 2 km of the crust (Brown and Hoek, 1978). A Brown-Hoek stress profile (BHSP) to a depth of 6 km in sedimentary basins (adapted from Plumb, 1994). Upper inset is an earlier BHSP including data from both crystalline and sedimentary rocks to a depth of 3 km where dashed line indicates R = 1 (adapted from Brown and Hoek, 1978). Lower inset shows a compilation of all 58 focal mechanisms from the United States east of longitude 104° (taken from the World Stress Map data base). Data divided into three tiers as indicated. TF – thrust fault mechanisms (R > 1), TS – thrust-strike slip mechanisms (R ≈ 1), SS – strike slip mechanisms (R < 1), NS – normal-strike slip mechanisms (R < 1), NF – normal fault mechanisms (R < 1).

(BHSP). This behavior is responsible for the development of sheet fractures in near-surface crystalline rocks, for example. Its presence in sedimentary rocks means that near-surface joint propagation might favor horizontal propagation because joints always propagate normal to the least principal stress. One old theory for joints is their upward propagation during exhumation. If this were true in the near surface where the BHSP holds true, then upward propagating joints should curve from vertical to horizontal.

## Joints

The success of shale-gas plays is largely dependent on finding or creating high permeability pathways that pervade an otherwise very low permeability (200 - 400 nanodarcy) rock. The idea is that gas is ecomonically recoverable as long as flow in ≈400 nanodarcy rock is limited to distances on the order of a meter. Joints in Devonian black shale have this spacing and it is also presumed that stimulation of unjointed black shale creates a comparably dense network of artificial joints by hydraulic fracturing. Some of the earliest borehole sampling specifically targeting black shale of the Appalachian Basin was that of the Eastern Gas Shales project (Cliff Minerals, 1982; Evans, 1994). Core of Devonian black shale recovered during the EGSP contain abundant joints from a number of the Devonian black shales including the Dunkirk-Huron interval (Figure 4). Subsequent horizontal drilling in the shallow (< 4000 ft) Dunkirk-Huron black shale of the Kentucky region of the Appalachian Basin result in 20% of the wells (of 80 drilled to date) flowing with enough volume so that further stimulation is not required, a clear indication of a lateral intersecting natural fractures (Gerber, 2008). The similar orientation of joints in the Dunkrik-Huron black shales of the Appalachian Basin and the $S_H$ of the contemporary tectonic stress field is intriguing to the extent that many authors assumed that these joints were neotectonic (e.g., Engelder, 1982; Dean et al., 1984; Hancock and Engelder, 1989; Evans, 1994).

Early mapping an ENE joint set in the Appalachian Basin dates back a century (Sheldon, 1912). Sheldon's early mapping was in the vicinity of Cayuga Lake, one of the Finger Lakes of New York where one prominent joint set has a vector mean average strike of 076 º which was given the label, strike orientation (Figure 5). A second joint set was observed in the cross-fold (i.e., dip) orientation. At the time one of the most salient observations concerning this ENE joint set was that "strike joints are better developed in the shales and dip joints in the sandy beds". What Sheldon does not tell the reader is that many of her measurements in shale come from black shales, mainly of the Geneseo (Burket of PA) Formation just above the Tully Limestone. Sheldon's work was expanded to cover much of the Finger Lakes District and eastward to the Hudson Valley by Parker (1942) who observed a persistent joint set in the ENE orientation (i.e., Parker Set III). Later regional mapping in western New York by Engelder and Geiser (1980) largely overlooked the ENE joint set because black shale outcrops are not common and thus contribute a relatively small statistic to a regional compilation. Following the publication of Engelder and Geiser (1980) it was 15 years before focus was directed specifically on joint development in black shales (i.e., Lash et al., 2004; Lash and Engelder, 2005).

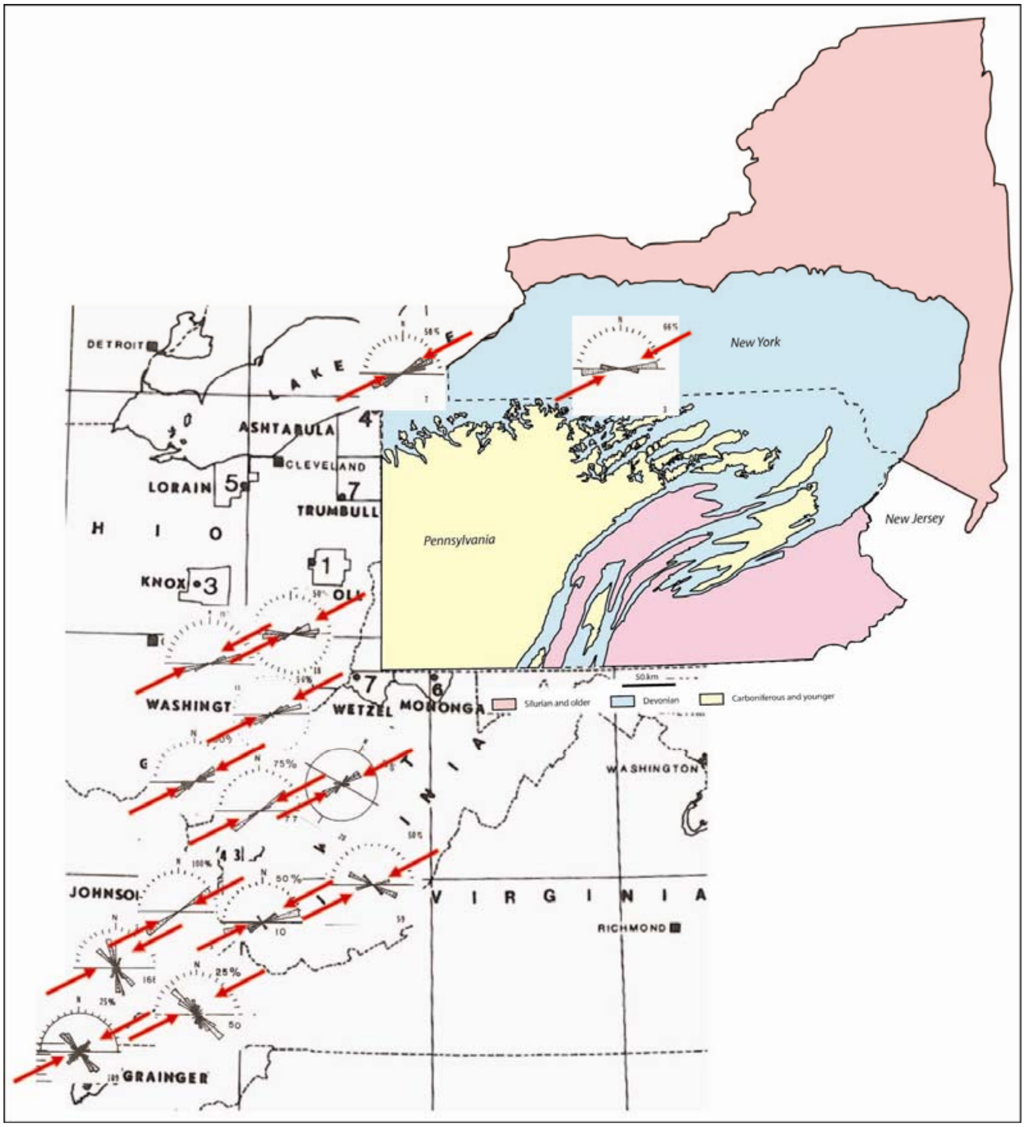
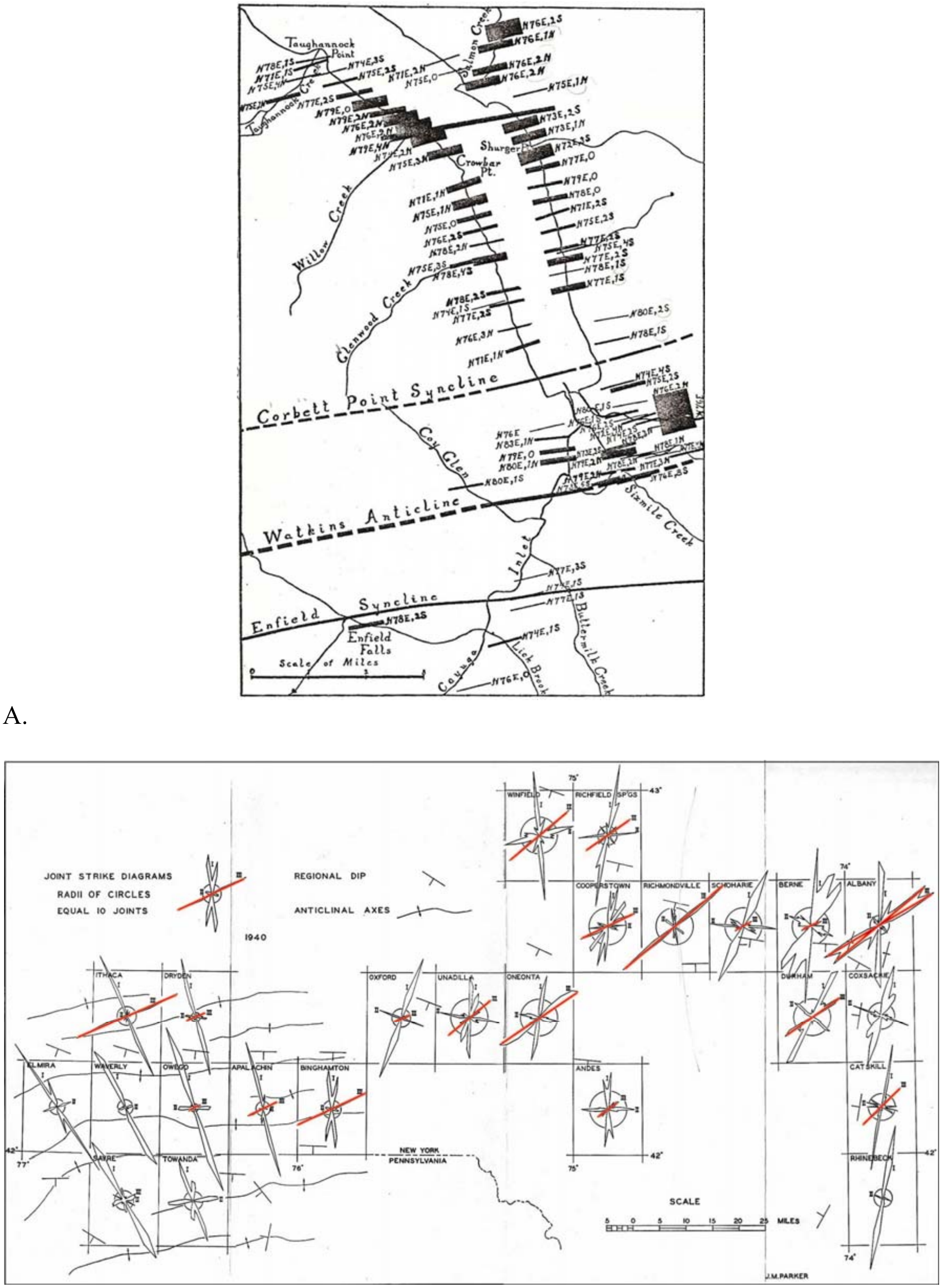


Figure 4. Rose diagrams of joints in core recovered from the Dunkirk-Huron interval of the Devonian section by the Eastern Gas Shales Project. Data compiled by Cliffs Minerals (1982).

Along the Appalachian Mountains this ENE joint set of Sheldon (1912) and Parker (1942) was mapped as the first to propagate in many outcrops of Devonian through Pennsylvanian rocks (e.g., Nickelsen and Hough, 1967; Nickelsen, 1979; Kulander and Dean, 1993; Pashin and Hinkle, 1997). These early joint sets (here called $J_1$) strike parallel to the orientation of the maximum horizontal stress, $S_H$, in a stress field that was a prelude to the Alleghanian orogeny. In total, these joint sets appear as one mega-set recording a rectilinear stress field extending for > 1500 km across three promontories separated by oroclinal embayments of the Central and Southern Appalachians (Figure 6). Given the arrangement of continental plates at the time of propagation at about 300 Ma, these joints actually propagated with a strike south of east.



A.

B.

Figure 5 A. Sheldon's (1912) map of $J_1$ joints in the Ithaca, New York area. Line thickness represents relative joint density. B. Parker's (1942) map of joint sets including $J_1$ (red) in upstate New York.

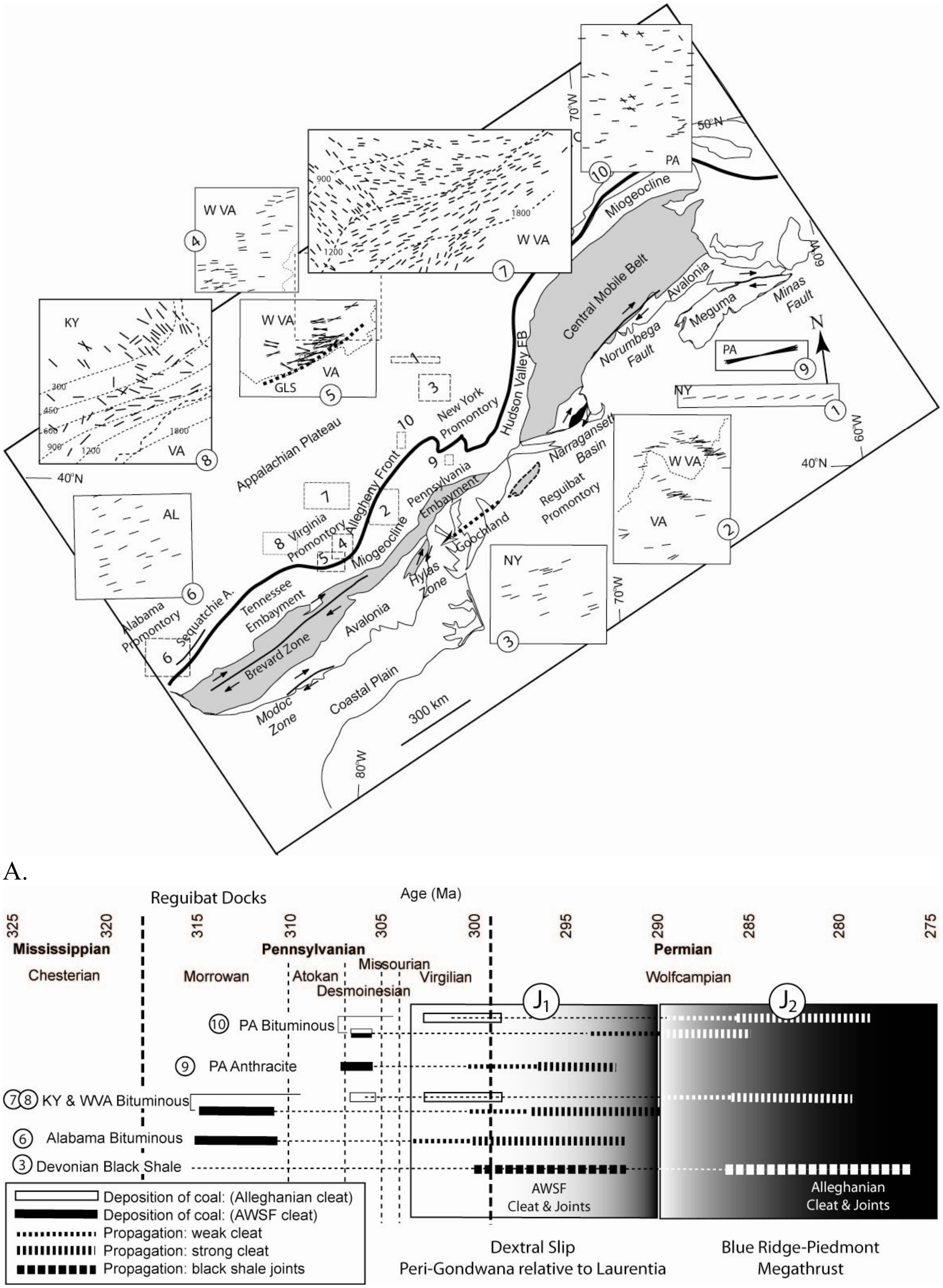


Figure 6. A.) The distribution of ENE joint sets along the Appalachian Mountains. Reference to insets and their map locations (dashed rectangles) are found in Engelder and Whitaker, 2006). B.) A time line for coal deposition and propagation of Appalachian cleat and joints. Ages are consistent with International Commission on Stratigraphy (www.stratigrapy.com) whereas the Stage names are North American.

The early ENE joint set defines a more or less rectilinear stress field that was transmitted into the smoothed margin of the Laurentian foreland for a period exceeding 10 My during the assembly of Pangea. Because this late-Paleozoic stress field was unaffected by the obvious serrations (i.e., promontories and embayments) of the present mountain belt and its predecessor, the post-Rodinian margin of Laurentia, it is one Appalachian-wide stress field (AWSF). The AWSF, a prelude to the Alleghanian orogeny, was disrupted when dextral transpression returned the Appalachian foreland to the shape of the Rodinian margin of Laurentia, by means of stratigraphically controlled décollement tectonics (Gates et al., 1988; Wise, 2004).

Three joint sets are common in the Appalachian Basin, designated as $J_1$, $J_2$, and $J_3$. Where present in outcrop, $J_1$ maintains its ENE orientation regardless of location relative to the oroclinal bends of the Central and Southern Appalachian Mountains (i.e., Engelder and Whitaker, 2006). In the Valley and Ridge, $J_2$ is found normal to fold axes, qualifying this set as a systematic cross-fold joint set (i.e., the so-called dip joint set of Sheldon, 1912). $J_1$ is not the strike joint of Engelder and Geiser (1980) whereas $J_2$ is the cross-fold joint described in that paper. In some cases, $J_2$ set appears to be normal to $J_1$, yet this is the exception to the rule; the typical angular relationship of the $J_1$ and $J_2$ joint sets is an acute angle. However, the angular relationship of $J_1$ and $J_2$ varies as a consequence of variation in strike of $J_2$ which remains normal to fold axes through two major oroclinal bends along the 1500 km length of the Central and Southern Appalachian Mountains. An additional set of ENE-striking vertical joints, $J_3$, appear in the black shales of the Appalachian Valley and Ridge. Vertical ENE joints (i.e., $J_3$) that postdate folding are consistent in style and orientation with neotectonic joints in Ordovician carbonates elsewhere in the Central Appalachian Valley and Ridge (Hancock and Engelder, 1989).

In several of the Devonian black shales, $J_1$ and $J_2$ mutually crosscut and therefore yield no information on relative age. $J_1$ was assigned the earlier date for several geological reasons with the strongest argument being that throughout folding, $J_1$ joints remain normal to bedding as they are rotated to shallower dips (Engelder, 2004). Slip on $J_2$ joints during the Alleghanian Orogeny displaces $J_1$ joints, again suggesting that $J_1$ propagated first (Engelder, et al., 2001). Of course, the orientation of $J_1$ joints is independent of the oroclinal bends of the Central and Southern Appalachians whereas $J_2$ is a dip joint with its strike changing with the oroclinal bends.

Placing $J_1$ of the Appalachian Plateau before Alleghanian folding, and presumably layer-parallel shortening, presents a geological conundrum of the first order by defying more parsimonious interpretations on two counts. First, the strike of $J_1$ is close to the range expected for neotectonic joints propagating under the influence of the contemporary tectonic stress field (Figure 1). Historically, $J_1$ in the Appalachian Basin was attributed to neotectonic processes controlled by the contemporary tectonic stress field (Engelder, 1982; Hancock and Engelder, 1989). The difficulty in distinguishing $J_1$ and neotectonic joints ($J_3$) is a geological conundrum. Second, if $J_1$ predates Alleghanian layer-parallel shortening, it remains unexpectedly pristine. This observation makes it very difficult for a number of very good structural geologists to accept the pre-layer-parallel shortening hypothesis. This PAPG field trip will focus on these two geological conundrums.

## Examining conundrum #1

Two important conclusions emerged from early observations of joints. First, Price (1966) concluded "it is unlikely…..that all joints are the result of a single mechanism". Second Nickelsen (1976) commented, "Fracture patterns are cumulative and persistent. Cumulative implies several episodes of fracturing…. Persistent means not easily erased by later tectonic events". From these observations sprang the general hypothesis that the effective tensile stress necessary for joint propagation is at the end of several loading paths involving stressed developed during burial, tectonic deformation, and/or later exhumation (Engelder, 1985). Further, 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, it should come as no surprise that it is difficult to jump from field observations to an interpretation concerning timing of joint propagation during the burial and exhumation cycle of a sedimentary basin.

Of all the characteristics of joints, the most striking is their planarity. The mechanical explanation is that stress controls joint propagation and a rectilinear stress field will act as a planar guide during joint growth (e.g., Pollard and Aydin, 1988; Lawn, 1993). This characteristic allows the development of sets with parallel joints spaced side-by-side. Vertical growth is dictated by thickness of mechanical unit containing a joint set. A bedded rock with interlayers of siltstone between shale, for example, will contain regularly spaced joints in the siltstone beds with a height restricted to the thickness of the bed (Figure 7A). Homogeneous, thick shales acting as a single mechanical unit will allow nearly unlimited vertical growth of joints (Figure 7B).

Joints within well-defined mechanical units (e.g., siltstone in shale) often have a regular spacing that is approximately the thickness of the mechanical unit or bed (Narr and Suppe, 1991). The popular explanation is that joints form a stress shadow which prevents the growth in regional immediately adjacent to an existing joint (Gross et al., 1995). The stress shadow extends about one bed height away from the existing joint and, hence, defines a no-growth zone outside of which other joints are free to grow. This rule is applicable to joint propagation when the driving mechanism is bedding extension but not to growth of natural hydraulic fractures (Fischer, et al., 1995). During natural hydraulic fracturing, stress shadows are compressive which negates any mechanical influence of adjacent joints with the neighbors might grow with a spacing much less than joint height (Figure 7B).

One common characteristic for joint growth in black shale is their close spacing relative to joint height (Figures 7B and 8A). This pattern is the first of several pieces of geological evidence supporting the natural hydraulic fracture mechanism for driving vertical joints in black shale (Fischer et al., 1995). Even when black shale has well developed and closely spaced joints in both $J_1$ and $J_2$ orientations (ENE vs. cross-fold), late-formed joints are present and easily identified by their curving characteristic in both cross section and plan view. In cross section, late-formed joints are not vertical but when propagating toward systematic joints of either the $J_1$ or $J_2$ sets, these late-formed joints curve to become parallel with the earlier, planar joints (Figure 8B and 8C). When present

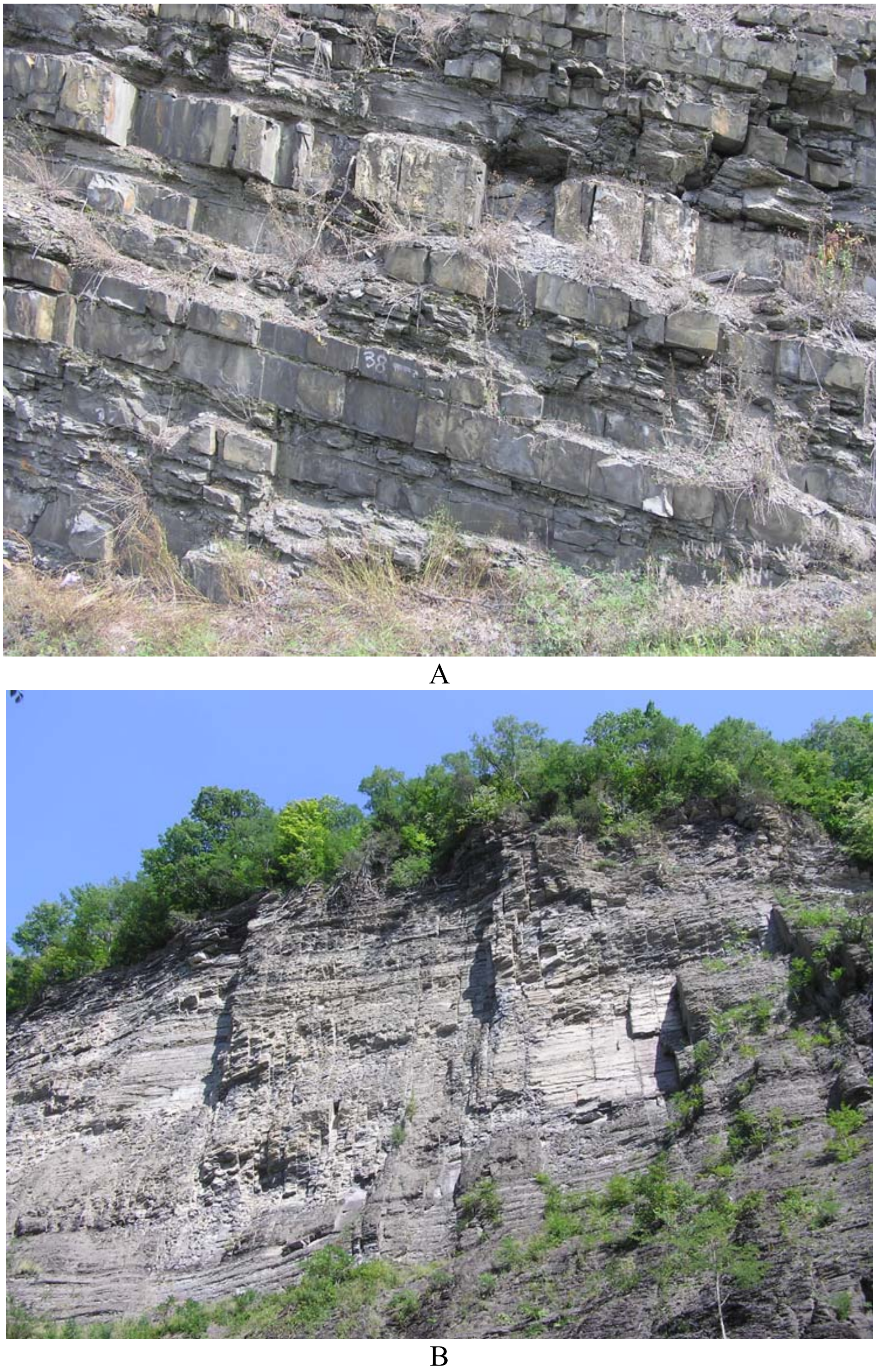


Figure 7. A. Joints in siltstone beds of the Braillier Formation near Huntingdon, PA. Here, joint spacing is proportion of bed thickness. B. Joints in shale of the Ithaca Formation at Taughannock Falls State Park, NY. Here joint spacing is much closer than joint height.

Figure 8. Skaneateles Formation at Moonshine Falls east of Aurora, N.Y. Looking SSE parallel to $J_2$. Neotectonic or exhumation joints parallel $J_2$.

in plan view, late-formed joints curve perpendicular to the systematic joints and abut them, hence, the name curving cross joints (Engelder and Cross, 1993). The mechanical explanation is that the crack-tip stress field of these late-formed joints is not transmitted across open joints and without the benefit of a crack-tip stress field, the late joints can not jump across the earlier, open joint (Gross, 1993). 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, 2008)

The upward growth of joints was popular in the literature more than 50 years ago (Nevin, 1931). The mechanical basis for this theory is that horizontal stress decreases upward in the earth as a consequence of gravitational component of the Earth's stress field (Engelder, 1993). Fluid-driven fractures would naturally climb because the decrease in fluid pressure through density is less than the decrease in the gravitational component of the horizontal stress. At the same time, the horizontal stress does not decrease at the rate of the vertical stress (Brown and Hoek, 1978; Plumb, 1994). This leads to the BHSP (Figure 3). Early formed joints that propagated below the depth of influence of the BHSP should manifest themselves as vertical joints right up to the erosional surface (Figure 9A). Evidence of upward growth of late joints in black share may be seen in the tendency for these joints to curve parallel to the Earth's surface (Figure 9B). In summary, there is plenty of evidence for late-formed joints the reflect the BHSP.

One important hypothesis concerning deep-formed joints, of which the $J_1$ set is an example, is that they reflect a homogeneous Earth stress field whose principal stresses are vertical and horizontal. There is a question about the depth at which the Earth stress becomes rectilinear and parallel with the Earth's surface. Clearly, principal stresses tracking with horizontal datum are less likely at depths where topographic variation overprints Earth stress (Savage, et al., 1985). Topographic stresses die out below depths on the scale of the topography. Early-formed joint sets such as $J_1$ and $J_2$ are themselves a gauge of an Earth stress that tracks with a horizontal datum in that they are well developed and dip within a degree or two of vertical when bedding is horizontal.

The argument that $J_1$ predates Alleghanian folding is based in part on these joints appearing orthogonal to bedding even when bedding has rotated during folding (Engelder, 2004). The idea is that Earth stress does not rotate with folding, particularly when overburden is large enough to mute the effect of topography. Vertical joints in dipping strata are cited as evidence that jointing post-dates folding and that Earth stress does not lean over with fold dip. In black shale of the Appalachian Plateau, $J_1$ joints remain normal to bedding even when bedding constitutes the limb of a gently dipping fold. In the Lavanna black shale of Moonshine Falls, $J_1$ joints cluster in a manner characteristic of deep-formed natural hydraulic fractures (Figure 10). The vector mean pole of this cluster dips 2º, exactly the extent to which bedding is folded. While one can argue that joint growth is constrained to a position normal to bedding, this behavior requires a well-defined mechanical unit. Even with well-defined mechanical units joint propagation is not constrained in such a manner (Figure 7A). Furthermore, black shale is generally thick enough to allow for propagation controlled exclusively by Earth stress without the superposition of stress induced by a local mechanical-unit anisotropy.

Figure 9. Union Springs Member of the Marcellus Formation at Union Springs, N.Y. A. Looking parallel to $J_1$ joints cutting vertically to the outcrop surface. B. J2 joints curving toward the outcrop surface.

Figure 10. Moonshine Falls east of Aurora, New York.

$J_1$ not only clusters in an outcrop, it also clusters over a region greater than 50 km on a side (Figure 11). The $J_1$ joints along Cayuga Lake show a strike of 076º for the vector mean pole from 74 outcrops (Sheldon, 1912). $J_1$ joints in the larger Finger Lakes region

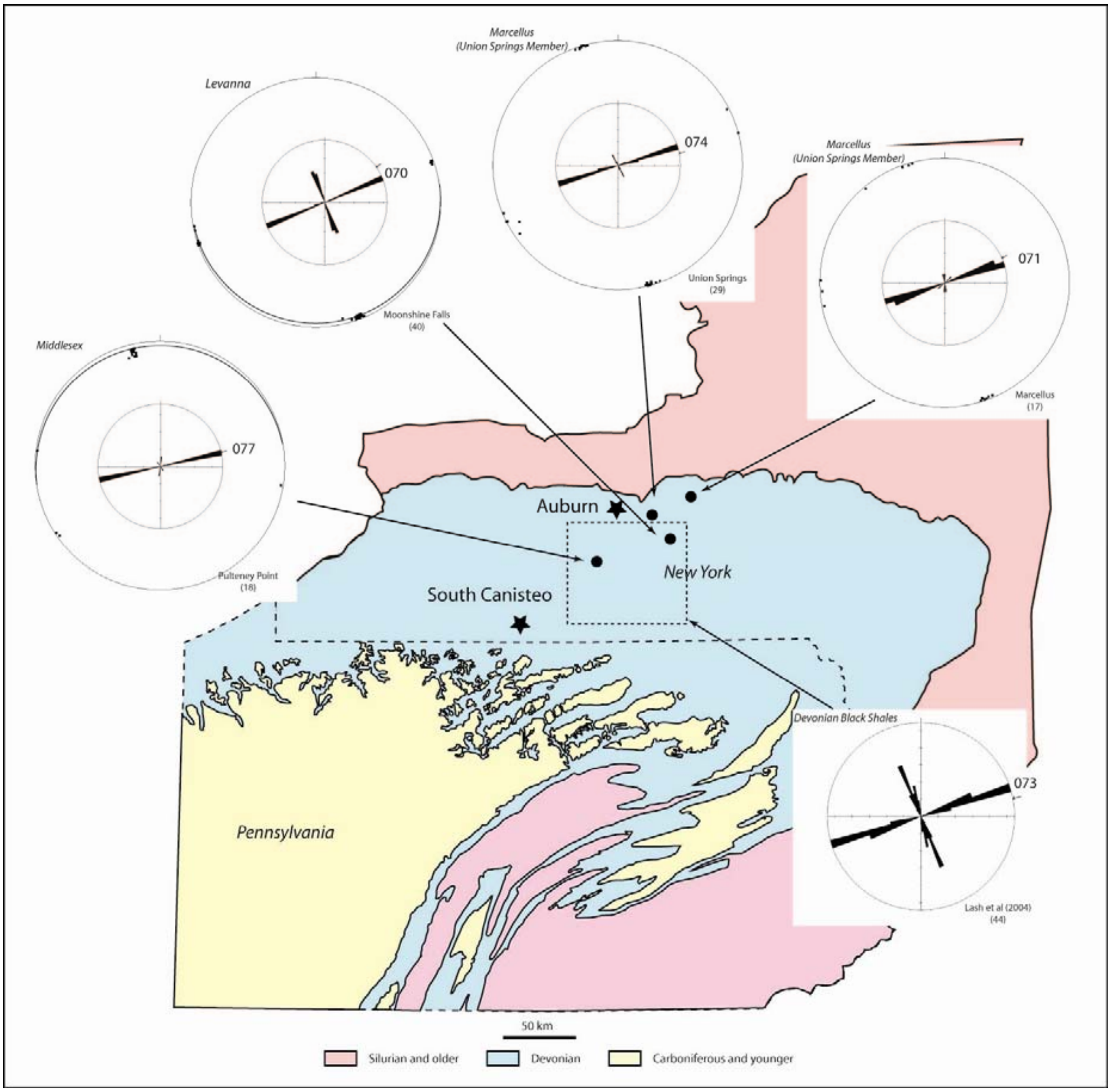


Figure 11. Joints of the $J_1$ orientation in outcrops of the Maracellus and other black shales in the Finger Lakes District, New York. The rose diagram from Lash et al., (2004) is a compilation of the mean vector poles from 23 outcrops in the region outline by the dashed box.

shows a strike of 073º for a vector mean pole from 23 outcrops consisting exclusively of black shale (Lash et al., 2004). These data fall outside of and clockwise from the range of the vector mean orientation for the contemporary tectonic stress field in eastern North America (i.e., 058º to 069º) indicated by each of four measures of modern stress (Figure 1). Of course, the extent to which the contemporary tectonic stress field has changed since mid Tertiary time is unknown. When *in situ* stress measurements nearest to the

Finger Lakes District are considered, the lack of correlation between contemporary tectonic stress and $J_1$ is not as compelling. To the west of the Finger Lakes District, hydraulic fractures from the Wilkins Well experiments show $S_H$ striking at 072° and in Auburn, NY hydraulic fractures show $S_H$ striking at 083° (Figure 11).

During burial of black shales, the maturation of hydrocarbons continued with increasing gas production and pressure buildup to the point of natural hydraulic fracturing. Several lines of evidence point to the propagation of both $J_1$ and $J_2$ as natural hydraulic fractures. First, tensile joints cleave concretions whereas the concretion acts as a barrier for natural hydraulic fractures (McConaughy and Engelder, 1999). A natural hydraulic fracture will propagate around the concretion while leaving the concretion intact (Figure 12). The outcrop for which the Marcellus is named at Marcellus, NY, contains a nice example of a $J_1$ joint propagating around a concretion without cleaving it.

One of the major tools for interpreting joint origin and driving mechanisms for both $J_1$ and $J_2$ joints is a surface morphology called plumose structure (Bahat and Engelder, 1984). The rupture process in rocks is irregular on a microscopic scale while the overall surface of a joint remains planar. An irregular rupture prints a surface morphology or plumose structure on the surface of joints. The depth of the irregularity varies with velocity of the rupture so that when a joint propagates in occasional spurts, there is an unmistakably characteristic pattern of starts and stops. Tensile stress will cause continuous crack propagation whereas internal pressure will lead to incremental propagation and arrest (Lacazette and Engelder, 1992).

Propagation in spurts 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). If a joint ruptures in a spurt, the volume suddenly goes up and by Boyles Law, the pressure inside the joint would decrease. Incremental rupture indicates that pressure builds again until the rupture starts anew and that the source of fluid can not feed fluid to the growing joint a the speed with which the joint propagates. The mechanism by which fluid is fed to the joint volume is through the pore space on either side of the joint. The decrease of pressure within the joint after each cycle leads to an inward pressure driving flow from the rock matrix to the open joint. With flow to the joint, its pressure gradually increases until rupture commences again, cycle after cycle. As many as 68 cycles have been counted on one joint interface.

Another characteristic of propagation within the shale sequence of the Catskill Delta is that rupture increment length gradually increases with length of the joint (Lacazette and Engelder, 1992). Increment length scales with the thickness of the bed with initial lengths shorter than bed thickness. Through several dozen cycles the increment length exceeds bed thickness. This behavior is characteristic of a compressible gas like methane. In fact, it comes as no surprise to find that methane drives natural hydraulic fracturing in the Catskill Delta complex given the long history of hydrocarbon maturation as the Appalachian Basin was buried to depths of 5 km. $J_1$ and $J_2$ are rarely filled which means that methane was retained during the subsequent 250,000,000 year history of the basin.

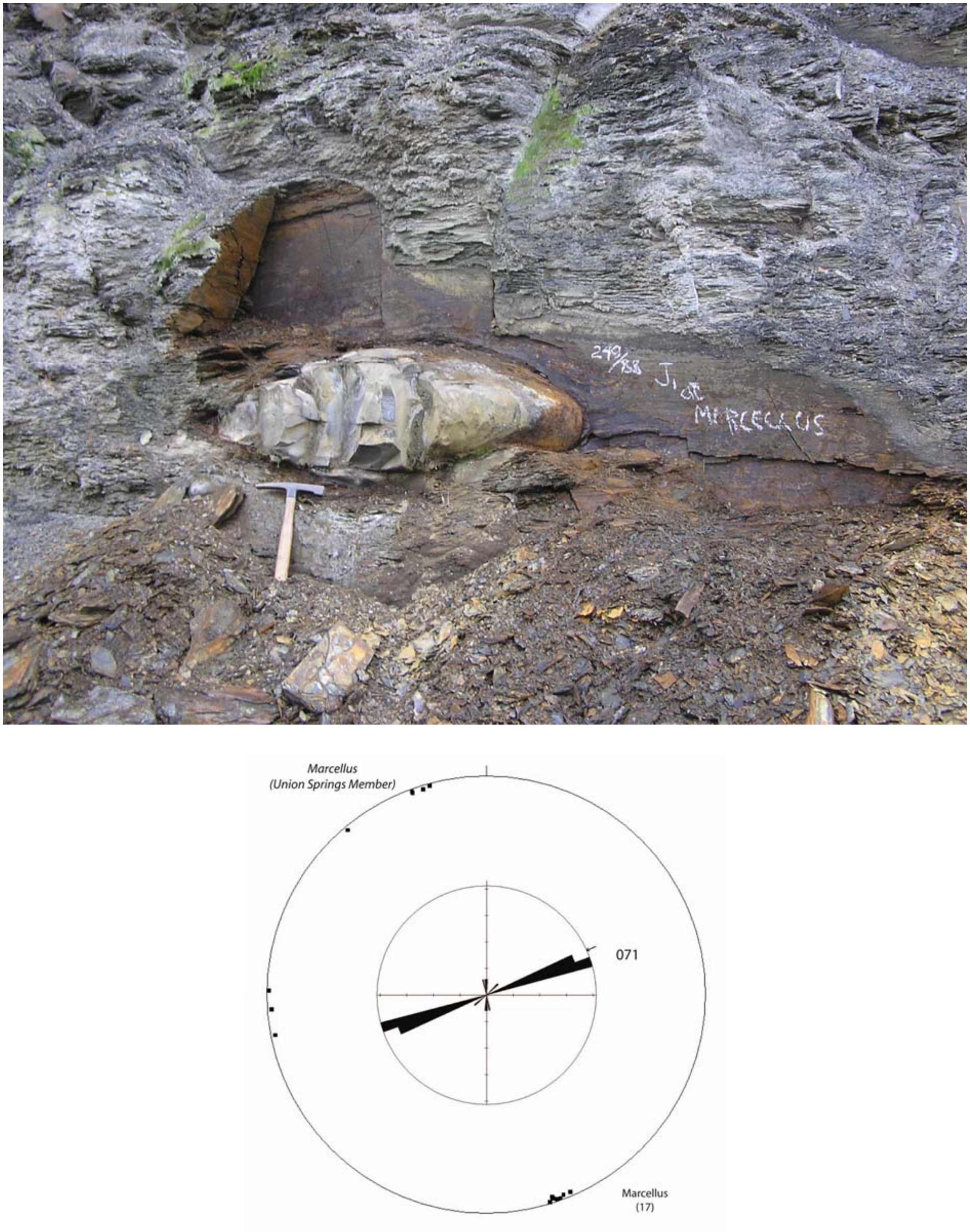


Figure 12. Union Springs Member of the Maracellus Formation at Marcellus, NY. Here J1 joints propagate around but do not cleave concretions, geological evidence for natural hydraulic fracturing.

Fluid pressure continued to build to the point that joints were driven upward out of the black shales and into the overlying gray shales (Figure 7B). These gas chimneys are remarkable for their height which extends vertically off the top of black shales for at least 50 m. These new joints ($J_2$) cut at right angles to $J_1$ in the black shales below largely because they propagated in the stress field set up by the collision of Gondwana as it pivoted clockwise into Laurentia.

## Examining conundrum #2

The Appalachian Plateau detachment sheet was subject to 10% layer-parallel shortening as indicated by deformed fossils in the marine section of the Catskill Delta throughout western New York (Engelder and Engelder, 1977; Geiser, 1988). The pattern of layer-parallel shortening is seen in sub-Marcellus rocks along the Helderburg Escarpment which occurs north of the outcrops of Marcellus in western New York (Engelder, 1979). There can be no doubt that the Marcellus, which rode the Appalachian Plateau detachment sheet on top of the Onondaga, was subject to the same 10% layer-parallel shortening. According to the work of a number of authors including Engelder and Whitaker (2006), the $J_1$ set was present in the Marcellus before it was subject to layer-parallel shortening. Yet, the surface of the $J_1$ set shows no indication evidence of this layer parallel shortening. Conunbrum #2 boils down to the question, “How can a pervasive fabric from layer-parallel shortening form without affecting $J_1$ joints in some visible manner?” Part of the answer might be found by tracing the Marcellus from the foreland to the hinterland along the Mohawk Valley and down along the Hudson Valley foreland fold-thrust belt.

The behavior of ENE joints in the Hudson and Mohawk Valleys does not mimic the behavior of $J_1$ joints in the Finger Lakes District (Figure 13). At Kingston, the lower portion of the Bakovan (Union Springs) Member of the Marcellus is exposed (Figure 14). In this outcrop the best developed joint set has a vector mean strike of 059º. This set exhibits four characteristics may be more consistent with neotectonic joints. First, the joints are not planar when vertical growth is more than a meter or two. Second, the outcrop contains many short joints with vertical growth restricted to less than 0.5 m. 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 in the range of the contemporary tectonic stress field in the eastern USA (058º-069º).

The pattern of ENE joints in the Bakovan (Union Springs) Member of the Marcellus at Catskill is closer to that at Kingston than found in the black shale of the Finger Lakes District. While the outcrop gives the impression of robust vertical growth of joints, most joints have visible top and/or bottom tips with vertical growth less than two meters (Figure 15). Clustering is weak which may be a manifestation of curving growth. Here, growth is not orthogonal to bedding, an indication that joints were not tilted during folding. In places the Bakovan contains bed-parallel veins and the joints abut rather then cut the veins, a sign that the joints post-date vein growth. In summary, joints in the two best exposures of the Marcellus along the Hudson Valley foreland fold-thrust belt give the impression of belonging to the $J_3$ neotectonic set. If ever present, the $J_1$ set was erased by the strong layer-parallel shortening of the Hudson Valley foreland deformation

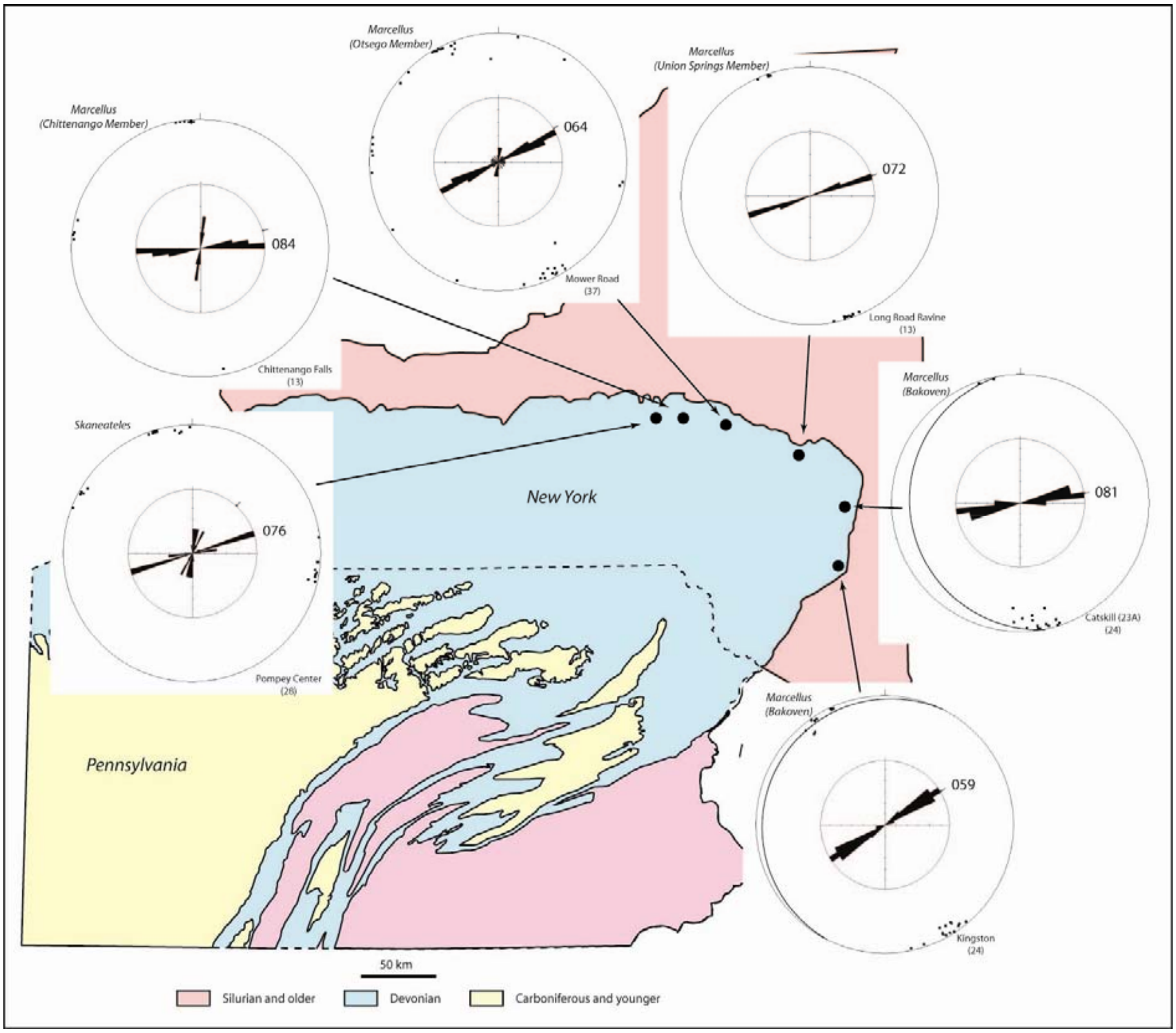


Figure 13. Joints of the $J_1$ orientation in outcrops of the Maracellus along the Hudson and Mohawk Valleys of New York. In general, the clustering of $J_1$ joints is poor relative to that seen in the Finger Lakes District.

(Marshak and Engelder, 1985). Of course there is the interpretation that the Hudson Valley foreland fold-thrust belt is Acadian and therefore, gas expulsion predates the episode of $J_1$ jointing by thermal maturation (Marshak and Tabor, 1989).

In the Marcellus along the Mohawk Valley, clustering of $J_1$ joints is tighter, particularly in Long Road Ravine and Chittenango Falls (Figure 13). It might be argued that this is a transition to the early $J_1$ joint set in a region that was affected by neither the early Hudson Valley thrusting nor by the later Main Phase Appalachian Plateau deformation (Geiser and Engelder, 1983). The Hudson Valley to Mohawk Valley experience suggests that when following the Marcellus into the Pennsylvania Valley and Ridge there is the possibility of discovering that $J_1$ is missing there as well.

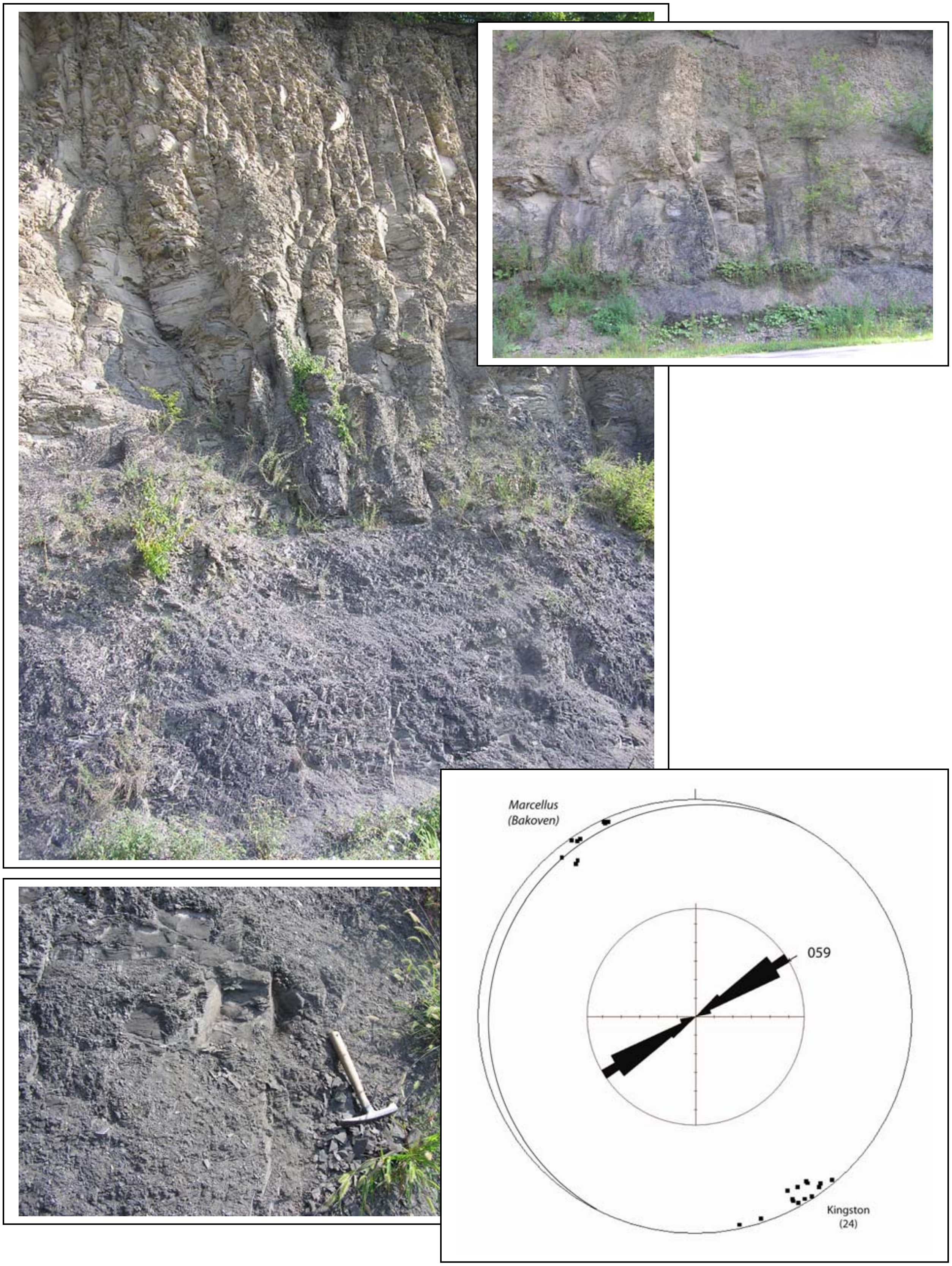


Figure 14. Suspected $J_3$ joints in the Bakovan (Union Springs) at Kingston, NY. View looking ENE.

Figure 15. Bakoven (Marcellus) along Route 23A southwest of Catskill, NY. Looking east. Dip of bedding is more forward than to the right.

## Examining conundrum #3

One of the striking features concerning the orientation of joints in core recovered during the EGSP is their radial pattern around the oroclinal bend of the central Appalachian fold-thrust belt (Figure 16). The Marcellus and other black shales are loaded with joints of the $J_2$ set [i.e., cross-fold (dip) joints] When mapping on an outcrop by outcrop basis in the Devonian Brallier Formation along the Allegheny Front, the same radial pattern of cross-strike joints appear (Figure 17).

Fold-thrust belts form largely by the thrust stacking of detached sections. In the Appalachian Valley and Ridge the major stiff layer is a > 2 km thick Cambro-Ordovician carbonate section (Wiltschko and Geiser, 1988). Such thrust faulting is presumably

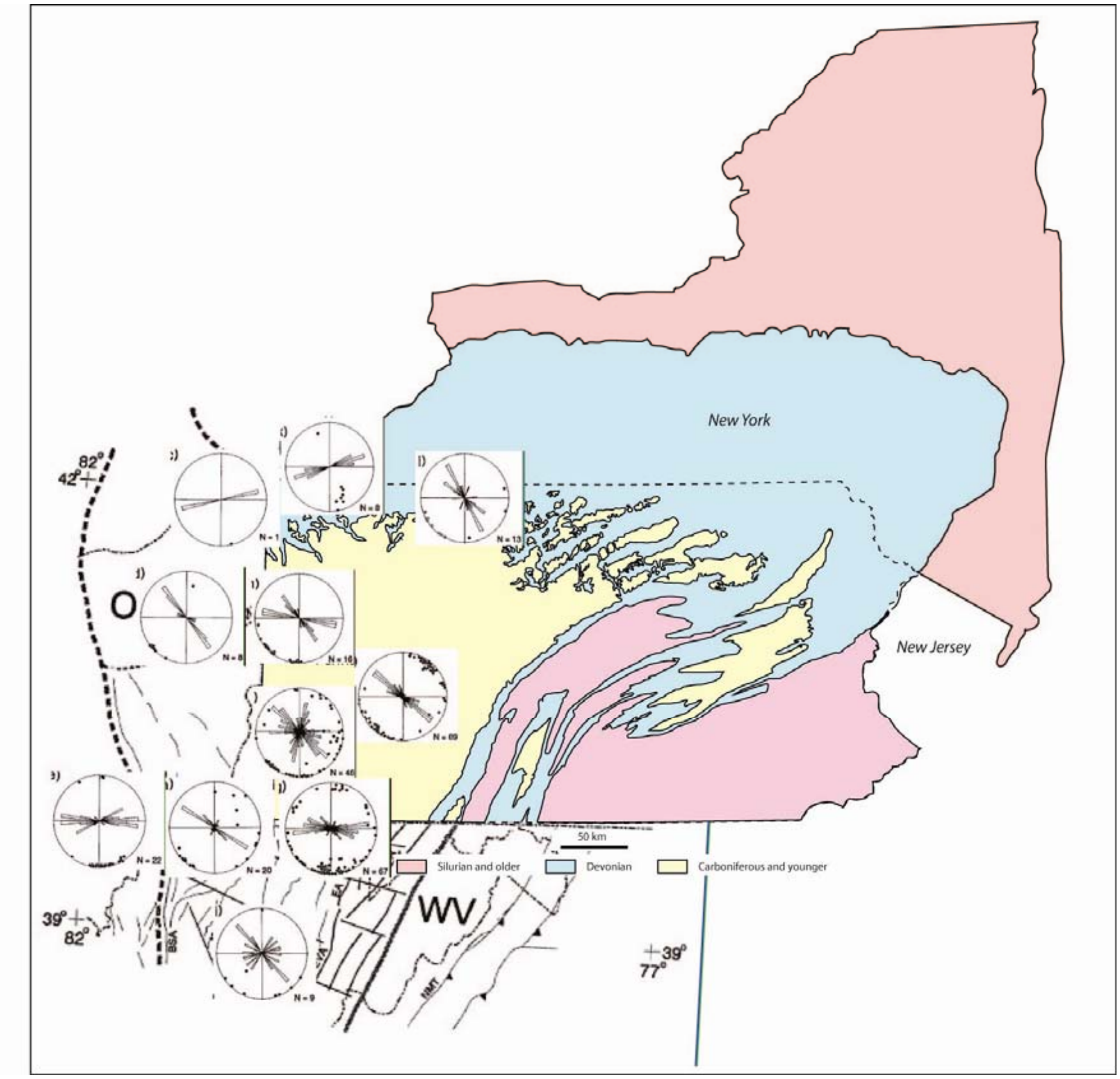


Figure 16. Equal-area lower hemisphere stereonets of poles to joints and veins in core recovered from black shale drilled during the Eastern Gas Shales Project (ESGP). The center of each stereonet is placed at the location of the well from which the core was taken. Data compiled by Evans (1994).

characterized by a state of stress where the least principal stress, $\sigma_3$, is vertical (Anderson, 1905). How else would thrust ramps with dips of 20º to 25º form? Yet, the major syntectonic joint set is vertical and in the cross-fold orientation. What mechanism is responsible for a horizontal $\sigma_3$ as indicated by the presence of $J_2$ joints across the entire width of the Appalachian foreland?

In the carbonate thrust sheets of the Appalachian Valley and Ridge, the last episode of crack propagation and vein development occurred after the carbonates were located on the upper flat of thrust duplexes. The propagation of cross-fold veins (CFV) was delayed

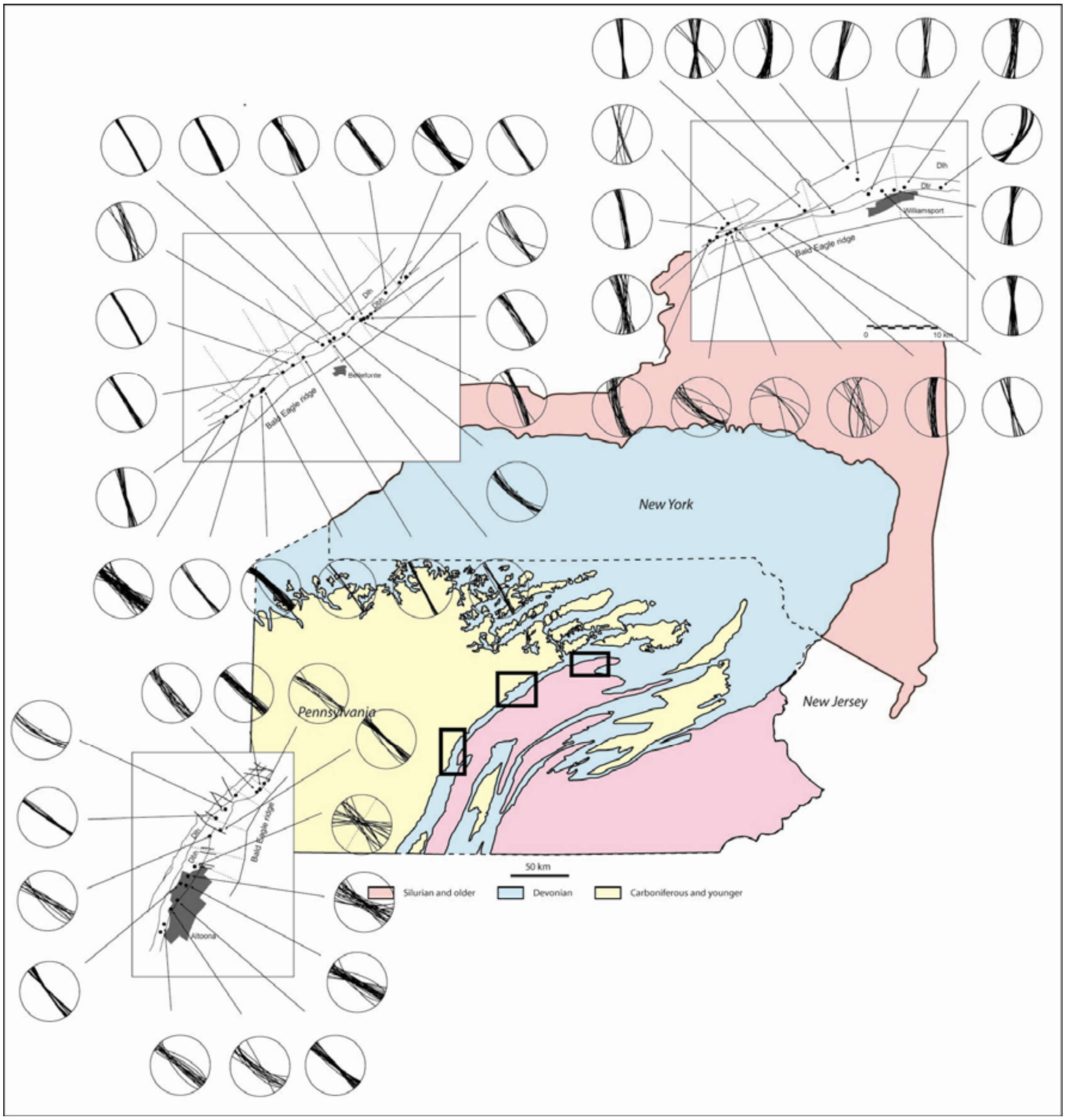


Figure 17. Present orientation of cross-fold joints in the vicinity of the Broadtop Syncline. Equal-area net projection. Dbh: Brallier and Harrel Fms. undivided, Dh: Hamilton Group, segmented line: local bedding trend, and dashed line: breaks in bedding trends. Adapted from Uzcatequi (2004).

until this point as indicated by crosscutting relationships (Srivastava and Engelder, 1999). The causal stress, $\sigma_3$, was parallel to the strike of the host rock and local fold axes. One mechanism for the evolution of a local stress field is the horizontal contraction due to cooling and removal of overburden during syntectonic erosion. Another mechanism for reducing strike parallel stress is strike-parallel stretching to accommodate an increase in radius of curvature around an oroclinal bend. Strike-parallel stretching is also required to accommodate lateral ramps in a foreland fold-thrust belts.

## A tectonic overprint other than joints

Regarding conundrum #2, the absence of an early $J_1$ in the Marcellus of the Hudson Valley begs the question why layer parallel-shortening between the Hudson Valley fold-thrust belt and the Finger Lakes District of the New York Appalachian Plateau had such a different affect. Penetrative strain in both locations is comparable with layer-parallel shortening on the order of 10% (Marshak and Engelder, 1985). The difference is the amplitude of folds and blind thrusting along the Hudson Valley is considerable greater. It is not intuitively obvious how penetrative strain could have consumed early $J_1$ joints in this setting and not on the Appalachian Plateau where folding is slight. A parsimonious explanation is that $J_1$ joints never cut the Marcellus of the Hudson Valley. This explanation is consistent with the joint pattern in EGSP core recovered from the deeper portion of the Appalachian Basin (Figure 16). Core recovered from the Marcellus and other black shales in the deepest portion of the Plateau Basin show a well-developed $J_2$ with no little evidence for a $J_1$ set (Evans, 1994). In fact, Evans (1994) interprets any ENE joints in ESGP core to be late and equivalent to the neotectonic $J_3$ joints.
The ESGP core from the deeper portion of the Appalachian Basin contain plenty of $J_2$ joints and veins. The major charactertistic of the $J_2$ set is that their orientation follows the oroclinal bend of central Appalachian Valley and Ridge folding to remain normal to strike (Figure 17). In mapping the $J_2$ set in the Valley and Ridge, it is more prominently developed in siltstones of the Brallier than the Marcellus (Uzcatequi, 2004). However, there are Marcellus outcrops in the Valley and Ridge that do display a well-developed $J_2$ set (Figure 18). Relative to joints, veins in the Marcellus are rare and account for < 0.01% of the mode I fracture population (Figure 19). The key here is that the pervasive fabric developed with layer-parallel shortening in the Valley and Ridge did not overprint $J_2$ joints and in many cases left them in pristine condition. These are the same pristine joints that were recovered from depths in excess of 7000' in the central portion of the Appalachian Basin.

In addition to joints, playing the Marcellus of the Appalachian Plateau involves issues associated with structural position and regional changes the result from lateral variation in the rocks of the Salina Group which serves as the detachment horizon of the Plateau detachment sheet (Scanlin and Engelder, 2003). The first order structures carrying the Marcellus on the plateau may be classified according to two regions: The Bedford-Pittsburgh Region and the Williamsport-Tioga Region. There is a moderate increase in the width of the Appalachian plateau detachment sheet along strike in Pennsylvania from 165 km in the southwest to over 175 km in the northeast (Fettke, 1954; Gwinn, 1964; Faill, 1998). These two portions of the detachment sheet (i.e., the Bedford-Pittsburgh region to the southwest and the Williamsport-Tioga region to the northeast) are separated by the Pennsylvania Culmination. One distinction between the two regions is that in the Williamsport-Tioga region and to the north in New York State, the Middle and Lower Devonian section is organized into more closely spaced, irregular anticlines (Bradley and Pepper, 1938; Van Tyne and Foster, 1979). In addition, the Silurian salt beds are considerably thicker and more continuous in the Williamsport-Tioga region (Fergusson and Prather, 1968). In the Bedford-Pittsburgh region, there is also a significant decrease in structural relief going toward the foreland leading Gwinn (1964) to identify an intra-plateau structural front separating the Inner plateau and the Outer plateau.

Within the Appalachian plateau detachment sheet of southwestern Pennsylvania tectonic thickening is a central element to the growth of anticlines in a Silurian-Devonian section containing a three-tiered mechanical stratigraphy (i.e., a basal detachment zone, a lower imbrication zone, and an upper wedge zone). The detachment zone is predominantly within disturbed shale of the Silurian Vernon Formation which sits above a disturbed surface on the Lockport dolomite. Large-scale anticline growth is, in part, a consequence of small-scale blind imbrication of the more competent mechanical layers in the lower portion of the detachment sheet (the imbrication zone). The Marcellus is part of the imbrication zone (Figure 20). Here, salt within the Silurian Syracuse Formation hosts secondary detachment responsible for imbrication and the development of triangle zones in the core of the anticlines. Some fold amplification is also accomplished by extensive, smaller-scale thrust wedging and concomitant tectonic thickening of the less competent Devonian section in the upper portion of the detachment sheet (the wedge zone). These spatially periodic anticlines are separated by horizontally bedded synclines characterized by the absence of thrust wedging and fault imbrication across all three zones. Tectonic thickening continued behind the foreland propagation of the detachment-tip line within the Vernon shale as indicated by a systematic hinterland increase in the cross-sectional width and amplitude of the anticlines.

On the basis of seismic images, each detachment sheet anticline is situated above prominent, periodically-spaced, pre-Alleghanian structures in the footwall of the detachment sheet. These footwall structures arise from a combination of thrust imbrication at the depth of the Ordovician Trenton Group and high-angle, basement-involved faulting at the depth of the Cambrian Gatesburg Formation. Some of the high-angle fault displacement is a consequence of Alleghanian inversion on faults associated with the extensional Rome Trough and other basement structures developed during the Late Proterozoic rifting of the eastern margin of Laurentia. Evidence for tectonic inversion is present in seismic reflection images that show buttress anticlines in the Cambro-Ordovician carbonate section.

A.

B.

Figure 18. $J_2$ joints in the Union Springs Member of the Marcellus along the Conrail railroad cut at Newton-Hamilton, PA. A. View looking NW B. View looking SE.

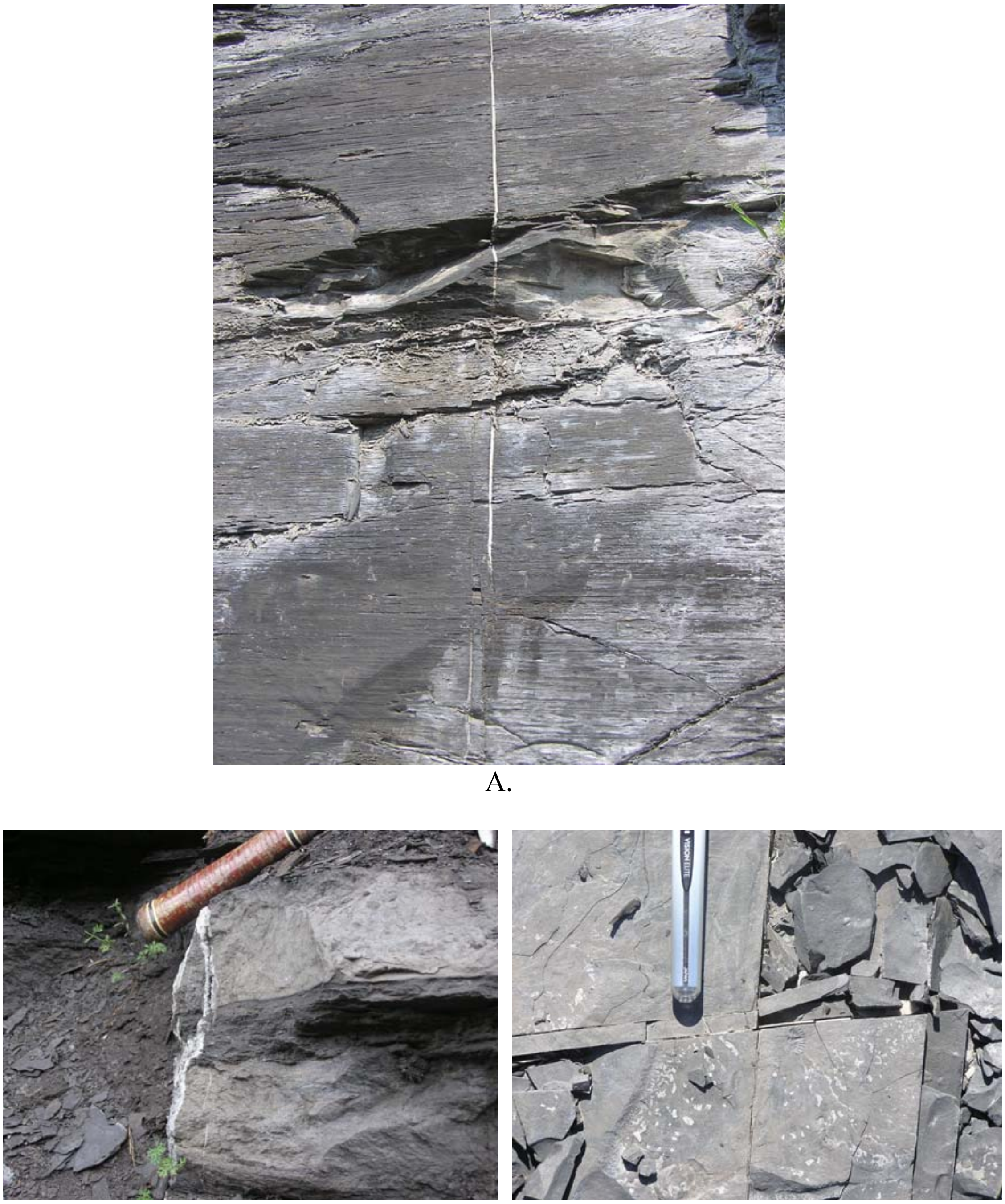


Figure 19. A. Filled vein ($J_2$ joint) in the Union Springs Member of the Marcellus along the Conrail railroad cut at Newton-Hamilton, PA. B. Open vein ($J_2$ joint) in the Onondaga Limestone along the Conrail railroad cut at Newton-Hamilton, PA. C. Filled veins in the Union Springs Member of the Marcellus in the Wolfe Quarry east of Union Springs, NY. The pen is aligned with a $J_1$ vein with a $J_2$ vein cutting through at about 80º.

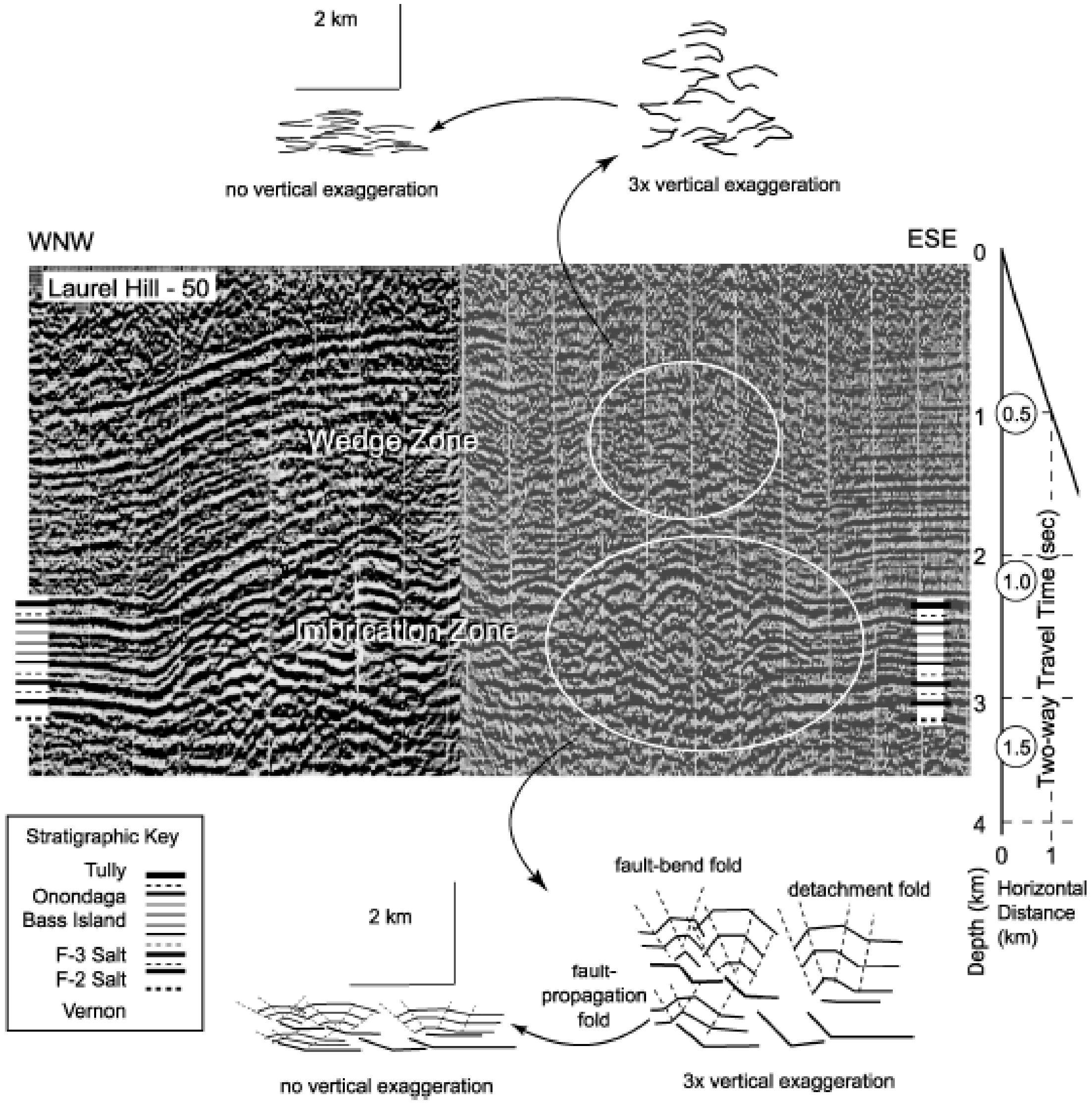


Figure 20. Interpretation of structural style within the wedge and imbrication zones of the detachment sheet as found in seismic profile LH-50 (migrated time section) through Laurel Hill anticline in Westmorland County, PA. Schematic line drawings are shown at 3:1 vertical exaggeration as portrayed on within seismic sections and with no vertical exaggeration. Taken from Scanlin and Engelder (2003)

The superposition of detachment-sheet anticlines above footwall structures strongly suggests that the foreland transport was disrupted by topographic bumps on the base of the detachment zone. Bending of the detachment sheet over these irregularities may have promoted the spatially periodic collapse and concomitant tectonic thickening in the over-riding sheet as it was pushed laterally toward the foreland. A strain hardening of the detachment zone part of the detachment sheet at the topographic irregularities permitted the growth of double-sided tapered wedges (i.e., each anticline). The overall structural profile of the detachment sheet is consistent with the growth of a Coulomb wedge whose low basal friction is interrupted by patches of strain hardening.

The extent of mesoscopic and microscopic deformation of the Marcellus gas shale, particularly within anticlinal regions of the plateau, must be considerable (Figure 20). For examples of structures within the Marcellus we look to exposures in the Valley and Ridge (the subject of this field trip). The Marcellus Shale becomes more heavily deformed to the southeast of the Allegheny Front into the interior of the Appalachian Valley and Ridge. Increased strain is manifested by development of a disjunctive cleavage that begins to overprint $J_1$, which appears in a few outcrops that are within 15 km of the Allegheny Front but are not evident further into the hinterland. However, $J_1$ is present in the anthracite district of PA (Nickelsen, 1979).

Layer-parallel shortening (LPS) of 10% or more is found within the Appalachian Plateau detachment sheet at distances of more than 150 km from the Allegheny Front (Nickelsen, 1966; Engelder and Engelder, 1977). To the hinterland side of the Allegheny Front LPS increases to 25% (Faill, 1977; 1979). The Jacks Mountain-Berwick Anticline system marks a further increase to as much as 50% on the south side (Nickelsen, 1983). The Jacks Mountain structural front divided uniformly-spaced folds to the southeast from a more irregular fold pattern to the northwest in the Valley and Ridge (Faill, 1998). 50% is representative of shortening throughout the anthracite coal district of PA (Nickelsen, 1979). Samples of deformed worm burrows from the transition between Onondaga and Marcellus on the south side of Jacks Mountain flattened in bedding but don't show a strain approaching the 50% LPS seen in the anthracite district to the east (Figure 21A).

Small-scale buckle folds in silt beds are another structure indicating the penetrative nature of LPS in the Marcellus (Figure 21B). The buckle folds develop because of viscosity contrasts between layers (Fletcher and Sherwin, 1978). On a larger scale, one theory for large-scale folding within the Appalachian Plateau detachment sheet is by buckle growth (Wiltschko and Chapple, 1977). Other explanations for the detachment sheet folds include Coulomb wedge theory (Scanlin and Engelder, 2003).

The most pervasive and wide-spread witness to layer-parallel shortening in the Marcellus is pencil cleavage (Figure 22). This type of cleavage, the so-called pencil structure, causes the Marcellus to break into long, slender (pencil-like) pieces. Typically it forms because shale parts along bedding and a penetrative cleavage that is subnormal to bedding (Reks and Gray, 1982). The lineation associated with pencil cleavage usually defines the local fold axes of the Valley and Ridge and Appalachian Plateau and becomes well developed when the host shale has seen 10% layer-parallel shortening (Engelder and Geiser, 1979). Its presence in Devonian shale of the New York foreland of the Appalachian Plateau detachment sheet witnesses to the extent that layer-parallel shortening takes place before fold amplitude increases in a fold belt. Both cleavage and bedding rotate with fold amplification so that either may define the more steeply dipping plane.

A.

B.

Figure 21. Lower portion of the Union Springs Member of the Marcellus along the Conrail railroad cut at Newton-Hamilton, PA. A.) Elliptical (deformed) worm borrows from the Onondaga-Marcellus contact. B.) Buckle folds in a stiffer siltstone of the Union Springs.

Figure 22. Pencil cleavage. A.) Newton Hamilton Railroad cut (Stop 9). B.) Samples from route 522 north of Orbisonia, PA (Stop 10).

Pencil cleavage is a manifestation of a penetrative deformation that is largely a manifestation of pressure solution on the microscopic scale (Engelder and Marshak, 1985). If pressure solution is spaced in hand samples, it forms a disjunctive cleavage (i.e., spaced cleavage). Carbonates of the Valley and Ridge are particularly prone to carry a disjunctive cleavage (Figure 23). Exposures of the Purcell Limestone, the central limestone member of the Marcellus, carry a strong disjunctive cleavage which is comparable to a layer-parallel shortening of more than 24% (Alvarez et al., 1978).

Pencil cleavage is an intermediate step in forming slaty cleavage from a shale or silty-shale protolith. The disjunctive cleavage intensifies to a slaty cleavage in the anthracite coal region of the eastern Valley and Ridge (Nickelsen, 1986). When this cleavage is present there is little doubt that pressure solution has played a strong role in generating a fabric which is most readily seen in weathered outcrops. Often core of the Marcellus does not show pencil cleavage but there should be no doubt that pressure solution during layer-parallel shortening imparted a fabric. In pristine core, the fabric leading to the development of a pencil structure is detected using X-ray pole-figure goniometry ( e.g., Oertel et al., 1989) or susceptibility of magnetic anisotropy (e.g., Hirt, et al., 1994).

The Marcellus also contains small-scale faulting and complex folding. The first type of fault in the Marcellus is a bedding-parallel detachment that manifests itself as a cleavage duplex (Nickelsen, 1986). A cleavage duplex is a zone of anastomosing cleavage that appears to be dragged in the direction of detachment (Figure 23B). In the case of the Marcellus detachment is always toward the foreland. When faulting is across bedding, it develops much like a classic ramp that has been folded by complex deformation associated with other local faults and folds (Figure 24). Such small-scale faulting and complex folding is most likely to occur in the tight cores of folds.

Figure 23. A.) Strong disjunctive cleavage in the Purcell Limestone of the Newton Hamilton railroad cut (Stop 10). B.) Small-scale cleavage duplex in Union Springs Member (Stop 8). The Swiss Army knife sits on the duplex which indicated thrusting toward the foreland (i.e., right to left).

A.

B.

Figure 24. Two minor thrust faults in the Union Springs Member at the Forgy Quarry east of Newton Hamilton, PA (Stop 9). In each case the marker bed is the G layer, a biotite-bearing crystalline tuff of the Tioga bentonites.

Pittsburgh Association of Petroleum Geologists (PAPG) Field Trip
September 12-13, 2008

AAPG-SEG Eastern Section Meeting Field Trip
October 11-12, 2008

# Structural geology of the Marcellus and other Devonian gas shales:

# A field guide

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## Introduction

The purpose of this field trip is to search for an ENE pre- or early Alleghanian joint ($J_1$) in Devonian black shale of the Pennsylvania Valley and Ridge with a focus on the Marcellus Formation. During this search three questions emerge: 1.) is it is possible to distinguish between early joints from neotectonic joints in the same orientation? 2.) can an early joint persist through the development of a penetrative fabric during layer-parallel shortening that exceeds 50% in places? 3.) How is it that vertical cross-fold joints form in association with layer-parallel shortening in a regime that presumably favors thrust faulting and a vertical $\sigma_3$? Focus is on the Marcellus because the presence of joints and specifically the $J_1$ set would greatly benefit the recovery of shale gas from a formation that otherwise has an intrinsic permeability on the order of 400 nanodarcies.

The thirteen stops of this field trip will visit a number of Upper Middle and Lower Upper Devonian Formations. While the Marcellus Formation of the Hamilton Group is the focus of this trip, parts of two of Ettensohn's (1985) tectonophases will be examined. Each tectonophase starts with a thicker limestone, presumably marking a period of tectonic quiescence before thrust loading at the margin of the Laurentian continent depressed the lithosphere enough to drop the seabed below the pycnocline. The key carbonate units are the Onondaga followed by the deposition of the Marcellus black shale and the Tully followed by the deposition of the Burket (Geneseo) black shale (Table 1). The carbonates represent a lull in tectonic activity and a eustatic rise in sea level.

The Devonian stratigraphic section is readily apparent in gamma-ray and density logs from the Appalachian Plateau detachment sheet (Figure 25). The Marcellus has a

### Table 1a.

Stratigraphic column for portions of the Middle and Upper Devonian in the Valley and Ridge of central Pennsylvania with Ettensohn's (1985) three tectophases.

| | |
|---|---|
| <u>GENESEE GROUP</u>: | |
| Brallier Formation ($D_{bh}$) | bedded sandstone, siltstone, and gray shale. Contains abundant cross-fold ($J_2$) joints. Equivalent to the Ithaca Formation in New York State and the Trimmer's Rock Formation in the eastern portions of the field trip. |
| Burket Formation ($D_{bh}$) | grayish black to black carbonaceous clay shale containing abundant pyrite. Equivalent to the Geneseo black shale in New York State where ENE ($J_1$) joints are well developed. |
| ***TECTOPHASE #3*** | |
| Tully Limestone ($D_{bh}$) | micritic limestone and limy shale. |
| <u>HAMILTON GROUP</u>: | |
| Mahantango Formation ($D_m$) | medium-gray to olive-weathering, fine to coarse-grained siltstone and numerous dark-gray to brown shale interbeds. Bottom of the formation consists of a calcareous shale equivalent to the Stafford Limestone in New York State. |
| Marcellus Formation ($D_{mh}$) | grayish black to black carbonaceous clay shale containing abundant pyrite, siderite concretions, and several layers of the Tioga bentonite. Members from bottom to top include the Union Springs, the Purcell Limestone, and the Oatka Creek. |
| | Tioga bentonite (390 Ma) |
| ***TECTOPHASE #2*** | |
| <u>HELDERBURG GROUP</u>: | |
| Onondaga Formation ($D_{on}$) | interbedded medium gray argillaceous limestone and dark-gray shale with Tioga bentonites at the top. Members from bottom to top include the Selinsgrove Limestone and the Needmore black shale. |
| Oriskany (Ridgeley) ($D_{or}$) | white siliceous sandstone with local calcite cement and friable. |
| Shriver Formation ($D_{or}$) | gray siltstone and shale with locally pinkish chert |
| Mandata Formation ($D_{or}$) | locally a black shale |
| ***TECTOPHASE #1*** | |

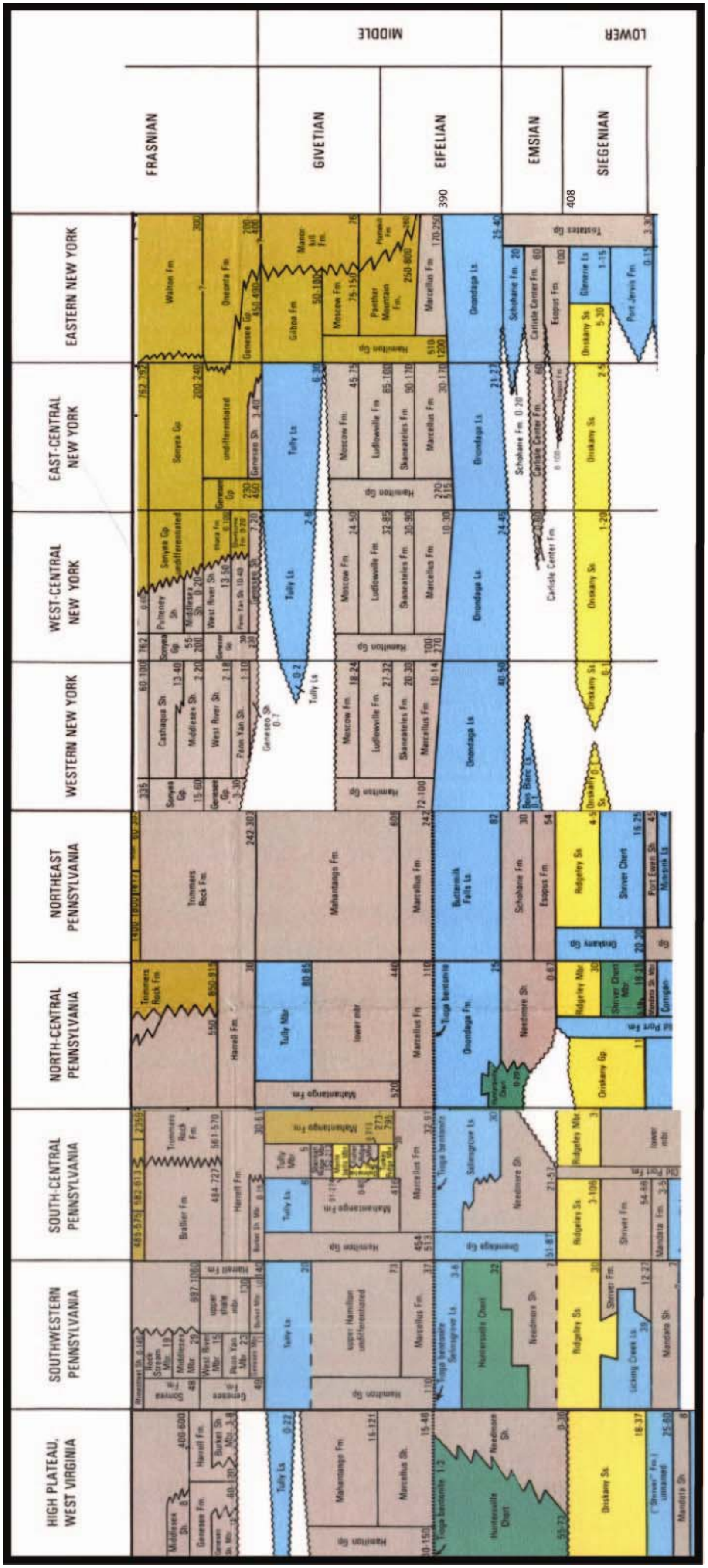

Table 1b. Chart from the Coorelation of stratigraphic units of North America (Cosuna) Project of the AAPG (Lindberg, 1985).

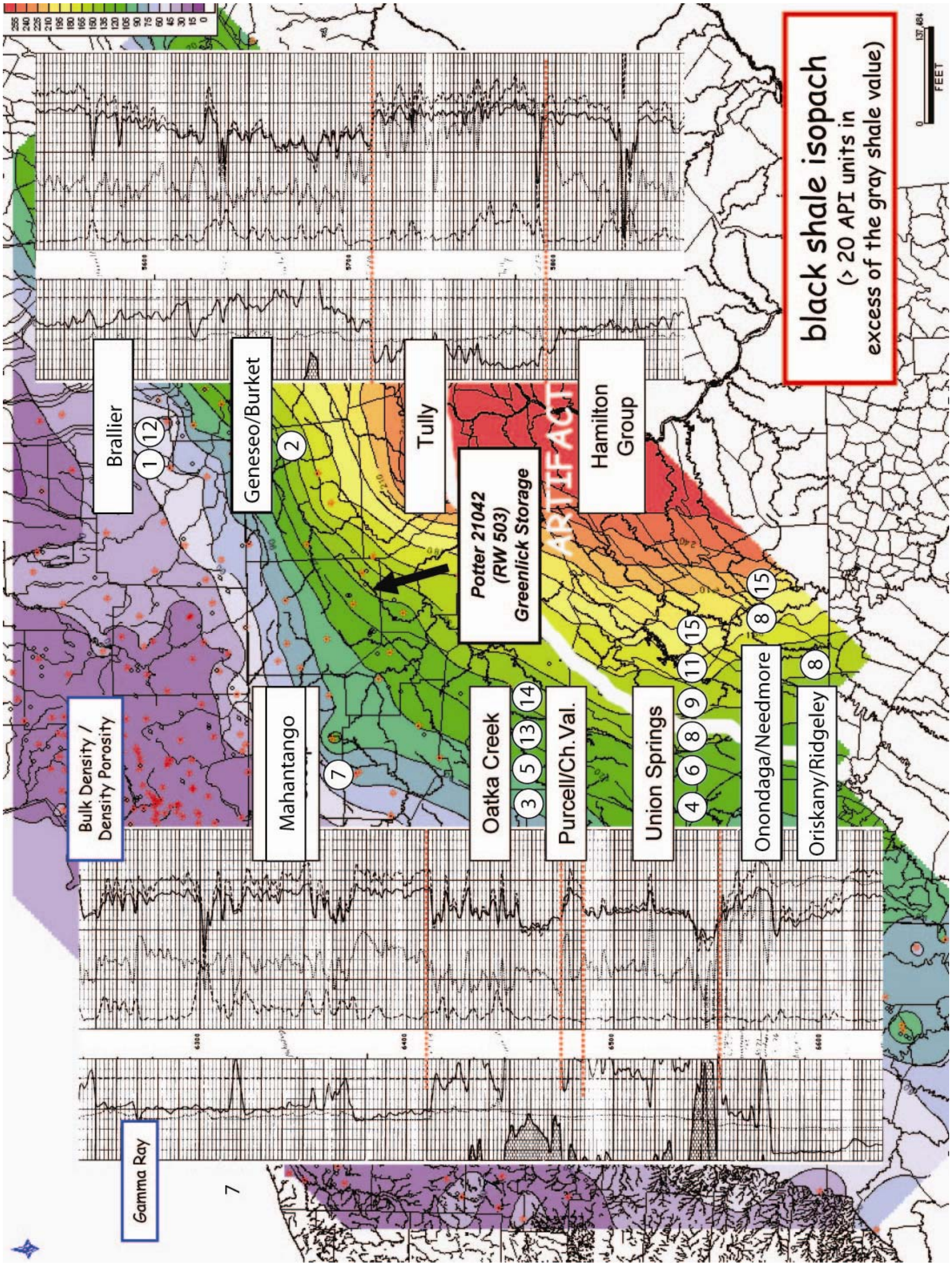

Figure 25. Representative log through the Devonian section of central Pennsylvania taken from southern Potter County. Relative stratigraphic position of field trip stops indicated by numbers 1-15.

gamma ray API of as much as 600 units and a density as low as 2.35 gm/cc. This low density is witness to a TOC of as much as 10% - 12%. The Burket (Geneseo) black shale does not exhibit these extremes although it stands out as having a high gamma-ray API and low density as well. Other units that are easy to spot on a log through the bottom three tectophases of Ettensohn include the Tully (low API – high density) and Onondaga (intermediate API – high density) limestones and the Oriskany (low API – low density) sandstone.

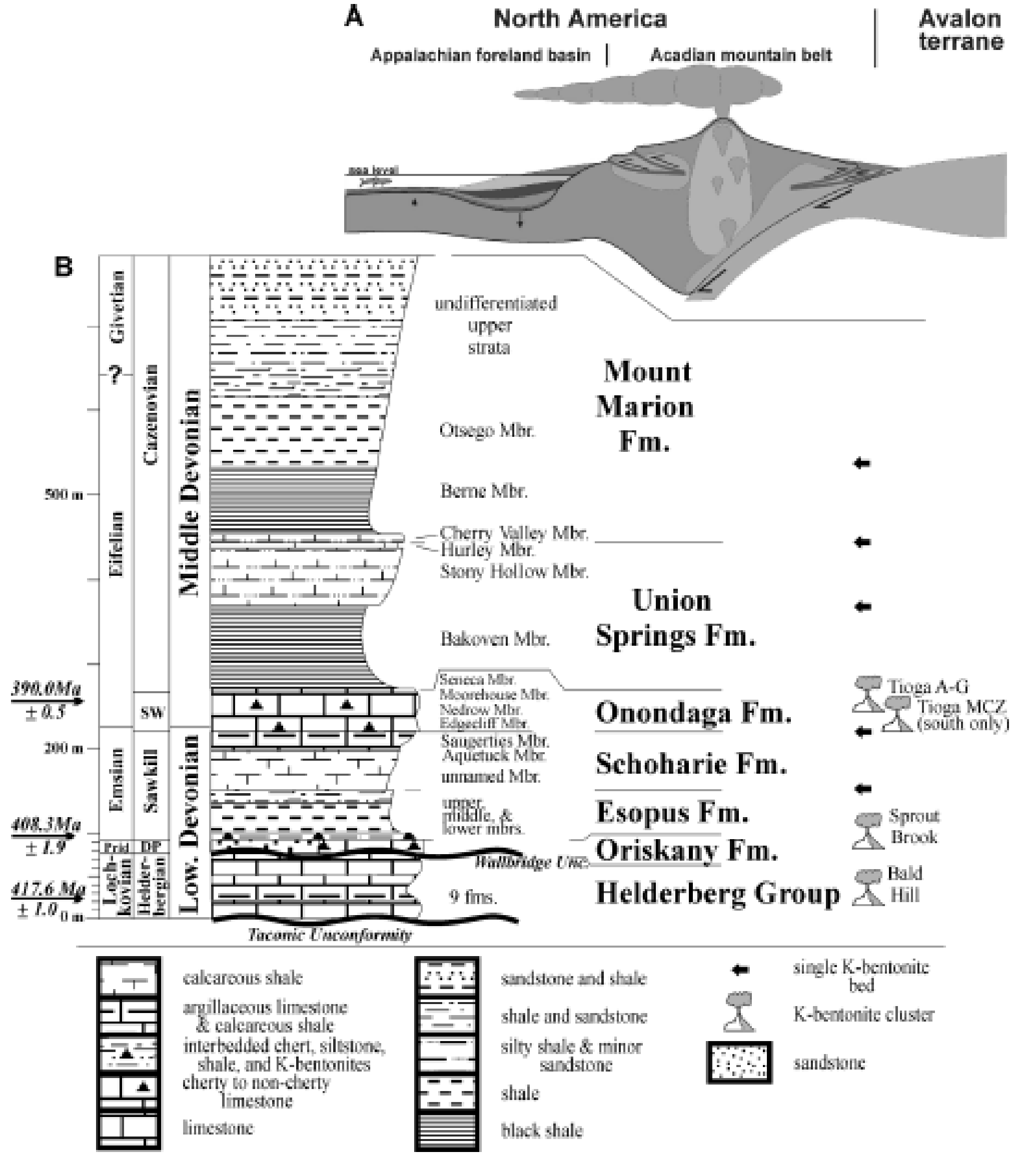

Figure 25a. Tectonic setting for deposition of the Marcellus (from ver Straeten, 2004). Three bentonite clusters are identified including the 390 Ma Tioga bentonites found at the base of the Marcellus.

The vigor of tectonic activity at the margin of Laurentia during the Upper Middle Devonian is witness by the abundance of the Tioga bentonites found in the lower portion Union Springs Member of the Marcellus (Figure 25a). These ashes were first designated the “Tioga Bentonite” based on experience drilling for sub-Marcellus natural gas, mainly in the Oriskany Sandstones of PA (Fettke, 1952). Later accounts identified six or more separate ash layers (Way et al., 1986; ver Straeten, 2004).

These ash beds from youngest to oldest are:

G – Crystal Tuff with biotite (Stop 9 & 13)

F – Thick vitric pyroclastic layer (Stop13)

E – thin (Stop 13)

D – thick (possibly Stop 7)

C – thin

B – thick: 20 cm

A – thin

Thermal maturation is of paramount interest, particularly in defining the extent to which the Marcellus is prospective as the Allegheny Front, Valley & Ridge, and Anthracite District of PA are approached. To this end, Appalachian Fracture Systems in collaboration with an Appalachian Operator has conducted an extensive study of the organic geochemistry of the Marcellus and other black shales of the Appalachian Basin. A portion of that study has been released and is reported here in the form of data Rock-Eval data from Humble Labs in Houston (Table 2). Sample localities are given on Figure 26.

Table 2. Samples sent to Humble Labs for TOC and Rock-Eval measurements**. The Rock-Eval data include S1 (the gas present in sample), S2 (the potential for further generation of gas), and S3 (the non-carbonate $CO_2$ in the sample).

| Rock (sample) | TOC | S1 | S2 | S3 | $T_{max}$ | $R_o$ (calc) |
|---|---|---|---|---|---|---|
| Dunkirk (A) | 7.12 | 2.18 | 15.24 | 0.38 | 441 | 0.78 |
| Oatka Creek (B) | 6.53 | 5.61 | 17.83 | 0.64 | 430 | 0.58 |
| Oatka Creek (C) | 4.92 | 2.3 | 16.11 | 0.35 | 440 | 0.76 |
| Oatka Creek (D) | 10.58 | 3.80 | 40.67 | 0.46 | 440 | 0.76 |
| Oatka Creek (E) | 1.54 | 0.66 | 1.66 | 0.35 | 448 | 0.90 |
| Union Springs (F) | 6.61 | 1.87 | 2.21 | 0.49 | 459 | 1.10 |
| Union Springs (G) | 6.70 | 3.65 | 8.47 | 0.49 | 440 | 0.76 |
| Geneseo (H) | 1.57 | 0.24 | 0.35 | 0.09 | 475* | 1.39 |
| Union Springs (J) | 2.39 | 0.53 | 1.61 | 0.09 | 448* | 0.90 |
| Llewellyn (K) | 8.05 | 0.02 | 0.42 | 0.09 | * | ? |
| Marcellus (L)*** | 0.69 | 0.02 | 0.00 | 0.00 | * | ? |
| Marcellus (M)*** | 0.56 | 0.05 | 0.04 | 0.05 | * | ? |
| Fossil Plant (2) | 3.22 | 1.56 | 4.28 | 0.29 | 457* | 1.07 |
| Burket (2) | 0.90 | 0.37 | 0.62 | 0.06 | 453 | 0.99 |
| Concretion (3) | 0.45 | 0.05 | 0.11 | 0.09 | 416* | ? |
| Oatka Creek (3) | 0.74 | 0.08 | 0.2 | 0.05 | 469* | 1.28 |
| Union Springs (4) | 6.05 | 0.04 | 0.22 | 0.56 | 593* | 3.51 |
| Oatka Creek (5) | 0.78 | 0.07 | 0.04 | 0.02 | * | ? |
| Union Springs (6) | 3.19 | 0.03 | 0.03 | 0.45 | * | ? |
| Cleavage Dup. (6) | 1.59 | 0.01 | 0.02 | 1.42 | * | ? |
| Mahantango (7) | 0.29 | 0.00 | 0.02 | 0.02 | * | ? |
| Union Springs (8) | 6.99 | 0.02 | 0.07 | 0.20 | * | ? |
| Union Springs (9) | 8.63 | 0.05 | 0.79 | 1.04 | * | ? |
| Union Springs (15) | 4.12 | 0.40 | 1.01 | 0.17 | 557* | 2.87 |
| Onondaga (15) | 0.10 | 0.03 | 0.07 | 0.16 | * | ? |

* $T_{max}$ unreliable due to poor S2 peak.

** Rock-Eval data from samples taken at outcrops of this trip are given in tables under the discussion for each stop.

*** A other samples were taken with the same results.

Locations of the stops are for the trip are given in Figure 26.

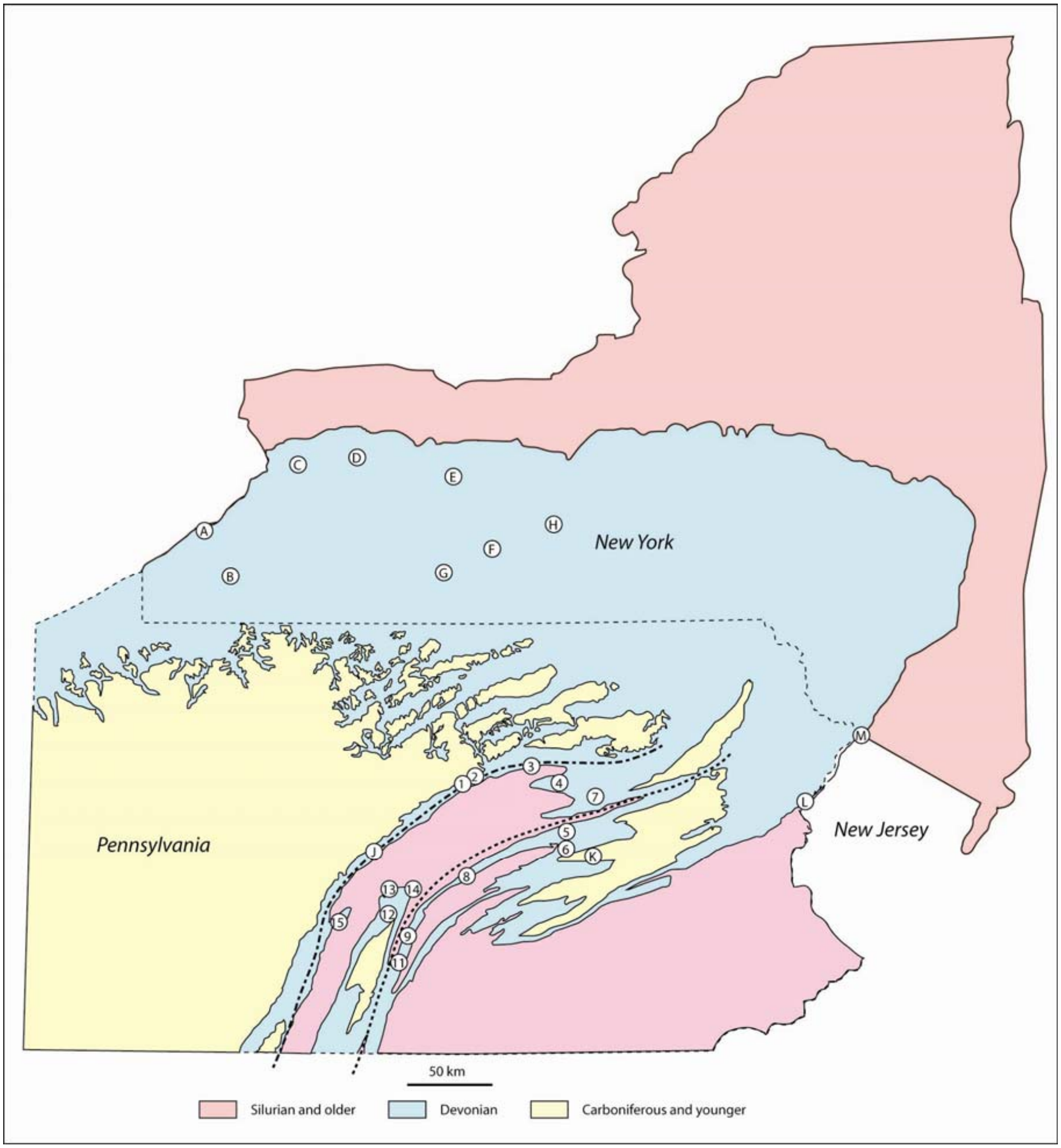

Figure 26. Field trip stop locations and geological base map. Locations are approximate. Triassic Basins of New Jersey and Pennsylvania not shown. Stops are: 1. Howard; 2. Howard; 3. Antis Fort; 4. Elimsport; 5. South Sunbury; 6. Selinsgrove Junction; 7. Washingtonville; 8. Lewistown; 9. Newton-Hamilton; 11. Orbisonia; 12. Huntingdon; 13. Hootenanny Quarry; 14. Jackson Corner; 15. Frankstown. Letters indicate the locations of extra samples for Rock Eval analyses.

## Day One: Transition between the Allegheny Front and the Anthracite District

Day One focuses on the Marcellus in the transition between the Allegheny Front and the Anthracite District of the Valley and Ridge. The initial two stops are along the Allegheny Front in the Brallier distal turbidites and Burket (Geneseo) black shale. The Marcellus is first encountered on the north side of Bald Eagle Ridge where rocks are vertical to overturned on the northern limb of the Nittany Anitclinorium (Stop 3). Next is a look at the Marcellus on the south limb of the Nittany Anticlinorium (Stop 4). The first four stops sit in a region where LPS measures little more than encountered within the Appalachian Plateau detachment sheet (i.e., < 20% ). Stops 5 and 6 are south of the Jacks Mountain structural front where LPS can approach 50%. They are also on strike with and about 15 km east of the famous Bear Valley Strip Mine (sample K; Nickelsen, 1979). In general, $J_2$ joints in the region strike between 340º and 350º (Figure 27).

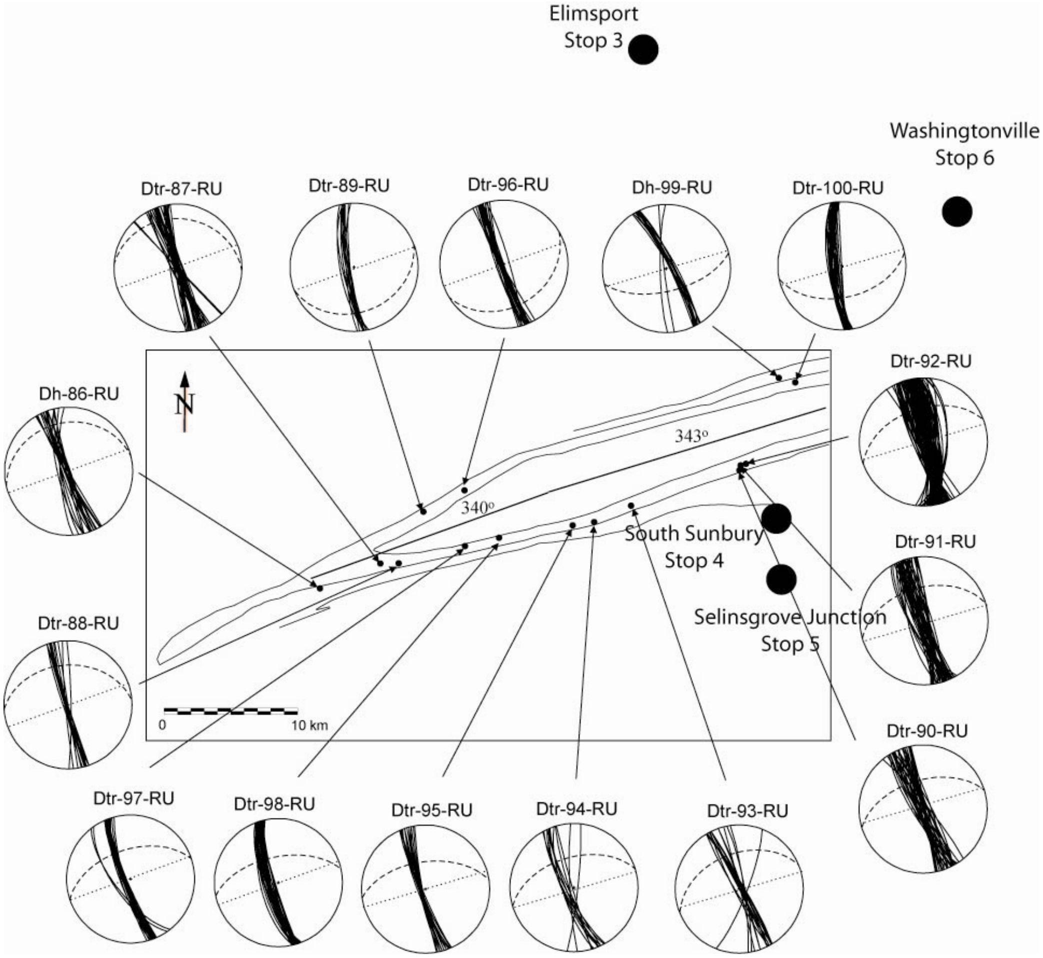

Figure 27. Present orientation of cross-fold joints in the vicinity of the Selinsgrove Syncline. Equal-area net projection. Dbh: Brallier and Harrel Fms. undivided, Dh: Hamilton Group, segmented line: local bedding trend. Adapted from Uzcatequi (2004).

## Stop 1: $J_2$ (cross-fold or dip) joints in the form of a gas chimney in the Brallier gray shale

West of Bald Eagle State Park (quarry along Route 150 between Milesburg and Howard)
[Google Earth UTM coordinates: 18 T 269969 m E - 4540077 m N]

Route 150 from Port Matilda to Bald Eagle State Park follows just south of a line of low ridges marking the position of the more resistive siltstones of the Brallier Formation. To the north of the road a well developed $J_2$ joint set is seen in a number of outcrops of the Brallier Formation. The Burket Formation, a black shale, is exposed just under the Brallier in a small quarry near Bald Eagle State Park (Stop 2). The trip will stop first at a Brallier outcrop Dbh-31-RU before stopping at Dbh-30-RU which is the small quarry (Figure 28).

The general rule of thumb for joint development in Devonian black shales of the Appalachian Basin is that $J_1$ is better developed in black shale and $J_2$ is better developed in gray shale. Our first stop is an outcrop of Brallier sitting just above the black shale of the Burket (Geneseo) black shale, the oldest Upper Devonian black shale above the Hamilton Group. The basal portion of the Brallier tends to be finer grained with coarser turbidites appearing further up section. We will visit the Brallier twice on the field trip with the second outcrop being higher in the section where turbidite siltstones are more common (Stop 12). The difference in joint development between stops 1 and 12 is the vertical height to spacing with joints at stop 1 having a height that far exceeds spacing. At stop 12, the height to spacing ratio is roughly 1:1, a characteristic of well-developed mechanical beds, usually either siltstone or carbonate beds interrupted by shale beds. At stop 1 the contrast in bedding is not sharp, giving the outcrop the property of a single mechanical unit.

When the spacing of joints is much closer than height, the standard explanation of jointing by bed-parallel extension (the stress-shadow theory; Gross et al., 1995) does not apply. Another idea for closely spaced joints is joint-parallel compression (a model that does not work for joint propogation at depth under the rules of linear elastic fracture mechanics; Lorenz et al., 1991). Rather, the preferred model for driving joints in the Brallier at Stop 1 is a natural hydraulic fracture (NHF) mechanism for which the stress-shadow theory does not apply (Fischer et al., 1995).

The NHF mechanism is appealing for joint development with a height to spacing ratio in excess of 10 because this situation occurs in the Devonian section of the Appalachian Basin only in gray shale just above black shale. The best examples of this behavior are found above the Geneseo black shale in Fillmore Glen and Taughannock Falls State Parks in New York State. At Stop 1 and in the state parks of New York, it is the J2 joint that displays a height to spacing ratio > 10. The idea is that thermal maturation of the black shale reaches a peak at maximum burial during the Alleghanian orogeny when the tectonic stress field is in the cross-fold (i.e., $J_2$) orientation (Engelder and Geiser, 1980). One characteristic of the entire Allegheny Front is that J2 is particularly well developed in the Brallier (Figure 28).

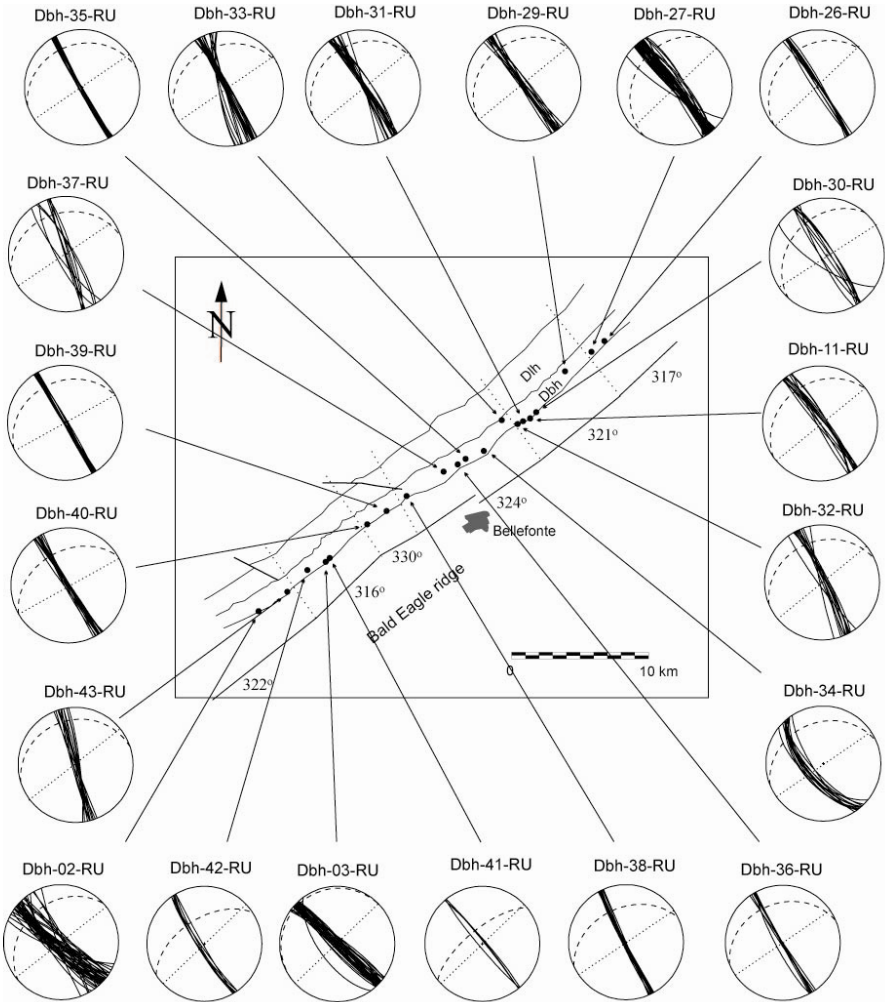

Figure 28. Present orientation of cross-fold joints in the vicinity of the Bellefonte. Equal-area net projection. Dbh: Brallier and Harrel Fms. undivided, Dh: Hamilton Group, segmented line: local bedding trend. Adapted from Uzcatequi (2004).

## Stop 2: $J_2$ (cross-fold or dip) joints in the Burket black shale

Bald Eagle State Park (quarry along Route 150 between Milesburg and Howard) [Google Earth UTM coordinates: 18 T 270465 m E - 4540329 m N]

The Burket Formation, a black shale, is exposed just under the Brallier in a small quarry near Bald Eagle State Park. The trip will halt at a Brallier outcrop Dbh-31-RU before stopping at Dbh-30-RU which is the small quarry (Figure 28).

Figure 29. $J_2$ joints in a quarry of Burket Black Shale at Stop 1 along Route 150 between Milesburg and Howard.

Samples taken from the Burket black shale for evaluation of organic chemistry suggest that the Marcellus and shallower gas shales are prospective right up to the Allegheny Front (Table 3).

Table 3. Samples were sent to Humble Labs for TOC and Rock-Eval measurements.

| | TOC | S1 | S2 | S3 | $T_{max}$ | $R_o$ (calc) |
|---|---|---|---|---|---|---|
| Fossil Plant | 3.22 | 1.56 | 4.28 | 0.29 | 457 | 1.07 |
| Matrix | 0.90 | 0.37 | 0.62 | 0.06 | 453 | 0.99 |

## Stop 3: Overturned Oatka Creek Member of the Marcellus with $J_1$ and $J_2$ joints propagating around concretions

Antis Fort (Snook quarry along Old Fort Road off Route 44 west of Antis Fort) [Google Earth UTM coordinates: 18 T 345024 m E - 4518489 m N]

One of the most compelling cases for the pre- to early Alleghanian propagation of $J_1$ joints is found at the Snook quarry in Antis Fort. Here, a relatively gray Oatka Creek member of the Marcellus is overturned to dip 72º to the south. The view looking north in the Snook Quarry is the underside of bedding with $J_2$ joints cutting vertically through the overturned bedding (Figure 30A). $J_1$ joints are seen cutting from upper left to lower right when northward toward the underside of bedding. In map view the acute angle between $J_2$ and $J_1$ is clockwise from $J_1$. Because the underside of bedding is exposed here, the acute angle between $J_2$ and $J_1$ is counter clockwise from $J_1$.

When observations were first made at Antis Fort in 2007, Concretions of all sized up to > 1m could be seen in bedding (Figure 30A). $J_2$ joints abut but don't cut the larger concretions as is expected for natural hydraulic fracturing. Some $J_2$ joints are mineralized as was the case for the EGSP core recovered from the deeper portion of the Marcellus over 200 km to the west of Antis Fort. At the time $J_1$ have a shallow dip to the east were better developed in the western portion of the quarry (Figure 30B). When bedding is rotated to horizontal, joints of the $J_1$ set are returned to a vertical position with a vector mean strike of 053º. Rotating joints in overturned beds to approximately the orientation of $J_1$ elsewhere in the Appalachian Basin supports the hypothesis that these are early and have survived 10% - 15% layer-parallel shortening as measured nearby (Faill, 1977). However, two observations that temper the $J_1$ hypothesis for joints in the Snook quarry are their weak cluster which looks like the clustering of ENE joints in the Hudson Valley fold-thrust belt (Figure 13) and the fact that their strike is as much as 20º counter clockwise from the best developed $J_1$ sets in black shale in the Finger Lakes District, NY (Figure 11).

Rotation of the $J_1$ joints to their position in horizontal bedding is accomplished about a rotation angle of 108º, assuming a plunge of 3º to the east for a fold axis at 074º. The rotation does not move the azimuthal mean to poles of joints to the horizontal (Figure 30B). Rather the rotation of bedding to horizontal leaves the joints dipping steeply to the south, on average. This phenomenon can be seen in Figure 30B where $J_1$ joints appear to make an angle with bedding of about 85º. One interpretation is that bedding was subject to a layer-parallel shear but this shear is inconsistent with flexural slip folding which should given the joints a steep dip to the north. At present the origin of this steep dip to the south is unknown.

Flexural slip did take place as the Marcellus was overturned. This is indicated by slip fibers not only on bedding planes but also in the surface of concretions (Figure 30C). Differential slip between bedding and concretions is common other parts of the Valley and Ridge (e.g., Nickelsen, 1979).

Figure 30A. Examples of joint development in the Oatka Creek Member of the Marcellus at the Ed Snook Quarry off along Old Fort Road off Route 44 west of Antis Fort. Bedding is overturned at 074º/72º. a. Top photo taken about March 2007. b. Bottom photo taken September 2008 after nearly meter of bedding including the layer of concretions have been ripped away.

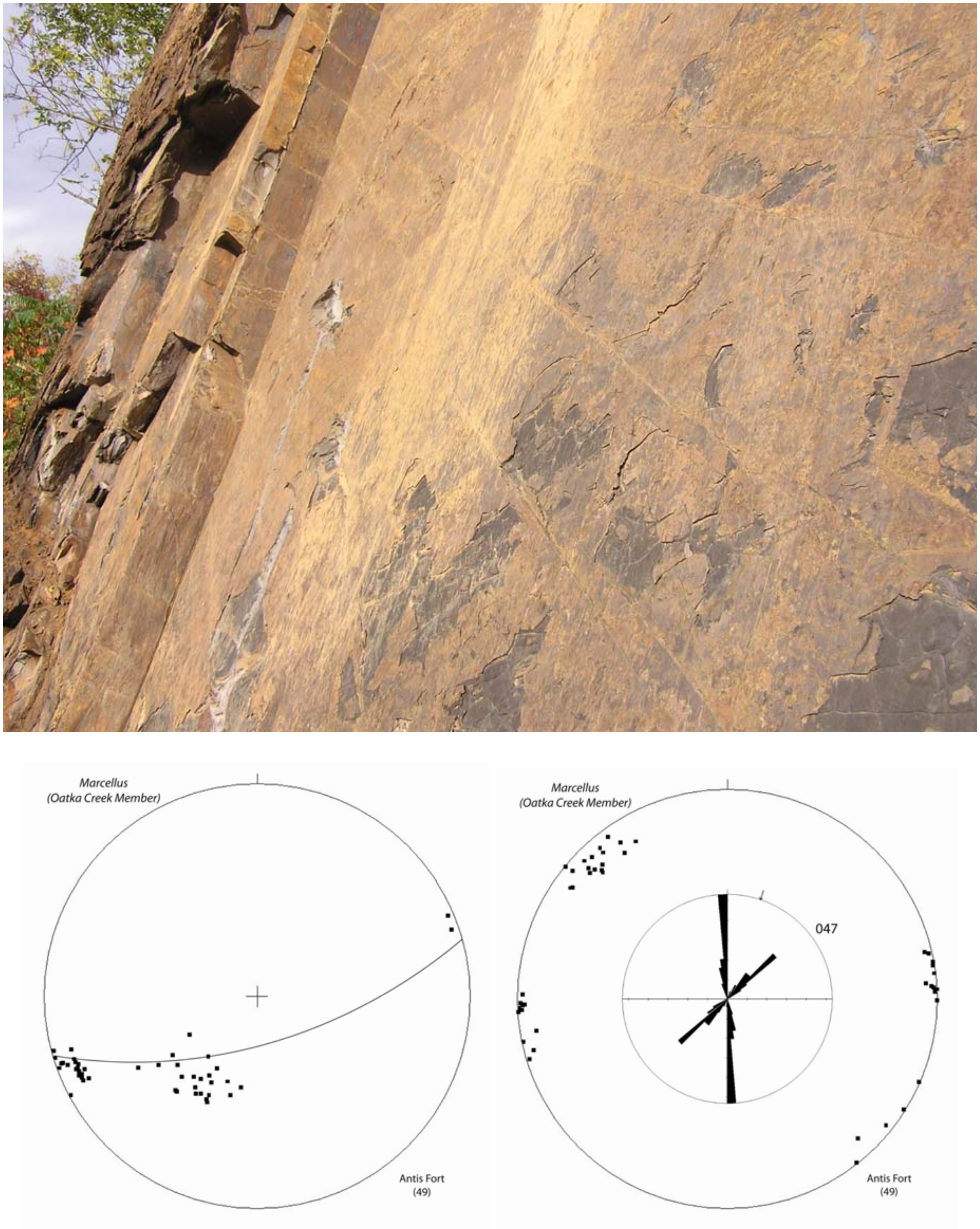

Figure 30B. Examples of joint development in the Oatka Creek Member of the Marcellus at the Ed Snook Quarry off along Old Fort Road off Route 44 west of Antis Fort. Bedding is overturned at 082º/65º. View looking west and parallel to $J_1$ joints. Joints plotted in present coordinates (left) and rotated to their position with horizontal bedding using a fold axis plunging 05º toward 082º with a rotation of 115º (right).

Figure 30C. (left) Concretion with fibers indicating differential slip between the concretion and bedding of Marcellus. (right) In places the Marcellus is fossil rich. Psilophytes are seen at the Ed Snock Quarry, for example. These are primitive vascular plants known as white ferns with both stems and branches looking like thick cylindrical pieces of grass. The picture above is the stem of a plant. Note the crinoids that have attached to othe stem. (Swiss Army knife shown for scale)

The most interesting aspect of the Rock-Eval work is that TOC in concretions relative to matrix (Table 4). During compaction TOC is preserved. Using a simple volumetric strain calculation, 39% of the volume of the initial rock (presumably sea floor mud) had to be removed to concentrate organic matter from 0.45% to 0.74%. This is consistent with compaction measurements made for concretions in Devonian shale elsewhere in the Appalachian Basin (Lash and Blood, 2004).

Table 4. Samples sent to Humble Labs for TOC and Rock-Eval measurements.

| | TOC | S1 | S2 | S3 | $T_{max}$ | $R_o$ (calc) |
|---|---|---|---|---|---|---|
| Concretion | 0.45 | 0.05 | 0.11 | 0.09 | 416 | ? |
| Matrix | 0.74 | 0.08 | 0.2 | 0.05 | 469 | 1.28 |

## Stop 4: Dipping Union Springs Member of the Marcellus with $J_2$ joints propagating around concretions

Elimsport (Finck quarry along Pikes Peak Road off of Route 44 east northeast of Elimsport) [Google Earth UTM coordinates: 18 T 332747 m E - 4556008 m N]

Jumping over to the south flank of the Nittany Anticlinorium moves us into the transition between the Allegheny Front where gas shale is prospective to a region of the Valley and Ridge is overmature (see Table 5 below). In fact, industry dogma at the time of preparation of this field guide is that vigorous leasing of the Marcellus should remain north of an E-W line marked by Rt 118 in Lucern, Columbia, and Lycoming Counties. Rt 118 is a virtual extension of the Allegheny Front east of the Susquehanna River.

The Finck quarry at Elimsport exposes the Union Springs Member of the Marcellus somewhere above the top bentonite in the Marcellus (Figure 31). The organic content of the shale (TOC > 6%) reveals that this portion of the Marcellus is in the hot bottom section as observed on gamma-ray logs.

$J_1$ is well developed in this portion of the Marcellus and exhibits the characteristics of natural hydraulic fracturing by passing around some large concretions within the Union Springs. In general, the surfaces are not as planar as see in outcrops of black shale in the Finger Lakes District, NY. Like the $J_1$ joints in the Snook quarry at Antis Fort, these joints form normal to bedding and when bedding is rotated to horizontal the $J_1$ joints return to vertical, again a sign of a prefolding origin. Also, like the Snook quarry, the $J_1$ joints have a relatively weak cluster. In the Finck quarry the vector mean strike for the $J_1$ set of 061°.

While clustering is weak at both Stops 2 and 3, it is significant to note that the orientation of $J_1$ on both sides of the Nittany Anticlinorium is counter clockwise from the strike of $J_1$ joints in the Finger Lakes District of NY.

Table 5. Samples sent to Humble Labs for TOC and Rock-Eval measurements.

| | TOC | S1 | S2 | S3 | $T_{max}$ | $R_o$ (calc) |
|---|---|---|---|---|---|---|
| Matrix | 6.05 | 0.04 | 0.22 | 0.56 | 593 | 3.51 |

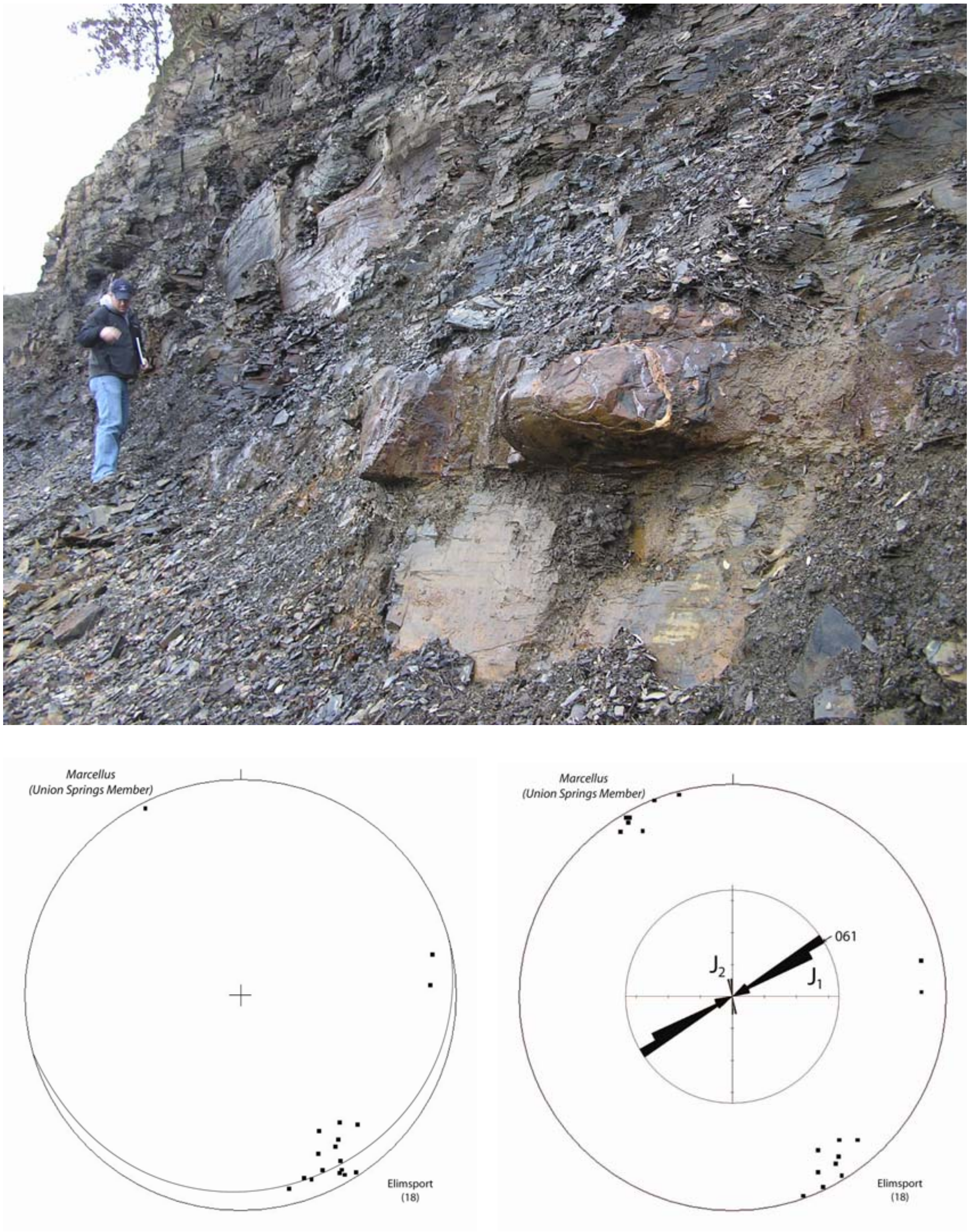

Figure 31. Examples of joint development in the Union Springs Member of the Marcellus at the Delmar Finck Quarry along Pikes Peak Road off of Route 44 east northeast of Elimsport. Bedding is 075/10. Joints plotted in present coordinates (right) and rotated to their postion with horizontal bedding using a fold axis plunging 05 toward 075 with a rotation of 10º (left).

Stop 5: Dipping Oatka Creek Member of the Marcellus under a cleaved limey shale at the base of the Mahantango
South Sunbury (road cut at the intersection of Route 147 and State Highway 4018 SH)
[Google Earth UTM coordinates: 18 T 347384 m E - 4521998 m N]

Stops 5 and 6 offer the opportunity to study exposures of both members of the Marcellus black shale. This section was made famous by Dick Nickelsen's 1986 cleavage duplex paper in which he argued that a detachment thrust tipped out in the Marcellus just to the south of Stop 5. Stop 4 is to the north of the Selinsgrove Junction second order anticline (Figure 32).

<u>Stop 5a</u> is located at the contact between the Marcellus and Mahantango with the bottom portion of the Mahantango consisting of a limy shale. Disjunctive cleavage in the limy shale is strong which means that LPS was > 24% according to the scale by Alvarez et al. (1978). Nickelsen (1983) estimates that LPS > 30% in the thick cleavage duplexes. Cleavage in the Mahantango is 260º/75º. Prominent cross fold joints have strike consistent with the regional pattern (Figure 33).

<u>Stop 5b</u> is thick section located in the Oatka Creek Member of the Maracellus black shale (Figure 33). Here, neither $J_1$ nor $J_2$ are particularly well developed. Some of the silty layers in the black shale have joints exhibiting a spacing equivalent to bed thickness. These are parallel to the local for axis and believed to have formed as a consequence of layer-parallel stretching as the local fold developed.

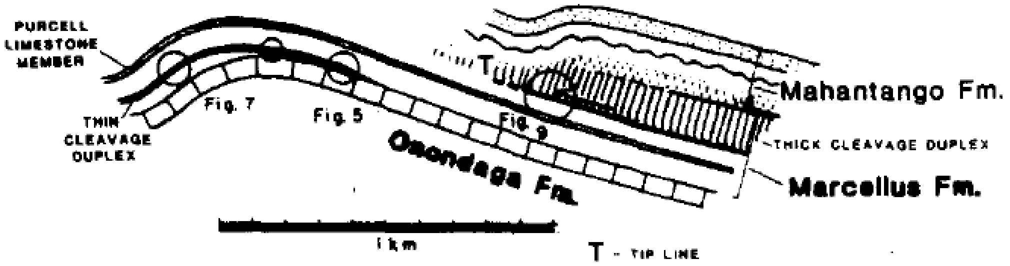

Figure 32. The Selinsgrove Junction second order anticline, showing the stratigraphic setting in the thin and thick cleavage duplexes. Stop 4 will be equivalent to the region marked Fig. 9. which is above the Purcell Limestone. Stop 5 is the area marked Fig. 7 with a north dipping thin cleavage duplex. Adapted from Nickelsen (1986).

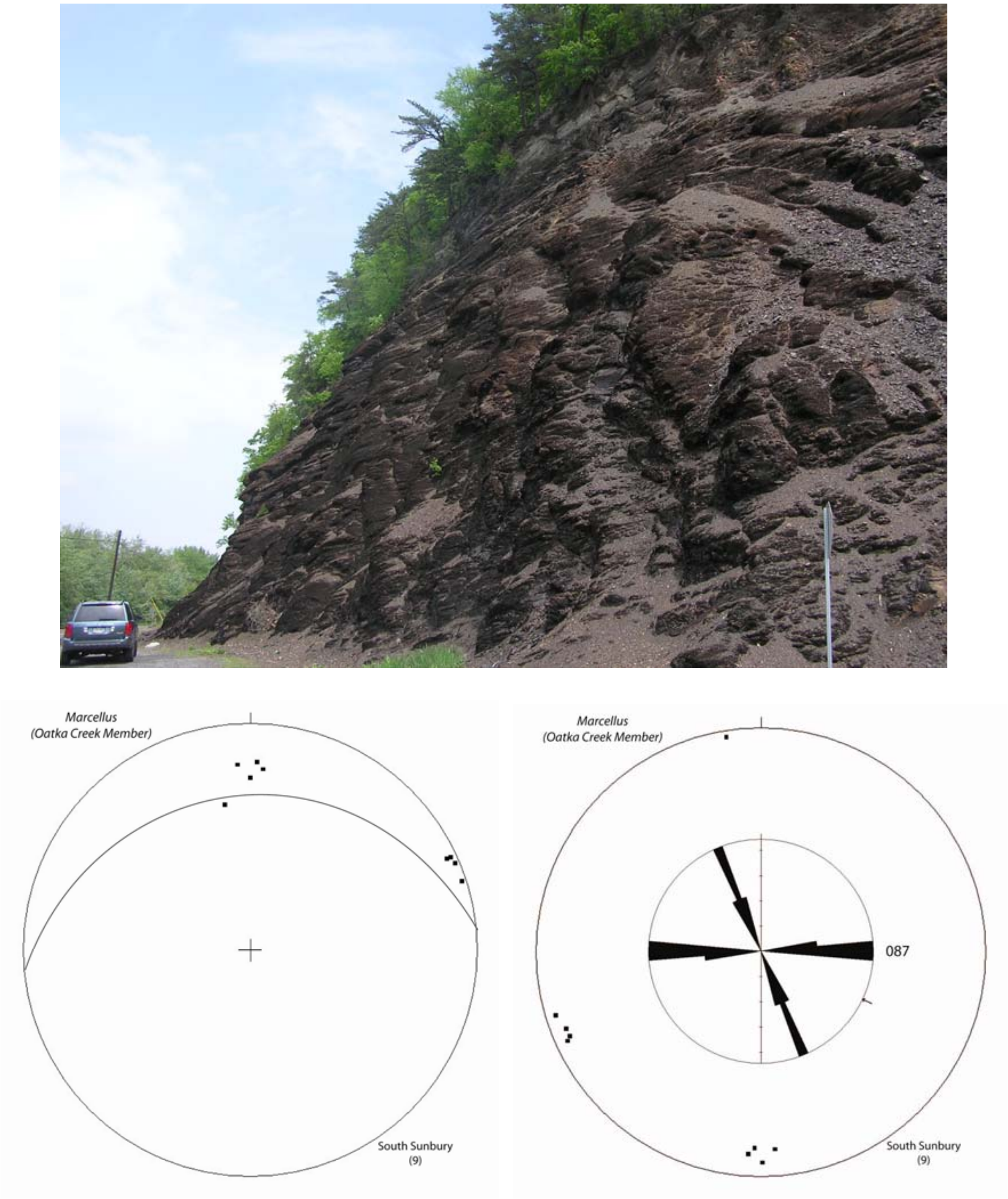

Figure 33. Oatka Creek Member of the Marcellus along Rt 147 south of Sunbury (Stop 5b). Joints plotted in present coordinates (left) and rotated to their position with horizontal bedding using a fold axis plunging 00º toward 265º with a rotation of 32º (right). E-W joints are interpreted as fold-related whereas $J_2$ joints are well developed near the top of the Oatka Creek and up into the cleaved limy beds of the Mahantango.

## Stop 6: Dipping Union Springs Member of the Marcellus with cleavage duplex

Selinsgrove Junction (quarry along Route 147 near the Selinsgrove Railroad Bridge over the Susquehanna River) [Google Earth UTM coordinates: 18 T 345024 m E - 4518489 m N]

The quarry exhibits a thin cleavage duplex dipping to the north. The duplex represents considerable shear strain in the form of a sigmodal cleavage with a sense of vergence (i.e., thrusting) toward the foreland (Figures 32 & 34). The sigmoidal cleavage terminates abruptly against the floor and roof thrusts at striking strain discontinuities (Figure 35). No cleavage or other evidence of LPS is evident in overlying or underlying shale.

Like the Marcellus at Stop 5, few joints have developed in this rock. With so little evidence for LPS here, it seems likely that this outcrop represents a place in the Appalachian Basin where $J_1$ joints did not propagate.

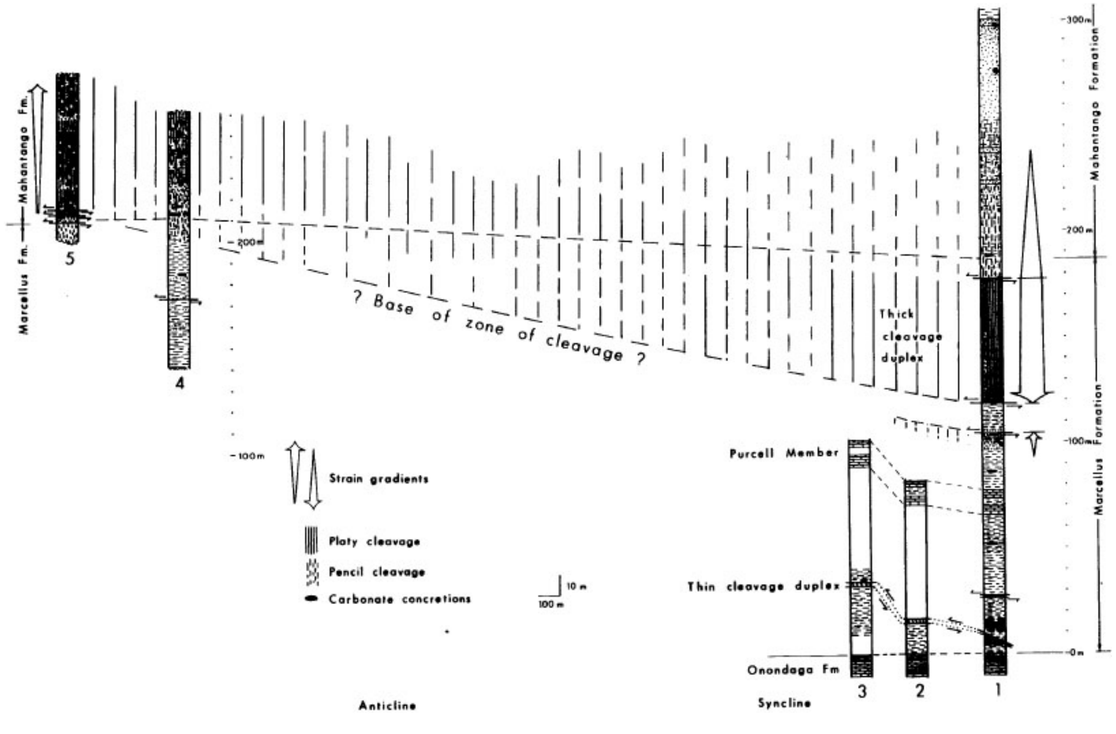

Figure 34. Correlated stratigraphic sections showing cleavage duplexes, thrust faults, and strain gradients. Section 3 is Stop 5, Section 4 is Stop 4b, and Section 5 is Stop 4a.

Figure 35. Cleavage duplex at Selinsgroove Junction. Looking to east with tectonic transport toward the foreland (left). See Nickelsen (1986).

Table 6. Samples sent to Humble Labs for TOC and Rock-Eval measurements.

| | TOC | S1 | S2 | S3 | $T_{max}$ | $R_o$ (calc) |
|---|---|---|---|---|---|---|
| Oatka Creek<br>Stop 5 | 0.78 | 0.07 | 0.04 | 0.02 | * | ? |
| Union Springs<br>Stop 6 | 3.19 | 0.03 | 0.03 | 0.45 | * | ? |
| Cleavage Dup.<br>Stop 6 | 1.59 | 0.01 | 0.02 | 1.42 | * | ? |

* $T_{max}$ unreliable due to poor S2 peak.

## Stop 7: Dipping Mahantango Shales with well-developed but widely spaced joints

Washingtonville (road cut along Route 54 south of Washingtonville) [Google Earth UTM coordinates: 18 T 358806 m E - 4543296 m N]

Figure 36. Widely spaced joints that have been rotated with bedding in the Mahantango Formation in a road cut along Route 54 south of Washingtonville, PA. Dick Nickelsen servers as the scale in this photo.

Table 7. Samples sent to Humble Labs for TOC and Rock-Eval measurements.

| | TOC | S1 | S2 | S3 | $T_{max}$ | $R_o$ (calc) |
|---|---|---|---|---|---|---|
| Mahantango | 0.29 | 0.00 | 0.02 | 0.02 | * | ? |

* $T_{max}$ unreliable due to poor S2 peak.

## Field Trip Stops: Day Two

### Stop 8: Tightly folded syncline in the Union Springs Member of the Marcellus

Lewistown (road cut along the 522 bypass west southwest of Lewistown) [Google Earth UTM coordinates: 18 T 277741 m E - 4495724 m N]

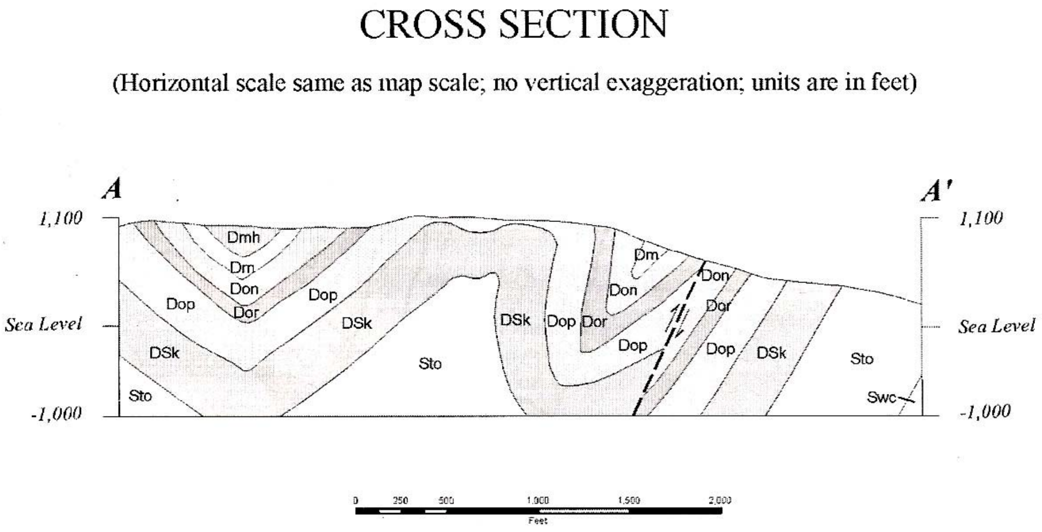

Figure 37. Structural cross section at Stop 7. View looking ENE. See Table 1 for a key to some formation names. $D_{op}$ – Old Port, $DS_{k}$ – Keyser, $S_{to}$ – Tonoloway. After McElroy, (2006).

This road-cut is of interest for the repetition of the lower Devonian strata exposed and repeated in an overturned syncline and fault, as well as the relics of early mining activity (see Figure ). Iron ore (secondary limonite and jarosite) was mined along the contact between the Selingsgrove Limestone and the Marcellus Shale. Sand has been extracted locally from the Ridgeley Member of the Old Port Formation. The construction of this interchange required engineering around existing underground mine workings, readjusting slope grade to stabilize the shaley rocks prone to slumping, and covering over the carbon-rich black shales that produce acid drainage. Not all of the re-vegetation has been successful, particularly over the Marcellus Shale slopes, where rill wash has exposed bedrock.

From the overpass bridge, anchored in limestones of the Keyser Formation , the following lithologies were encountered successively as one progresses northwestward by the Old Port Formation made up of the following members: Ceoymans (Limestone), New Scotland (Limestone), Mandata (Black pyritic Shale), Schriver (variegated light gray to white yellow chert with brown to purple interlayers and rusty hydration rinds) and Ridgley (Sandstone) and the Needmore Shale Member of the Onondago Formation. As

one progresses up hill to the west, fault juxtaposes the Ridgley Sandstone and Needmore Shale units as well as the upper Onandago strata of the Selinsgrove Limestone Member and the basal Black Shale beds of the Marcellus Formation. The latter two units were exposed in the steeper slope (2.25H:1V) above the road bed. Approximately 100 feet of the Marcellus Black Shales (Union Springs Member) is present in the road bank, bounded below (upright) and above (overturned) by the Selingrove Limestone in a tight overturned syncline (see Figure 37). The rest of the slope to the northwest is underlain by overturned Needmore Shale, Ridgley Sandstone and Schriver Chert.
Their distribution, of these units, photographed during the construction, is shown in Figure 38, with the axis of the overturned syncline in the center of the black band (Marcellus Shale).

The Union Springs Member of the Marcellus at Stop 8 is a highly fissile, dark gray to black shale with very fine grained framboidal pyrite generally disseminate throughout but more abundant near the base: tightly folded lenses, 5 to 10 cm thick, of fromboidal pyrite concentrations were observed near the center of the outcrop. Pyrite leaching is apparent in the orange stain (yellow boy) in the rip-rap at the bottom of the bank below the Marcellus Shale outcrop. The source in the blooms of efflorescent minerals (copiapite and melanterite) that may be present (depending on weather conditions) on the surface of the Mandata shale, and in the overhang areas on the Marcellus slopes (Gold *et al.*, 2006). In the latter, pyrite-rich zones occur a meter or two above the Tioga-A ash bed and pyrite nodules up to 5 cm long were found in the Tioga-B ash bed. Seven ash beds (meta-bentonites) were exposed in the road-cut (see Figure 39), consistent with those reported elsewhere by Way et al. (1986). The total carbon and organic hydrocarbon content of three samples of Marcellus Shales ranges from 6.78 to 11.5 % (Gold *et al.*, 2006). The elevated concentrations in trace elements (V, Ni, Cu, Cr, Mn, Ag, Au, etc.,) are consistent with those of Black Shale deposits.

The tight syncline is a third-order fold (Nickelsen's classification) with numerous faults and fourth-order folds within it. The syncline is overturned and faulted with beds dipping 60º-80º. The syncline plunges out about 1.5 km to the west of Stop 7. The fault is interpreted as a back thrust (south vergent). Along the west-bound exit ramp, complete section of the footwall may be sampled including the Needmore and Selinsgrove Members of the Onondaga Limestone, the Ridgley Sanstone, The Shriver chert, and the black shales of the Mandata Formation.

The organic content of this section is typical of the Union Springs and the thermal maturity is consistent with other samples taken on the south side of the Jacks Mountain structural front (Table 8).

Table 8. Samples sent to Humble Labs for TOC and Rock-Eval measurements.

| | TOC | S1 | S2 | S3 | $T_{max}$ | $R_o$ (calc) |
|---|---|---|---|---|---|---|
| Union Springs | 6.99 | 0.02 | 0.07 | 0.20 | * | ? |

* $T_{max}$ unreliable due to poor S2 peak.

Figure 38. Union Springs Member of the Marcellus Formation along the 522 bypass west southwest of Lewistown. A.) Marcellus in the core of an overturned syncline with axis plunging to the ENE and axial plane dipping NNW. Needmore and Selinsgrove Members of the Onondaga Limestone immediately above and below the Marcellus. B.) Upright kink fold near the axial plane of the overturned syncline with Marcellus in the core. C.) View of unchartered iron ore drift in Ridgley Sandstone on the southwest slope. These underground workings were discovered during construction. when a bulldozer was damaged by a cave-in (Photograph by Tom McElroy).

A.

B.

Figure. 39 A. View to northeast along the axis of the overturned syncline in center of black shale band. Beds of Selingrove limestone were exposed at the road bed level below (upright) and in the slope above (overturned) the black band. (Photograph by Tom McElroy).
B. View to northeast of three ash beds (meta-bentonites) in the Marcellus Shale at road-level during construction. ( Photograph by D.P. Gold: Hugh Barnes for scale).

## Stop 9: Folded Union Springs Member of the Marcellus with a Tioga ash bed, cleavage duplex, and small-scale buckle folds

Newton-Hamilton (Forgy quarry along Ferguson Valley Road east of Newton-Hamilton)
[Google Earth UTM coordinates: 18 T 260194 m E - 4475715 m N]

The Union Springs Member of the Marcellus black shale contains seven bentonites, some of which were seen at Stop 7. The Forgy Quarry carries one bentonite which is a 4 cm layer of crystalline tuff with biotite (Figure 40B). We believe this layer to be the seventh or top ash bed, the G-Layer of Way et al. (1986).

The G bentonite serves as a superb marker bed in a 4 meter section that Penn State graduate student, Reed Bracht, has mapped (Figures 24B & 40B). The notable layers in the Forgy quarry include a carbonate (unit 1) that we take to be the top of the transition zone from the Onondaga Limestone. At the Newton Hamilton railroad cut (Stop 9) the transition zone is several meters thick with shale layers thickening as the limestone layers thin (Figures 41, 42 & 43B). These layers are not scraggy carbonates like those at the top of the Union Springs (Figure 43A). The 4-cm crystalline tuff is a half meter above the top limestone. Unit 6 is a layer that remains relatively intact and can be traced throughout the quarry. Unit 8 is an unusually low density material that is not even lithified in spots where it is similar to the gumbo-clay recovered from depths over 10,000 ft in the Tertiary section of the Texas Gulf Coast. Unit 10 is a cleavage duplex with sense of vergence toward the Appalachian foreland to the WNW (Figure 30A). This is thickest of several cleavage duplexes in the Forgy quarry (Figure 23B).

The cleavage duplexes are a manifestation of a complexly faulted and folded Marcellus that is characteristic of its behavior to the SE of the Jacks Mountain structural front.

Table 9. Samples sent to Humble Labs for TOC and Rock-Eval measurements.

| | TOC | S1 | S2 | S3 | $T_{max}$ | $R_o$ (calc) |
|---|---|---|---|---|---|---|
| Union Springs | 8.63 | 0.05 | 0.79 | 1.04 | * | ? |

* $T_{max}$ unreliable due to poor S2 peak.

A.

B.

Figure 40. Lower Union Springs Member of Marcellus in the Forgy Quarry along Ferguson Valley road east of Newton-Hamilton. A. Cleavage duplex with vergence toward the foreland (top to the left). Michael Arthur for scale. B. Tioga ash bed.

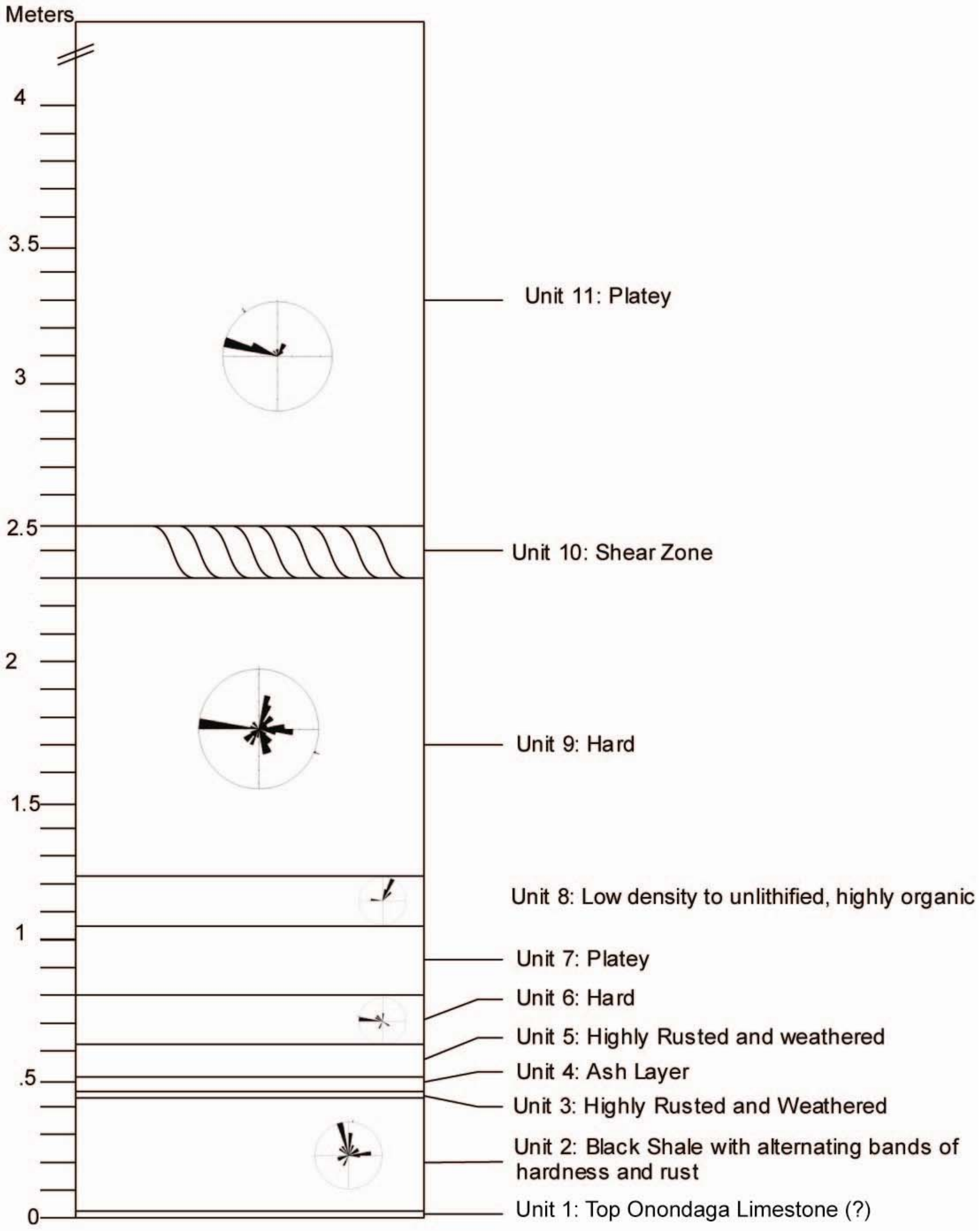

Figure 41. A 4-m stratigraphic column of the Union Springs Member of the Marcellus black shale at the Forgy Quarry, Newton-Hamilton, PA. Mapped by Penn State graduate student, Reed Bracht. The rose diagrams give here are in the form of half-strike plots.

### Stop 10: Entire secton of the Marcellus including the Purcell Limestone (not accessible for large groups)

Kistler (railroad cut along the Harrisburg to Altoona Conrail line at Newton-Hamilton)
[Google Earth UTM coordinates: 18 T 257646 m E - 4474003 m N]

The Kistler railroad cut is the finest exposure of the Marcellus in the state of Pennsylvania and the only complete section of which we are aware (Figure 42). The section is dipping gently to the WNW and just to the SE of the axis of a third order syncline that folds the Marcellus just to the SE of the Jacks Mountain structural front. The outcrop has a number of structural features including deformed strain markers, small-scale buckle folds, and pencil cleavage (Figures 21 & 22). The transition between the Onondaga Limestone and the Marcellus is particularly impressive (Figure 43B). Here, the Onondaga is an interlayered carbonate and shale, the reason why it has a gamma ray signature that fluctuates with an API reading well above that for a massive limestone like the Tully. Interbeds of scraggy limestone are seen at the top of the Union Springs Member (Figure 43A). The Purcell is intensely cleaved (Figure 23A). The Oatka Creek is a dark gray shale with local gray-black layers of higher organic content.

Figure 42. Google Earth image of the Kistler railroad cut. Penn State students are actively involved in a number of projects involving the Kistler section including the effect of weathering on the Marcellus.

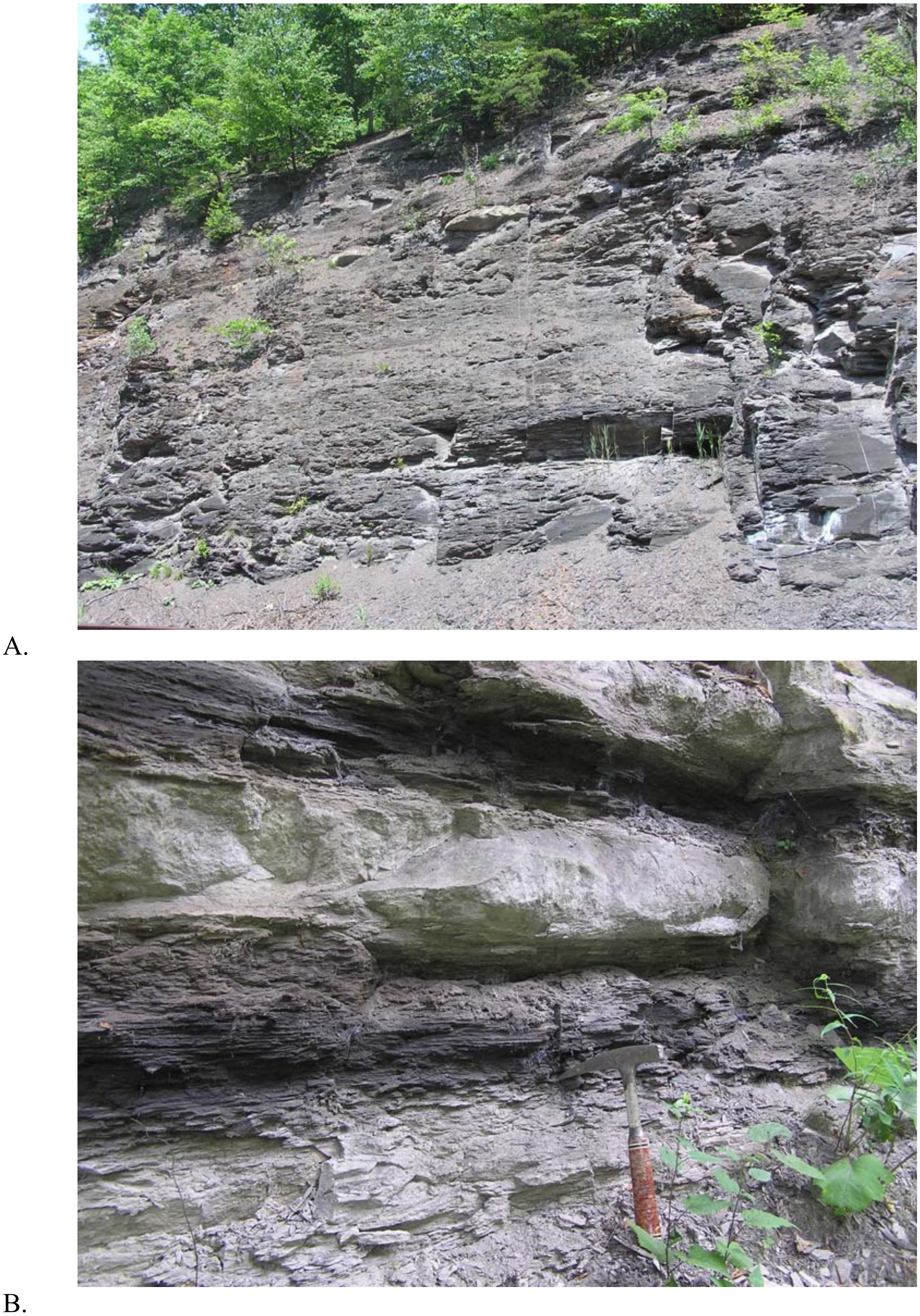

Figure 43. Top and bottom portions of the Union Springs Member of the Marcellus along the Conrail railroad cut at Kistler, PA. A. The top portion showing scraggy lime layers. B. The bottom transition to the Onondaga limestone.

## Stop 11: Well-developed pencil cleavage in the Marcellus

Orbisonia (road cut along Route 522 between Shirleysburg and Orbisonia) [Google Earth UTM coordinates: 18 T 254453 m E - 4461581 m N]

The Union Springs Member of the Marcellus exposed at Orbisonia presents a nice example of the importance of weathering in developing pencil cleavage. The fabric responsible for pencil cleavage is a consequence of pressure solution during layer-parallel shortening. The pencil structure usually appears during weathering (Figure 44).

A.

B.

Figure 44. Pencil cleavage in the Union Springs Member of the Marcellus. Bedding is dipping gently to the NNW. A.) a bedding surface pencil structures developing on the exposed portion of the bedding surface. B.) a $J_2$ joint cutting a bed of Marcellus.

## Stop 12: Well-developed $J_2$ joints in the Brallier siltstones

Huntingdon (road cut along Penn Street off Route 22 in Huntingdon) [Google Earth UTM coordinates: 18 T 245732 m E - 4485062 m N]

The Brallier Formation is a clastic unit with distal turbidites and shale interbedded immediately over the Burket black shale. Unlike the Mahantango above the Marcellus, this unit has a significant volume of sheet sands that act as distinct mechanical units. With such mechanical units, the pattern of fracturing in the Brallier is distinct from other units visited during this field trip. The Brallier, like its counterpart in New York (i.e., the Ithaca Formation), gradually becomes more coarse grained up section. At stop 1A where the lower portion of the Brallier was exposed near the Burket, the siltstone interlayers were thinner and finer grained. $J_2$ joints propagated through these thinner mechanical beds without stopping at bed boundaries. The same is true of Stop 12 where the earliest joints are mineralized $J_2$ joints. There is no evidence for $J_1$ joints which favor black shales of the Appalachian Basin. Presumably $J_1$ would have an affinity for black shale in proximal portions of the Basin as well (i.e., Stops 3 and 4).

At Stop 12, three episodes of joint propagation are evident starting with the mineralized $J_2$ set often covered with euhedral crystals of quartz (Ruf, et al., 1998). The second set is strike joint with either unmineralized surfaces or coated with a delicate pattern of microscopic crystals of unknown composition. The third episode of jointing is a late-stage $J_2$ joint set that by statistical analysis seem to behave like cross joints (Ruf et al., 1998). Certainly, these late joints abut strike joints more commonly than the other way around (Figure 45 B). It is, however, common to see these cross joints (late $J_2$ orientation) cross cut the strike joints in the Brallier (Figure 45B). The strike joints are tilted slightly relative to bedding, a sign of fold-related joint growth (Engelder and Peacock, 2001) (Figure 7A).

The development of surface morphology on the joints of the Brallier siltstones is magnificent (Figure 45). Two sets of systematic joints cutting the same bed may exhibit different rupture styles (Ruf et al., 1998). In the Stop 12 example, joints oriented parallel to the strike of bedding formed prior to dip-oriented joints, as inferred from cross-cutting relationships. The strike joints typically have a surface morphology consistent with that of a short blade crack (Figure 45B), whereas the dip joints exhibit a more complex morphology (Figure 45B). The earlier joints have surfaces with a typical plume-related topography (i.e., 1-3 mm within any $cm^2$) that greatly exceeds the grain size (< 0.125 mm) of the host bed whereas the later joints have surfaces that are smooth to the touch and a topography on the order of the grain size of the host.

The complex, irregular surface morphology on dip joints resembles a frosty window (Figure 45B). Joint surfaces often contain one or more irregular primary plume axes with several small secondary detachment ruptures (as indicated by secondary plume axes) branching off of them. The detached ruptures behave as individual crack tips each propagating independently and each having a unique propagation velocity, $v_{tl}$. One detached rupture may outrun an adjacent rupture. It is common for such detached ruptures to terminate against or cut off other ruptures. As a result, the bed-bounded joint

Figure 45. Joints in interbedded siltstone of the Brallier Formation in a road cut along Penn Street off Route 22 in Huntingdon, PA. A.) Multiple en-echelon cracks propagate upward into a siltstone layer from a shale-siltstone interface with a $J_2$ joint in shale acting as the parent. B.) Late-stage $J_2$ joint abutting a strike joint (joint propagating toward hammer).

Figure 46. $J_2$ joints in the Ithaca Formation at Taughannock Falls State Park where multiple en-echelon cracks propagate down into shale from a siltstone-shale interface.

surface is a composite of numerous secondary ruptures whose growth direction and $v_{tl}$ were impacted by nearby crack-tip stress concentrations. These are interpreted as subcritical joints with a much slower propagation velocity.

In Devonian clastic sections dominated by interlayered siltstones and shales, joint initiation usually starts in the siltstone layer (McConaughy and Engelder, 2001). During natural hydraulic fracturing least horizontal stress ($S_h$) is the governing parameter in dictating whether siltstones or shales should joint first and siltstones appear to carry the lower $S_h$ (Engelder and Lacazette, 1990). This is largely because during consolidation siltstones have a lower consolidation coefficient which leads to the lower least horizontal stress ($S_h$) during compaction (Karig and Hou, 1992). The difference in horizontal stress leads to later jointing in shales at a higher fluid pressure. If there is no rotation of the principal stresses, fluid-driven joints will propagate into the shale in plane with the earlier joints in siltstone. However, if the horizontal stress does rotate, then later, higher fluid pressures will drive en-echelon cracks (i.e., fringe cracks) into bounding shale beds (Pollard et al., 1982; Carter, et al., 2001).

Fluid driven jointing in the Brallier at Huntingdon is witnessed by the trapping pressures of fluid inclusions in euhedral quartz along early $J_2$ joints (Lacazette and Engelder, 1988; Srivastava and Engelder, 1991). The Braillier also the same natural hydraulic fracture pattern as found in the Ithaca Formation with fringe cracks being driven from the interface of a parent joint (compare Figures 44A & 45).

### Stop 13: Dipping Oatka Creek Member of the Marcellus with J1 and J2 mutually cross cutting

Huntingdon at the Hootenanny Quarry (Cold Springs Road about 1 miles off of Route 26 to State College) [Google Earth UTM coordinates: 18 T 249019m E - 4493501m N]

The Oatka Creek Member of the Marcellus at Hootenanny Quarry, on the north flank of the Broadtop Syncline, has one of the nicest examples of $J_1$-$J_2$ joint development found in the Valley and Ridge Marcellus (Figure 47 & 48). Both joint sets are normal to bedding and rotate to vertical when bedding is restored to horizontal. The sharp corners of blocks defined by the cross-cutting joints are well developed. The outcrop also contains neotectonic joints with irregular planes. Aside from their irregular or curving planes and their non-systemic nature, there is very little else to allow a distinction between the $J_1$-$J_2$ sets and the curving neotectonic joints. This is what the outcrop of Marcellus featured on the cover of the March 2008 AAPG Explorer might look like in cross section (see back cover).

Figure 47. The Marcellus at the Hootenanny Quarry. Photo looking to the WNW along $J_2$ joints. $J_1$ joints cut parallel to the road and define the faces of blocks in this view. Duff Gold for scale.

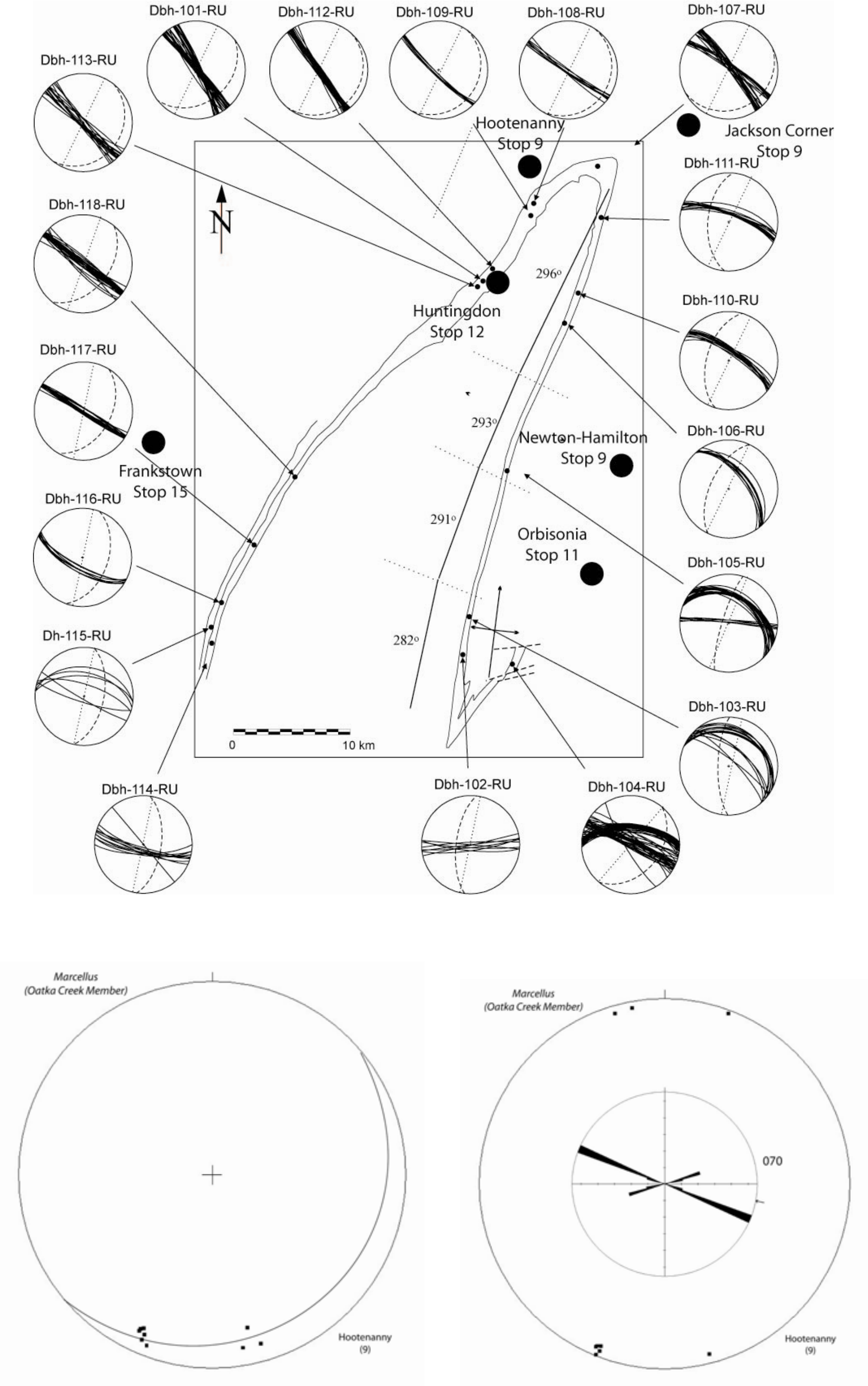

Figure. 48. Present orientation of cross-fold joints in the vicinity of the Broadtop Syncline. Equal-area net projection. Dbh: Brallier and Harrel Fms. undivided, Dh: Hamilton Group, segmented line: local bedding trend. Adapted from Uzcatequi (2004). Joints plotted in present coordinates (left) and rotated to their position with horizontal bedding using a fold axis plunging 00º toward 050º with a rotation of 16º (right).

## Stop 14: Dipping Oatka Creek Member of the Marcellus

Jackson Corner (quarry along East Branch Road off Route 26 near Jackson Corner)
[Google Earth UTM coordinates: 18 T 259403m E - 4497813m N]

The Oatka Creek near Jackson Corner is at the nose of the Broadtop-Lackawanna Syncline system, an intermediate position between the south flank of the Nittany Anitclinorium and the Jacks Mountain structural front. The Marcellus Shale becomes more heavily deformed to the southeast of the Allegheny Front into the interior of the Appalachian Valley and Ridge. Increased strain is manifested by development of a disjunctive cleavage that begins to overprint $J_1$, a confirmation of the early and deep propagation of these joints. The extent of strain is apparent when looking at fractures believed to be the $J_1$ joint set (Figures 48 & 49B). These joints are no longer planar, as if consumed by the process of generation of a penetrative fabric in the shale. Vertical ENE joints (i.e., $J_3$) that postdate folding are consistent in style and orientation with neotectonic joints in Ordovician carbonates elsewhere in the Central Appalachian Valley and Ridge (Hancock and Engelder, 1989).

Most joints labeled as $J_1$ are neither orthogonal to bedding nor are they symmetrically disposed about vertical and they do not cluster like the $J_1$ joints on the Appalachian Plateau. If the entire thickness of Marcellus shears toward the foreland in a manner like the cleavage duplexes but in a much milder tilt as is the mechanism for axial planar cleavage, these feature may be an example of a penetrative deformation mechanism overprinting the $J_1$ joints. In many ways these $J_1$ joints resemble those seen in the Marcellus at Kingston, NY (Figure 14).

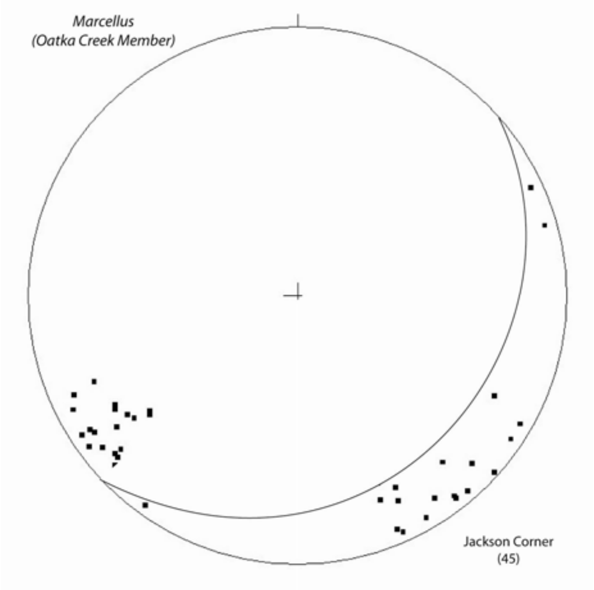

Figure 48. Joints in the Oatka Creek Member of the Marcellus near Jackson Corner.

Figure 49. Oatka Creek Member of the Marcellus dipping to the SSE at Jackson Corner. A.) View looking to the NNW and parallel to $J_2$. B.) View looking to the ENE and parallel to $J_1$ which is leaning over with bedding. A vertical $J_3$ may also be seen.

## Stop 15: Dipping Union Springs Member of the Marcellus with internal limestone beds

Frankstown (New Enterprise quarry off Locke Mountain Road in Frankstown) [Google Earth UTM coordinates: 17 T 725264m E - 4479249m N]

The Union Springs Member of the Marcellus at the New Enterprise quarry in Frankstown is in the same structural postion as the Finck quarry in Elimsport (Stop 3) which is to say that this location is on the hinterland side of the Nittany Anticlinorium but to the foreland of the Jacks Mountain structural front. The thermal maturation of the rock at stops 3 and 13 is also similar and in both cases maturation has crossed into the non-prospective realm (compare Tables 5 & 10).

Joints in this section of Union Springs is less-well clustered than its counterpart at Stop 3. The strong NS joint trend resembles that seen at Newton-Hamilton (Stop 8) but its significance is unknown (Figure 50).

Marcellus of the New Enterprise quarry carries three ash beds which are interpreted to be the E-, F- and G-ash beds of Way et al. (1986).

Table 10. Samples sent to Humble Labs for TOC and Rock-Eval measurements.

| | TOC | S1 | S2 | S3 | $T_{max}$ | $R_o$ (calc) |
|---|---|---|---|---|---|---|
| Union Springs Matrix | 4.12 | 0.40 | 1.01 | 0.17 | 557* | 2.87 |
| Onondaga Transition zone | 0.10 | 0.03 | 0.07 | 0.16 | * | ? |

* $T_{max}$ unreliable due to poor S2 peak.

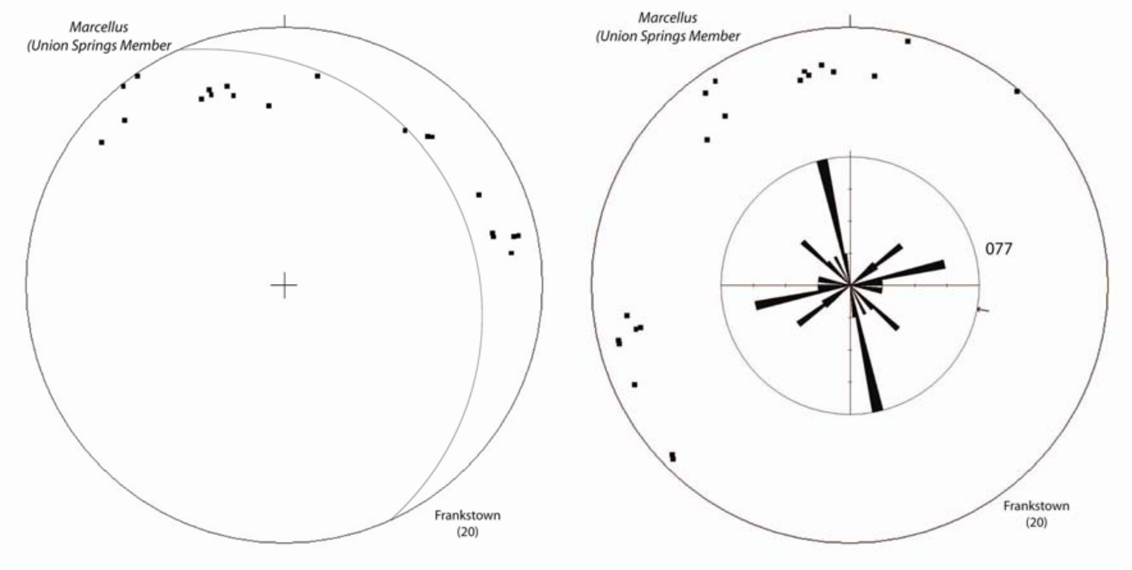

Figure 49. Examples of joint development in the Union Springs Member of the Marcellus at the New Enterprise Quarry off Locke Mountain Road in Frankstown, PA. Bedding is 336/27. Joints plotted in present coordinates (right) and rotated to their postion with horizontal bedding.

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## Field Trip Road Log

### Day 1

**Itinerary:** Leave from Ramada Inn State College

| Interval | Cumulative | |
|---|---|---|
| 0.0 | 0.0 | Turn right from parking lot on North Atherton Street |
| 0.1 | 0.1 | Turn left at traffic light, onto University Drive |
| 1.5 | 1.6 | Cross bridge over E. College Ave |
| | 2.44 | Bryce Jordon Center on right |
| 0.55 | 2.5 | Turn right onto Curtin Road |
| 0.2 | 2.7 | Turn right in Park Avenue |
| 0.6 | 3.3 | Traffic light: hospital to right. Continue on Park Avenue and follow road signs to Bellefonte on Rte 220 N |
| 0.8 | 4.1 | Innovation Park exit |
| 11.5 | 15.6 | Take I-80 West exit |
| 0.7 | 16.3 | Follow I-80 West |
| 2.9 | 19.2 | Follow Exit #158 to Milesburg |
| 0.4 | 19.6 | Turn left onto Rte 150 N |
| 0.1 | 19.7 | Meet bus from Pittsburgh at TA Travel Court: assemble in Restaurant |
| 2.3 | 22.0 | **Stop 1:** on Rte 150, 50 feet west of guard rail. Disembark and walk behind guard rail to road cut bank. Examine fracture sets in Brallier Shale (NAD27-CONUS: UTM Co-ords; 18T0269865 /4539849) |
| 0.7 | 22.7 | **Stop 2:** Park at Puff Discount Store and walk left across Rte 150 and enter borrow pit quarry (approximately 300 feet) to examine joint set in Burket Black Shale. (NAD27-CONUS: UTM Co-ords; 18T0270453 /4540180) |
| 0.7 | 23.4 | Nursery cross roads |
| 3.3 | 26.7 | Intersection with Rte 26 |
| 4.0 | 30.7 | Intersection with Marsh Creek Road |
| 1.4 | 32.1 | Blanchard exit |
| 0.3 | 32.4 | Beech Creek Bridge |
| 4.7 | 37.1 | Intersection with Lusk Run Road |
| 1.1 | 38.2 | Bridge |
| 0.8 | 39.0 | Junction with Rte 64 |
| 0.5 | 39.5 | Exit right onto Rte 220 N |
| 15.2 | 54.7 | Take Rte 44S on Main Street through Jersey Shore |
| 0.9 | 55.6 | Turn left and cross bridge over West Branch of Susquehanna |
| 0.7 | 57.3 | Turn right onto Old Fort Rd |

| | | |
|---|---|---|
| 0.45 | 57.75 | **Stop 3:** Snook Quarry. Park in farm yard on right side of road, and walk into borrow pit quarry 200 feet ahead. Examine the joints in Oatka Creek Member of the Marcellus Formation, and note the concretions as well as the unconformity with colluvium and varved lake sediments. (NAD27-CONUS: UTM Co-ords; 18T0312121 /4562167) |
| 0.5 | 58.3 | Return to Rte 44. Turn right (east) |
| 2.55 | 60.35 | Junction with Rte 880 |
| 4.05 | 64.4 | Junction with Rte 654 in Collomsville |
| 7.85 | 72.25 | Turn right onto Elimsport Road |
| 0.55 | 72.8 | Elimsport |
| 0.2 | 72.0 | T junction: left on Gap Road (Rte 44S) |
| 0.45 | 72.45 | Left on Pikes Peak Road |
| 2.35 | 74.8 | **Stop 4:** Finck Quarry (borrow pit) on right. Union Springs Member of Marcellus with $J_2$ joints around concretions. (NAD27-CONUS: UTM Co-ords; 18T0332722 /4555797) |
| 2.35 | 76.15 | Return (south) to junction with Rte 44 and turn left on Rte 44 |
| 6.5 | 82.65 | Junction with Rte 15. Turn right on Rte 15S |
| 10.65 | 93.3 | Junction with Rte 192 |
| 9.95 | 103.25 | Exit to Rte 61 to Sunbury |
| 1.2 | 104.45 | Exit to Rte 147S, after crossing bridge at Dam |
| 0.9 | 105.35 | **Stop 5a:** Spaced cleavage and fold in basal Mahantango beds. (NAD27-CONUS: UTM Co-ords; 18T0341598 /4539262) |
| 0.35 | 105.7<br>of | **Stop 5b:** Junction with Brush Valley Road. Examine large exposure<br>Oatka Creek Member of Marcellus in road cuts. (NAD83: UTM Co-ords; 18T0347398 /4521981) |
| 3.5 | 109.2 | **Stop 6a:** Borrow pit quarry on left (east) side of road. Union Springs Member of Marcellus Formation. (NAD83: UTM Co-ords; 18T0344915 /4518310) |
| | | **Stop 6b:** Similar "borrow-pit" quarry 300 feet to north of Stop 5a. Union Springs Member of Marcellus Formation. Note cleavage duplex and beds of soft, black mudstone. (NAD83: UTM Co-ords; 18T0344936 /4518377) |
| 5.9 | 115.1 | Return (north) on Rte 147 to junction with Rte 11N in Northumberland |
| 2.1 | 117.2 | Cross river on bridge |
| 11.9 | 129.1 | Left on Rte 54 in Danville |

| | | |
|---|---|---|
| 2.85 | 131.95 | Pass under I-80 |
| 3.45 | 135.4 | **Stop 7.** Borrow pit on left (west) side of Rte 54, south of Washingtonville.<br>Widely spaced joints rotated with bedding in Mahantango Shales.<br>(NAD27-CONUS: UTM Co-ords; 18T0358767/4543173) |
| 3.45 | 138.85 | Return south along Rte 45. Underpass beneath I.80 |
| 1.05 | 139.9 | Turn right on Rte 422W towards Milton |
| 5.0 | 144.9 | Left at junction onto Rte 45 |
| 6.85 | 151.75 | Junction with Rte 147S |
| 1.85 | 153.6 | Junction with Rte 405 |
| 0.1 | 153.7 | Middle of bridge |
| 0.9 | 154.6 | Junction with Rte 15 |
| 9.05 | 163.65 | Mifflinburg |
| 22.2 | 185.85 | Aaronsburg |
| 1.8 | 187.65 | Millhein |
| 11.4 | 199.05 | Old Fort |
| 7.55 | 206.6 | Right at Junction with Rte 322 and follow Rte 322 into State College |
| 2.85 | 209.45 | Ramada Inn, State College. |

## Day 2

**Itinerary:** Leave from Ramada Inn State College

| Interval | Cumulative | |
|---|---|---|
| 0.0 | 0.0 | Turn right from parking lot on South Atherton Street |
| 2.5 | 2.5 | Town of Boalsburg |
| 0.3 | 2.8 | Junction with Rte 45 |
| 0.8 | 3.6 | Merge onto Rte 322 E |
| 8.2 | 11.8 | Potters Mills Village |
| 3.4 | 15.2 | Ridge crest of Seven Mountains, a synclinorium “highlands” between two breached anticlinoria |
| 2.1 | 17.3 | 3rd to 4th order chevron folds in Tuscarora strata exposed in road-cut to right (south), and in the high-wall cut beyond the dam wall to the left (north) |
| 1.3 | 18.6 | 1100 feet of Reedsville Formation exposed in road-cut on the left (north) side of the road |
| 2.2 | 20.8 | Milroy exit |
| 2.6 | 23.4 | Reedsville exit |
| 0.3 | 23.7 | Black Shale (Antes Member of Reedsville Fm) exposed in road-cut on left (north side) |
| 2.9 | 26.6 | Burnham exit |
| 1.05 | 27.65 | Take exit to Rte 522 S |
| 1.95 | 29.6 | Note pinnacles of Ridgley Sandstone on right |

| | | |
|---|---|---|
| 1.8 | 31.4 | **Stop 8.** Park on road side near entrance to exit ramp to examine exposures of ash fall in black shales (basal Marcellus Formation) in the trough of an overturned syncline. The traces of the underlying Selingsrove Limestone, Needmore Shale, Ridgley Sandstone, Shriver Chert and Mandata Black Shale, some repeated by a fault and folds, are apparent in the dressed slopes. (NAD27-CONUS: UTM Co-ords; 18T0277619 /4495271) |
| 0.4 | 31.8 | Continue south on Rte 522. Overpass bridge |
| 2.7 | 34.5 | Merge with old Rte 522 |
| 0.6 | 35.1 | Strodes Mills |
| 5.1 | 40.2 | McVeytown |
| 9.95 | 50.15 | Turn left on SR 3019 to Newton Hamilton. |
| | | **CAUTION:** The railroad underpass near Newton Hamilton has height restriction of 9.5 feet. Higher vehicles should access Newton Hamilton from the south via Rte 522 S and Country Club Rd through Kistler. |
| 1.85 | 52.0 | Rail Road Bridge |
| 0.15 | 52.15 | Left at T intersection on Atkinson to Norton Road |
| 0.9 | 53.05 | **Stop 9.** Park in driveway to Chicken Farm. Walk 100 feet across road to west into a small quarry in Union Springs Member shales containing two ash beds. (NAD27-CONUS: UTM Co-ords; 18T0260176 /447511) |
| 0.9 | 53.95 | Retrace route through Newton Hamilton: junction with SR 3019 |
| 0.95 | 54.9 | Walnut Ave: access to trail-road cut |
| 0.8 | 55.7 | Turn right at T intersection onto Country Club Rd |
| 0.8 | 56.5 | School |
| 0.5 | 57.0 | Bridge |
| 0.4 | 57.4 | Turn left onto Franklin Street – cross railroad lines |
| 0.1 | 57.5 | Turn left on East Shirley Street |
| 0.65 | 58.15 | Turn right at traffic light ont Rte 522S |
| 1.45 | 59.6 | Note the well developed cross-strike joints in Mahantango Shale road bank on right, at Bigler & Boozel ConstructionYard |
| 4.3 | 63.9 | Shirleysburg |
| 2.0 | 65.9 | Borrow pit near hill top on left in Marcellus Shale |
| 0.6 | 66.5 | **Stop 11.** Disembark to examine pencil cleavage in Black shales of |
| | the | |
| | | Union Springs Member of the Marcellus Formation in the road cut (NAD27-CONUS: UTM Co-ords; 18T0254105 /4460782).<br>Bus turn around |
| 9.7 | 76.2 | Return on Rte 522N through Shirleysburg to T intersection and |

| | | |
|---|---|---|
| | | turn left (west) on Rte 22 |
| 0.4 | 76.6 | Turn off to Mount Union |
| 2.1 | 78.7 | Approximate location of Jacks Mountain Structural Front |
| 0.5 | 79.2 | Turn off to Rte 655 |
| 0.4 | 79.4 | Sulfide veins (sphalerite, galena and pyrite) exposed in Tuscarora Quartzite in road cut |
| 3.0 | 82.6 | Traffic light; Rte 655 intersection |
| 4.65 | 87.25 | **Stop 12.** Long road cut in Brallier Formation. Park at Self Storage facility (Ansley RV sign) on Rte 22 and walk west along nearby exit ramp to Rte 26 for 400 feet. (NAD27-CONUS: UTM Co-ords; 18T025673 /4484787). |
| 0.05 | 87.3 | Continue west on Rte 22 and exit onto Rte 26 |
| 0.7 | 88.0 | Turn right on Second Street and follow Rte 26N |
| 6.35 | 94.35 | Cold Springs Road (Road-side quarry in Marcellus Shale, 0.5 miles along Cold Springs Road) |
| 0.45 | 94.8 | Hootenanny Lions Club facility on left. |
| 0.05 | 94.85 | Park approximately 100 yards ahead for access to shale “borrow” pit. On left (west) side of road. |
| | | **Stop 13.** Hootenanny Quarry: note the well developed $J_1$ and $J_2$ Joints exposed in the Marcellus Shale in the “borrow” pit wall. (NAD27-CONUS: UTM Co-ords; 18T0249014 /4493308). |
| 0.5 | 95.35 | Return to T – junction with Rte 26 and turn left (north) on Standing Stone Road |
| 5.85 | 101.2 | Drive on Rte 26N to Jacksons Corner. Turn right on East Branch Road. (NAD27-CONUS: UTM Co-ords; 18T0257788 /447664). |
| 1.1 | 102.3 | **Stop 14.** Three sets of joints exposed in the shale quarry **(**borrow pit**)** on left (west) side of road, in Oatka Creek Member of Marcellus Formation. (NAD27-CONUS: UTM Co-ords; 18T0259369 /4497573). |
| 1.1 | 103.4 | Return on East Branch Rd to Jackson Corner and turn right onto Rte 26 |
| 2.1 | 105.5 | Road cuts in Shale (Mahantango Fm) |
| 1.35 | 106.85 | Turn left at T intersection on to Rte 305 to Mooresville |
| 3.15 | 110.0 | Saulsburg |
| 4.3 | 114.3 | Mooresville/Neffs Corner |
| 6.6 | 120.9 | Petersburg |
| 1.3 | 122.2 | Left on Rte 305 S at intersection |
| 1.9 | 124.1 | Jog through town of Alexandria |
| 0.7 | 124.8 | Turn right on to Rte 22 |

| | | |
|---|---|---|
| 2.6 | 127.4 | Intersection with Rte 453 in Water Street |
| 15.5 | 142.9 | Turn left off Rte 22 onto Reservoir Road (SR 27) at Frankstown |
| 0.05 | 142.95 | Turn left onto Locke Mountain Road |
| 1.0 | 143.95 | **Stop 15.** Stop in parking area opposite gate to NESL Quarry. Follow trail beyond gate marked with pink flagging for approximately 300 yards. Outcrop 13a (NAD27-CONUS: UTM Co-ords; 17T0725274 /4479062). Outcrop 13b (NAD27-CONUS: UTM Co-ords; 17T0725199 /4479068). |
| 1.05 | 145.0 | Return to Rte 22. Turn left and follow Rte 22 to Pittsburgh |
| 94.2 | 239.2 | Pittsburgh |

AAPG
EXPLORER
March 2008

# Appalachian Spring

## A new shale play emerges in the East