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An introduction to structures and stratigraphy in the proximal portion of the Middle Devonian Marcellus and Burket/Geneseo black shales in the Central Appalachian Valley and Ridge

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ABSTRACT

A Marcellus-Burket/Geneseo field trip in the Appalachian Valley and Ridge features both brittle and ductile structures. The degree to which these structures have developed depends on both lithology, which is a function of the stratigraphic architecture of the Devonian Appalachian Basin and position relative to the foreland during the Alleghanian Orogeny. Joints are best developed in the black shales and the units immediately above with the J_2 joint set most prominent in the Brallier Formation just above the Burket/Geneseo Formation. Faults are seen in the form of cleavage duplexes and bedding-parallel slip accompanying flexural-slip folding. Cleavage duplexes are found in the Marcellus whereas bedding-parallel slip is more common in the overlying Mahantango Formation and further up the section in the Brallier Formation. Layer-parallel shortening decreases from greater than 50% to approximately 10% when crossing the Jacks Mountain–Berwick Anticline structural front from the hinterland portion to the foreland portion of the Valley and Ridge. Disjunctive cleavage, the primary mechanism for layer-parallel shortening, is best developed in carbonates whereas pencil cleavage is best developed in shales.

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OVERVIEW

During the first decade of the twenty-first century, the American energy portfolio was dramatically realigned after operators in Texas learned to use horizontal drilling and massive hydraulic (slickwater) fracture stimulations to recover natural gas from the Mississippian Barnett black shale, a source rock once considered of little economic value. In 2004, the Middle Devonian Marcellus black shale of the Appalachian Basin was first tested in a vertical well using slickwater fracturing. Late in 2007, Range Resources announced that their horizontal wells in the Marcellus were producing natural gas and associated liquids at economic rates. A Penn State press release on 17 January 2008 introduced the vast economic potential of natural gas production from the Marcellus to the public (Engelder and Lash, 2008). Production from the Marcellus through 30 June 2010 validated the earlier volumetric calculations verifying that the Marcellus of the Appalachian Basin was a super giant gas field and one of the largest in the world (Engelder, 2009). Because of the economic value of natural gas in the Marcellus, this formation has become a central focus for geological research in Appalachia.

This field trip visits some of the key outcrops straddling a minimum of 1420 m of the Lower to Upper Devonian section in the Appalachian Valley and Ridge with a focus on the Marcellus black shale (Fig. 1). Of particular interest is the extent to which the structural fabric in the Middle Devonian section is dependent on the sedimentary geometry of the Appalachian Basin (Lash and Engelder, 2011). Sedimentary geometry is in turn controlled by a combination of global eustasy and a more local tectonically driven sea level change (Ettensohn, 1985). The fundamental observations for this trip were laid through a century of field work and herein we weave the threads of this work together in a context of a modern understanding of plate tectonics, sequence stratigraphy, and fracture mechanics. For example, the Marcellus Formation and associated strata, consist of at least four third-order depositional sequences, dividing the strata into lowstand (LST), transgressive (TST), and highstand systems tracts (HST) (Fig. 2). These sequences are defined by sequence boundaries associated with the Oriskany Sandstone (The Wallbridge Unconformity; Swezey, 2002), within the Selinsgrove (Senaca) Member of the Onondaga Limestone, the base of the Purcell/Cherry Valley Limestone, and the base of the Stafford Limestone (Lash and Engelder, 2011) (Fig. 2).

The outcrops of the Middle Devonian section in the Appalachian Valley and Ridge reflect Laurentian plate tectonics from deposition during the early Acadian Orogeny (ca. 389 Ma) through the Alleghanian Orogeny (ca. 265 Ma). Before 390 Ma, the southeastern margin of Laurentia was loaded by the convergence of a microcontinent, Avalonia, which had an active volcanic arc (Ettensohn, 1987). This load created the accommodation space for the Marcellus transgressions (Ettensohn, 1994). At this time, Gondwana and Laurentia were separated by an ocean basin that was closing rapidly. The Middle Devonian Eifelian and Givetian Stages are characterized by two black shale sequences (i.e., Marcellus Formation and the Geneseo/Burket Formation) both of which will be visited during this field trip (Fig. 1).

Convergence culminated at approximately 315 Ma when Gondwana and Laurentia collided obliquely and slid past each other for at least 15 m.y. (Ferrill and Thomas, 1988). The oblique slip between Gondwana and Laurentia was dextral with Gondwana slipping west relative to Laurentia. This phase of the Alleghanian orogeny is characterized by major strike-slip faults

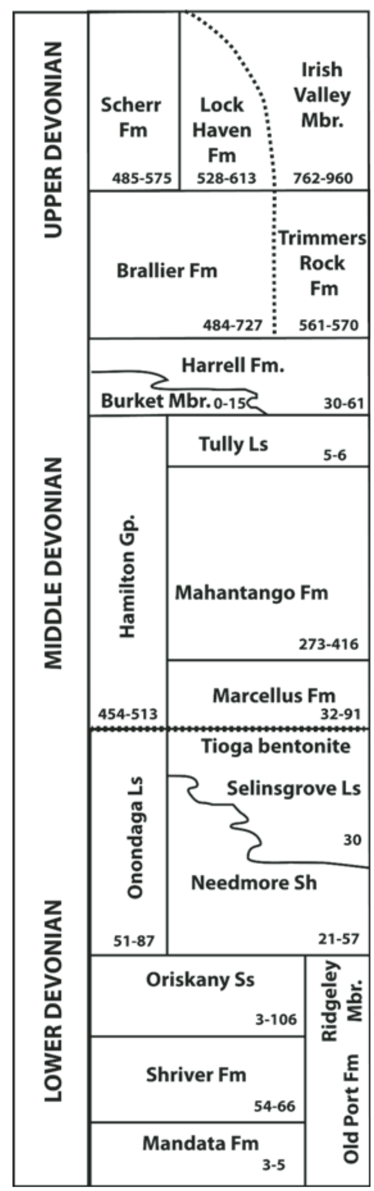

Figure 1. Stratigraphic column of the Devonian section in the vicinity of the Juniata Culmination of the Appalachian Valley and Ridge (adapted from the AAPG CSUNA Northern Appalachian Sheet). All thicknesses given in meters (Lindberg, 1985).

including the Brevard fault zone and other faults in the Appalachian Piedmont (Gates et al., 1988) and a joint set that is found along the length of the Central and Southern Appalachians (the J_1 set; Engelder and Whitaker, 2006). By 290 Ma, Laurentia and Gondwana ceased to slip in a dextral fashion and locked at the New York Promontory. The New York Promontory served as a fulcrum for a clockwise pivot of Gondwana relative to Laurentia (Hatcher, 2002). This clockwise pivot drove Gondwana directly into Laurentia, causing the fold-thrust belt of the Central and Southern Appalachians (Hatcher et al., 1989). The Northern and Maritime Appalachians were characterized by transform tectonics with no sign of a foreland arising from a direct continent-continent collision. The timing of the head-on collision between Africa (Gondwana) and North America (Laurentia) during the Alleghanian Orogeny of the Central and Southern Appalachians is poorly constrained but may have lasted as much as 35 m.y. (300 Ma to 265 Ma), depending on what geological indicator is used as a measure of this orogeny.

Our field trip will cross the Appalachian Valley and Ridge by traveling from the Appalachian Plateau side of the Allegheny Front (Stops 1–2) to the middle coal fields of the Anthracite District (Stops 5–7) (Fig. 3). The trip starts along the Allegheny Front where beds are overturned, passes through the Nittany Anticlinorium where layer-parallel shortening strain is 15%, and then crosses the Jacks Mountain–Berwick Anticline structural front where layer-parallel shortening strain is greater than 50% on the hinterland side (Nickelsen, 1983). A layer-parallel shortening strain of 50% in the Marcellus is indicated by a strong

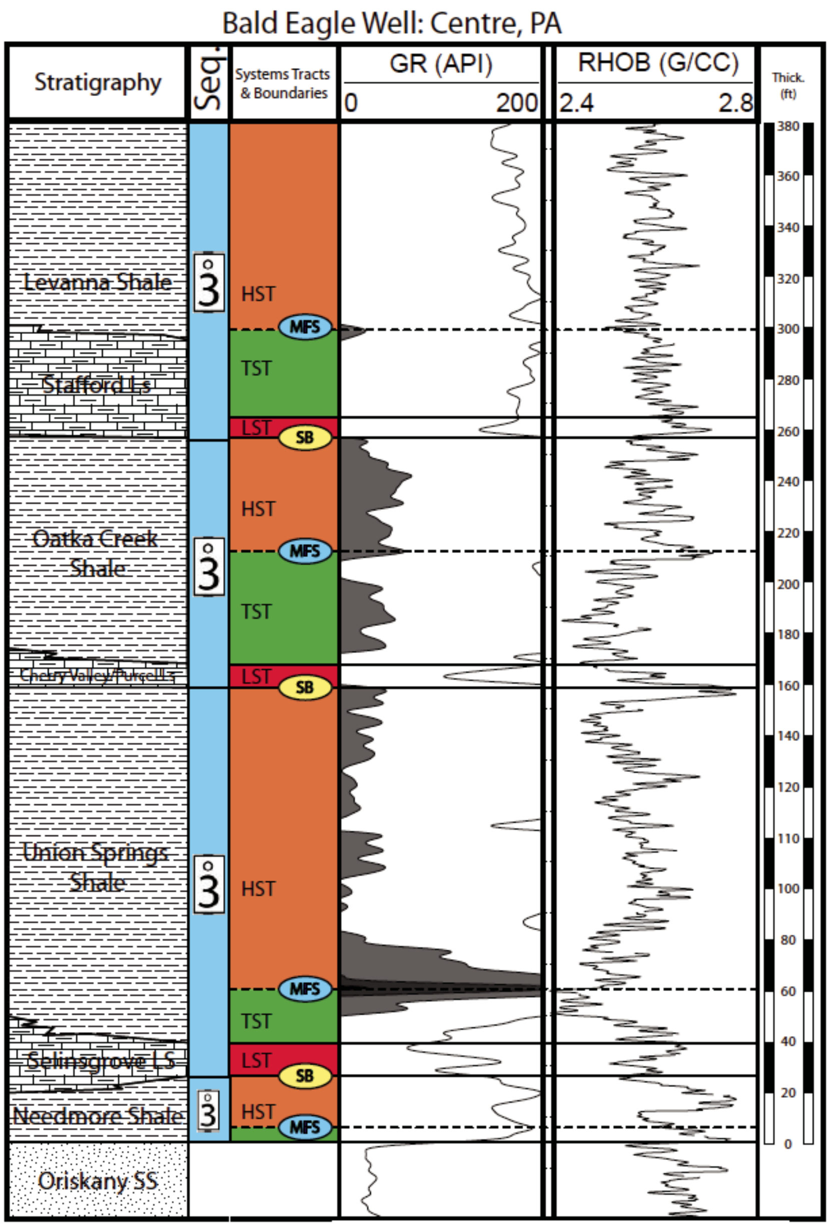

Figure 2. Gamma ray (GR; in American Petroleum Institute units) and bulk density (RHOB; in g/cm^3) log typical of the Marcellus Shale and associated strata. This log is part of the suite of logs from the Appalachian Valley and Ridge that Penn State's Appalachian Basin Black Shale Group has acquired with industrial support. LST—lowstand systems tract; TST—transgressive systems tract; HST—highstand systems tract; SB—sequence boundary; MFS—maximum flooding surface.

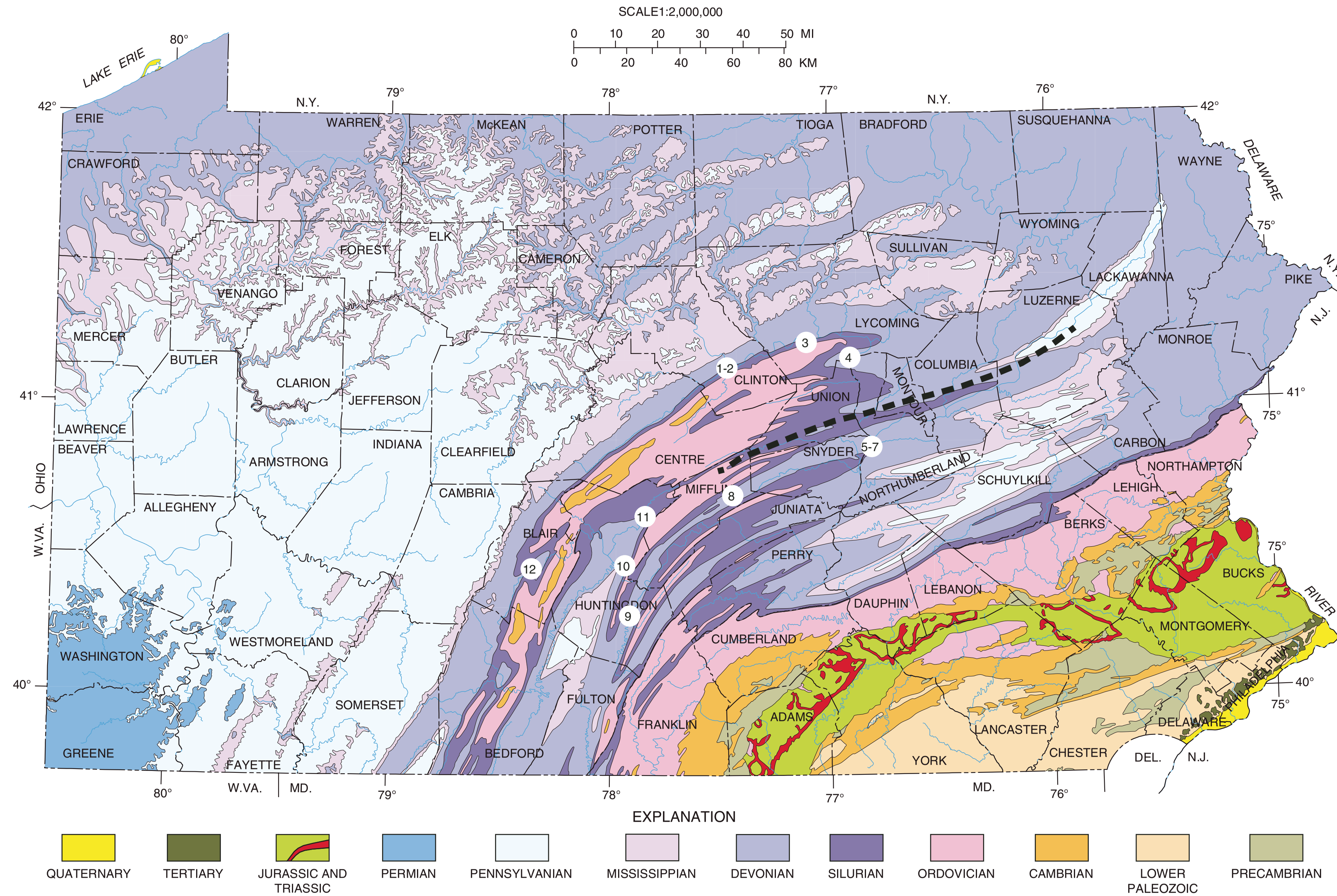

Figure 3. The geology of Pennsylvania showing the location of field stops along the Allegheny Front (Stops 1 and 2) and into the Valley and Ridge. Dashed line indicates the approximate location of the Jacks Mountain–Berwick Anticline structural front. (Adapted from PA-DCNR Map 7; www.dcnr.state.pa/us/topogeo.)

disjunctive cleavage, strain fibers about pyrite nodules, and cleavage duplexes. The second day of this trip (Stops 8–12) runs in the opposite direction across the Jacks Mountain–Berwick Anticline structural front.

STOP 1. J_2 (CROSS-FOLD OR DIP) JOINTS IN THE FORM OF NATURAL HYDRAULIC FRACTURES IN THE BRALLIER GRAY SHALE

Brallier Formation: Chronostratigraphic Equivalent to the Genesee Group of New York
Series (Eur. Stage): Middle Devonian (Givetian)
Location: Howard, Pennsylvania (outcrop on north side of road along Route 150 between Milesburg and Howard)
Coordinates: 40.992980° by –77.709799° (datum WGS84 spheroid)

Background: Joint growth in the Middle and Upper Devonian section of the Appalachian Basin correlates with the presence of black shale (Lash et al., 2004; Lash and Engelder, 2005; Engelder, et al., 2009). Two major joint sets are found with the earlier set, J_1, better developed within black shale and the later set, J_2, better developed within the gray shale immediately above. In western areas of the basin where black shales are stacked, joints populate each black shale. In eastern portions of the basin where the Marcellus is the sole black shale, joint development decreases with distance above the black shale until the Carboniferous section is reached where jointing is very sparse. The correlation between jointing and black shale is largely a function of the driving mechanism for joint propagation which comes from internal pressure during maturation of kerogen to produce hydrocarbons, mainly natural gas (Lacazette and Engelder, 1992). These are natural hydraulic fractures (NHF) where tectonic stress controls the orientation of the joint set but tectonic stress is not the cause of joint propagation. Some of the best examples of black-shale–related NHF are found above the Geneseo/Burket black shale in the Finger Lakes District, New York (Fig. 4).

Observations: 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 in several outcrops a well developed J_2 joint set is seen in numerous of outcrops of the Brallier Formation (Fig. 5). The Burket Member, a black shale, is exposed just under the Brallier Formation in a small quarry near Bald Eagle State Park (Stop 2). The trip will stop at a Brallier outcrop Dbh-31-RU before stopping at Dbh-30-RU which is the small quarry of Burket black shale (Fig. 5).

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 farther up section (Fig. 6). We will visit the Brallier twice on the field trip with the second outcrop being higher in the section where turbidites vary in thickness up to nearly a meter (Stop 12).

The difference in joint development between Stop 1 and Stop 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 and a characteristic of turbidite or carbonate beds interrupting shale beds. At Stop 1, the silt beds are thin (<5 cm), and the shale is laminated on such a fine scale that it acts as a single mechanical unit relative to joint growth (Fig. 6).

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 mechanism 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 NHF mechanism for which the standard 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, a situation found only in the Devonian section of the Appalachian Basin when gray shale occurs just above black shale. The best examples of this behavior are found above the Geneseo (Burket) black shale in

Figure 4. J_2 joints propagating as natural hydraulic fractures into the Penn Yan gray shale just above the Geneseo/Burket black shale at Taughannock Falls State Park, New York. Both units are members of the Genesee Group of western New York. The Penn Yan is chronologically equivalent to the Brallier Formation in Pennsylvania.

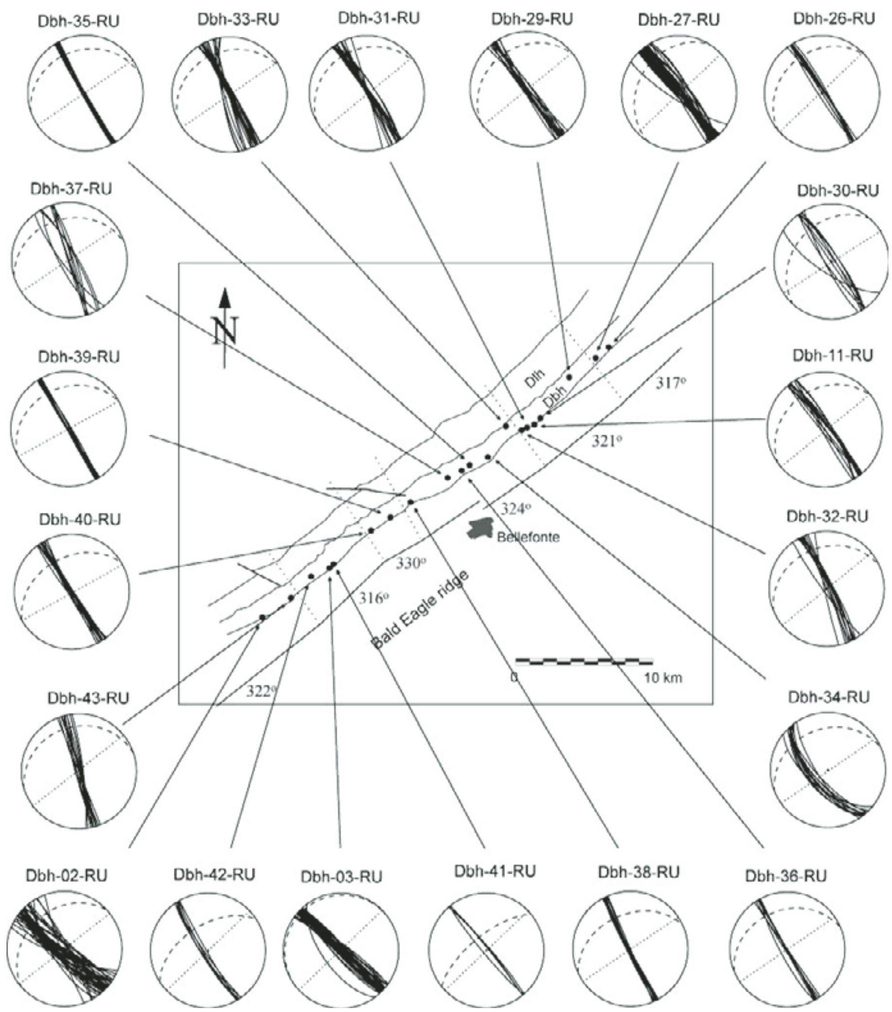

Figure 5. Present orientation of J_2 joints in the vicinity of Bellefonte, Pennsylvania. Equal-area net projection. Dbh—Brallier and Harrel Formations undivided; Dh—Hamilton Group; dashed line—outcrop bedding; dotted line—local fold axis trend. Adapted from Engelder et al. (2009).

Fillmore Glen and Taughannock Falls State Parks in New York State (Fig. 6). At Stop 1 and in the previously stated locations in New York, it is the J_2 joint that displays a height to spacing ratio greater than 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 J_2 is particularly well developed in the Brallier (Fig. 5).

STOP 2. J_2 (CROSS-FOLD OR DIP) JOINTS IN THE BURKET BLACK SHALE

Burket Formation (sometimes called the Burket Member of the Harrell Formation): Chronostratigraphic equivalent to Geneseo black shale of the Genesee Group in New York
Series (Eur. Stage): Middle Devonian (Givetian)
Location: Howard, Pennsylvania (quarry along Route 150 between Milesburg and Howard)
Coordinates: 40.998761° by –77.699038°

Observations: The Burket Formation, a black shale, is exposed just under the Brallier in a small quarry near Bald Eagle State Park. This black shale correlates with the Geneseo black shale of the Genesee Group, New York. Of note here is the absence of the J_1 joint set which is present in many exposures of the Geneseo black shale in central New York. J_2 joints are moderately developed, perhaps because of the low total organic carbon (TOC) in the parent rock. The thermal maturation of samples taken from the Burket black suggest that the Marcellus and shallower gas shales are prospective right up to the Allegheny Front (Table 1).

TABLE 1. SAMPLES SENT TO HUMBLE LABS FOR TOTAL ORGANIC CARBON 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

Figure 6. An example of a J_2 joint cutting through laminated bedding in the Harrell Formation at Stop 1.

STOP 3. OVERTURNED OATKA CREEK FORMATION WITH J_1 AND J_2 JOINTS PROPAGATING AROUND CONCRETIONS

Oatka Creek Member of the Marcellus Formation of the Hamilton Group
Series (Eur. Stage): Middle Devonian (Eifelian)
Location: Antis Fort, Pennsylvania (Snook quarry along Old Fort Road off Route 44 west of Antis Fort)
Coordinates: 41.191066° by –77.239754°

Background: An ENE joint set was the first to propagate in many outcrops of Devonian, Mississippian, and Pennsylvanian rocks of the Central and Southern Appalachian Mountains (Kulander and Dean, 1993; Nickelsen, 1979; Nickelsen and Hough, 1967; 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 when Gondwana was sliding with dextral sense of slip relative to Laurentia between 315 Ma and 300 Ma. In total, these joint sets appear as one mega-set recording a rectilinear stress field extending for greater than 1500 km across three promontories separated by oroclinal embayments of the Central and Southern Appalachians (Fig. 7). Given the arrangement of continental plates at the time of joint propagation, the plates were in the southern hemisphere and the maximum horizontal stress, S_H, controlling the direction of propagation was oriented south of east relative to the earth's axis between 315 Ma and 300 Ma.

Observations: 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 72° 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 (Fig. 8). J_1 joints are seen cutting from upper left to lower right when looking northward toward the underside of bedding. In map view, the acute angle between J_2 and J_1 appears clockwise from J_1. Because this is the underside of bedding, the acute angle between J_2 and J_1 in map view is counterclockwise from J_1.

When observations were first made at Antis Fort in 2006, concretions of all sizes up to greater than 1 m could be seen in bedding (Fig. 8). 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 Eastern Gas Shales Project core recovered from the deeper portion of the Marcellus over 200 km to the west of Antis Fort (Evans, 1995). J_1 joints have a shallow dip to the east (Fig. 9). When bedding is rotated to horizontal, joints of the J_1 set are returned to a vertical position with a vector mean strike of 053°. J_1 joints in overturned beds have approximately the orientation of J_1 joints elsewhere in the Appalachian Basin, which 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 and the fact that their strike is as much as 20° counterclockwise from the best developed J_1 sets in black shale in the Finger Lakes District, New York.

Rotation of the J_1 joints to their position in horizontal bedding is accomplished about a rotation angle of 108°, assuming a plunge of 3° to the east for a fold axis at 074°. The rotation does not move the azimuthal mean to poles of joints to the horizontal (Fig. 9). Rather the rotation of bedding to horizontal leaves the joints dipping steeply to the south, on average. This phenomenon can be seen in Figure 9 where J_1 joints appear to make an angle with bedding of ~85°. One interpretation is that bedding was subject to a layer-parallel shear but this shear is inconsistent with flexural slip folding which should be 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 (Fig. 10). Differential slip between bedding and concretions is common other parts of the Valley and Ridge (Nickelsen, 1979).

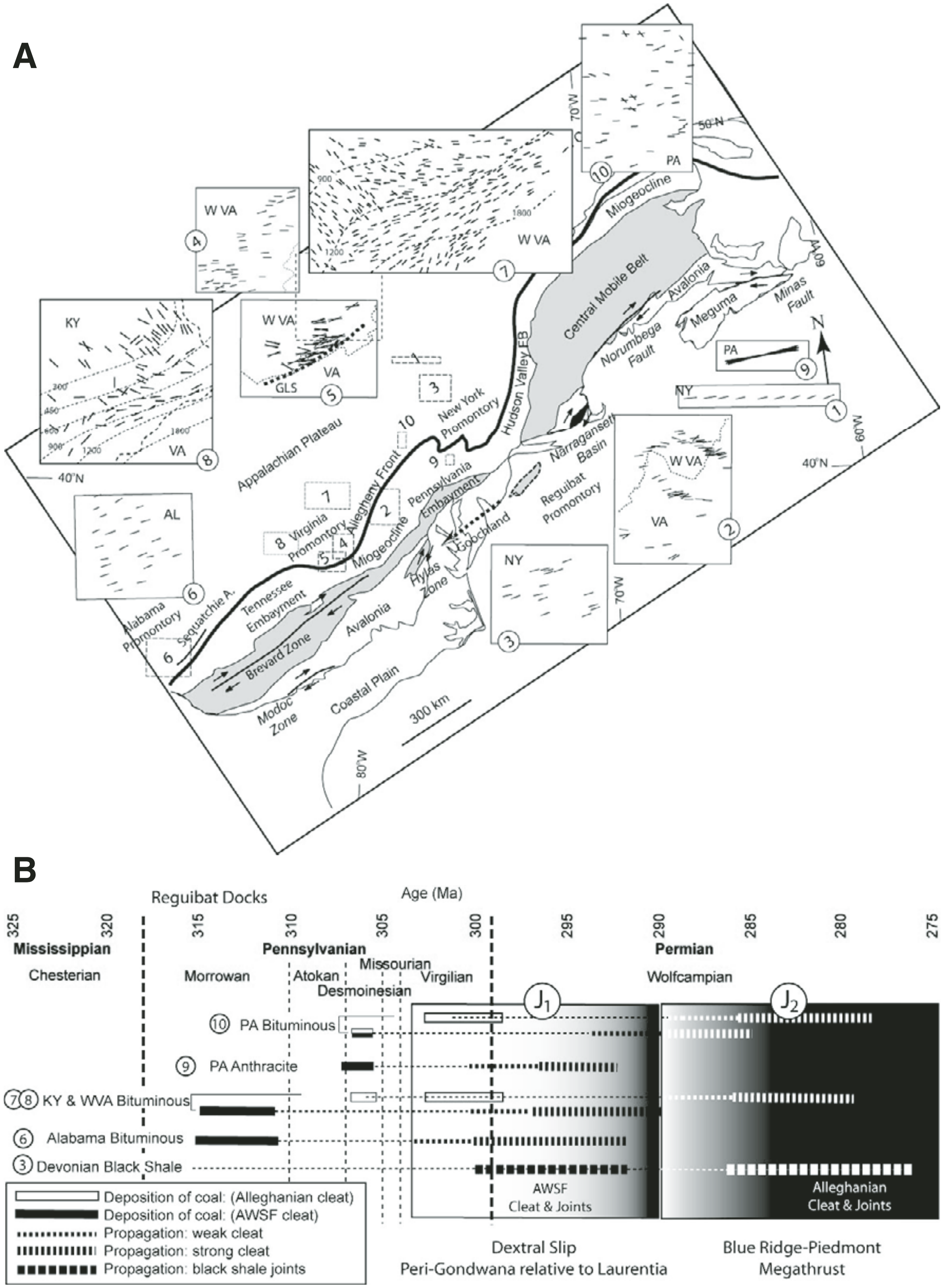

Figure 7. (A) The distribution of ENE joint sets along the Appalachian Mountains. Reference to insets and their map locations (dashed rectangles) are found in Engelder and Whitaker (2006). (B) A time line for coal deposition and propagation of Appalachian cleats and joints. Ages are consistent with International Commission on Stratigraphy (www.stratigraphy.org) whereas the stage names are North American. AWSF—Appalachian-wide stress field.

The most interesting aspect of the Rock-Eval work is that TOC in concretions relative to matrix (Table 2). 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, 2007).

The samples for TOC were taken toward the top of the Oatka Creek. Overturned Purcell and organic rich Oatka Creek are visible down section at the eastern end of the quarry (Fig. 11).

STOP 4. UNION SPRINGS MEMBER OF THE MARCELLUS WITH J_1 JOINTS PROPAGATING AROUND CONCRETIONS AND TILTED BY FOLDING

Union Springs Member of the Marcellus Formation of the Hamilton Group

Series (Eur. Stage): Middle Devonian (Eifelian)

Location: Elimsport, Pennsylvania (Finck quarry along Pikes Peak Road off of Route 44 east northeast of Elimsport)

Coordinates: 41.138081° by –76.992672°

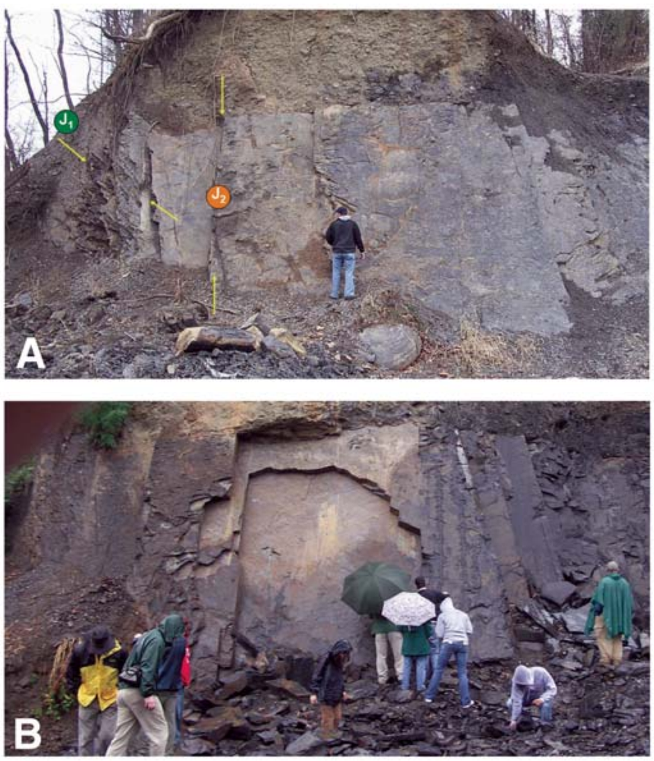

Figure 8. Examples of joint development in the Oatka Creek Member of the Marcellus at the Ed Snook quarry along Old Fort Road off Route 44 west of Antis Fort. Bedding is overturned at 074°/72° (strike and dip by the right-hand rule). (A) Photo taken about March 2007. (B) Photo taken September 2008 after nearly a meter of bedding, including the layer of concretions, had been ripped away.

TABLE 2. SAMPLES SENT TO HUMBLE LABS FOR TOTAL ORGANIC CARBON 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

TABLE 3. SAMPLES SENT TO HUMBLE LABS FOR TOTAL ORGANIC CARBON 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

Background: 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 where gas shale is overmature (Table 3). 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 PA Route 118 in Lucerne, Columbia, and Lycoming Counties. PA Route 118 is a virtual extension of the Allegheny Front east of the Susquehanna River.

Observations: The Finck quarry at Elimsport exposes the Union Springs Member of the Marcellus somewhere above the top bentonite in the Marcellus (Fig. 12). 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 (Fig. 2).

J_1 joints are well developed in this portion of the Marcellus and exhibit the characteristics of NHF by passing around some large concretions within the Union Springs (McConaughy and Engelder, 1999). In general, the surfaces are not as planar as seen in outcrops of black shale in the Finger Lakes District, New York. Like the J_1 joints in the Snook quarry at Antis Fort, these joints form normal to bedding. 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 is 061°.

While clustering is weak at both Stops 3 and 4, it is noteworthy that the orientation of J_1 joints on both sides of the Nittany Anticlinorium are counterclockwise by approximately 10° from the strike of J_1 joints in the Finger Lakes District of New York. This is consistent with the orientation of J_1 joints along the entire Appalachian chain (Engelder and Whitaker, 2006).

STOP 5. CLEAVED LIMEY SHALE AT THE BASE OF THE MAHANTANGO

Mahantango Formation of the Hamilton Group

Series (Eur. Stage): Middle Devonian (Eifelian)

Location: Sunbury, Pennsylvania (road cut along Route 147 less than 2 miles south of the intersection with Route 61 in Sunbury, Pennsylvania)

Coordinates: 40.839552° by –76.806962°

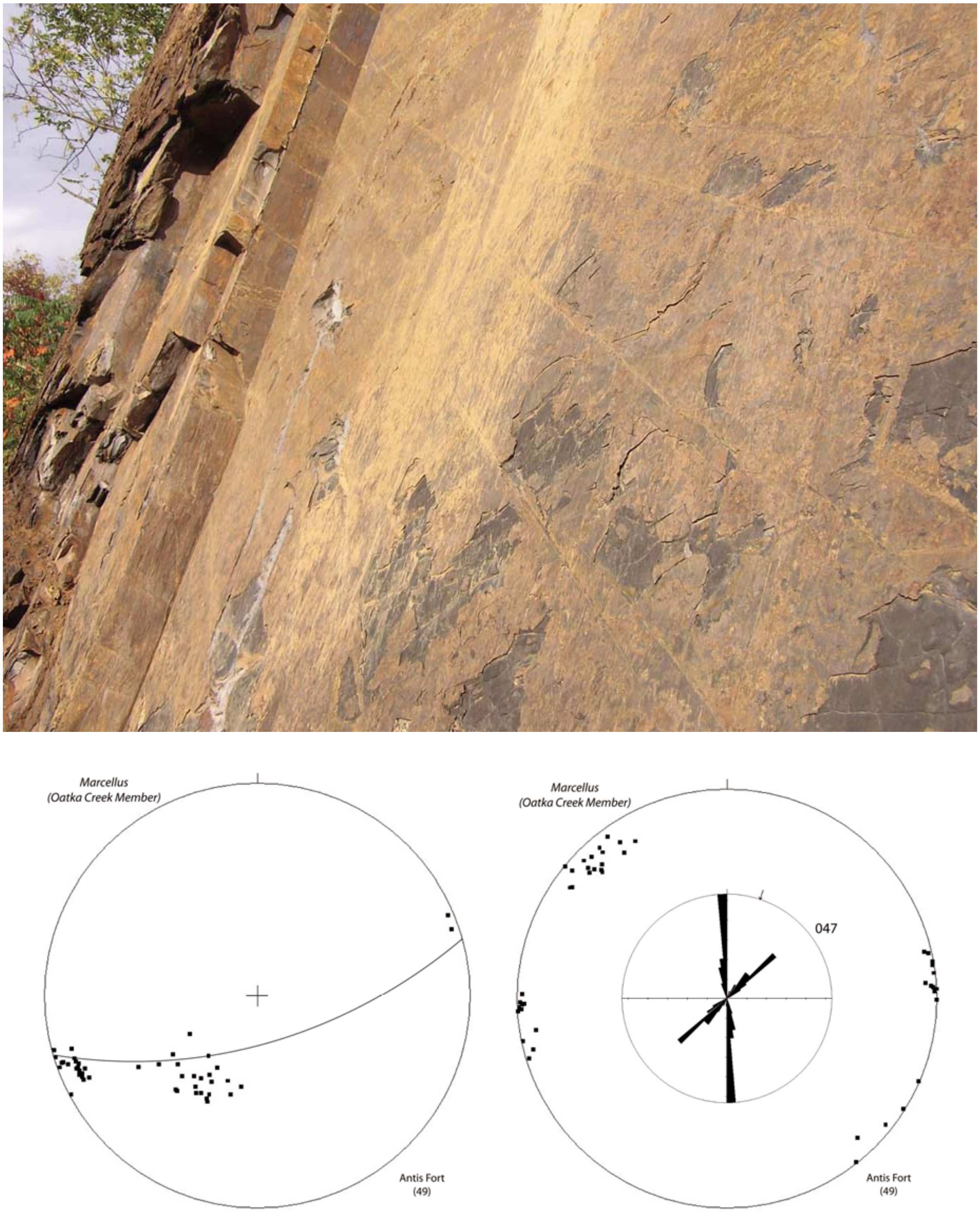

Figure 9. Examples of joint development in the Oatka Creek Member of the Marcellus at the Ed Snook quarry along Old Fort Road off Route 44 west of Antis Fort. Bedding is overturned at 082°/65°. View looking west and parallel to J_1 joints. Joints plotted in present coordinates (left) and rotated to their position with horizontal bedding using a fold axis plunging 05° toward 082° with a rotation of 115° (right).

Figure 10. 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 Snook 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 the stem. (Swiss Army knife shown for scale.)

Background: Day 1 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 Anticlinorium (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 layer-parallel shortening (LPS) measures little more than that encountered within the Appalachian Plateau detachment sheet (<15%) (Engelder and Engelder, 1977). Stops 5–7 are south of the Jacks Mountain–Berwick Anticline structural front where LPS can approach 50%. They are also on strike with and approximately15 km east of the famous Bear Valley Strip Mine (sample K of Nickelsen, 1979). In general, J_2 joints in the region strike between 340° and 350° (Fig. 13). The larger LPS on the hinterland side of the Jacks Mountain–Berwick Anticline structural front appears to have no affect on the regional development of J_2 joints.

Figure 11. Overturned Purcell exposed at Antis Fort quarry.

Observations: This outcrop is at the contact between the Marcellus and Mahantango Formations 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 greater than 24% according to the scale by Alvarez et al. (1978). Nickelsen (1983) estimates that LPS was greater than 30% in the thick cleavage duplexes. Cleavage in the Mahantango is 260°/75°. Prominent cross fold joints have strike consistent with the regional pattern (Fig. 14).

One interpretation for this cleavage duplex is a detachment thrust tipping out in the Mahantango just to the north of Stop 5 (Nickelsen, 1986). Small-scale folds are found on the north flank of the Selinsgrove Junction anticline, a second-order fold in the Appalachian Valley and Ridge.

STOP 6. FORELAND TRANSPORT ON CLEAVAGE DUPLEX IN UNION SPRINGS FORMATION

Union Springs Member of the Marcellus Formation of the Hamilton Group

Series (Eur. Stage): Middle Devonian (Eifelian)
Location: Selinsgrove Junction, Pennsylvania (quarry along Route 147 near the Selinsgrove Railroad Bridge over the Susquehanna River)
Coordinates: 40.801418° by –76.838735°

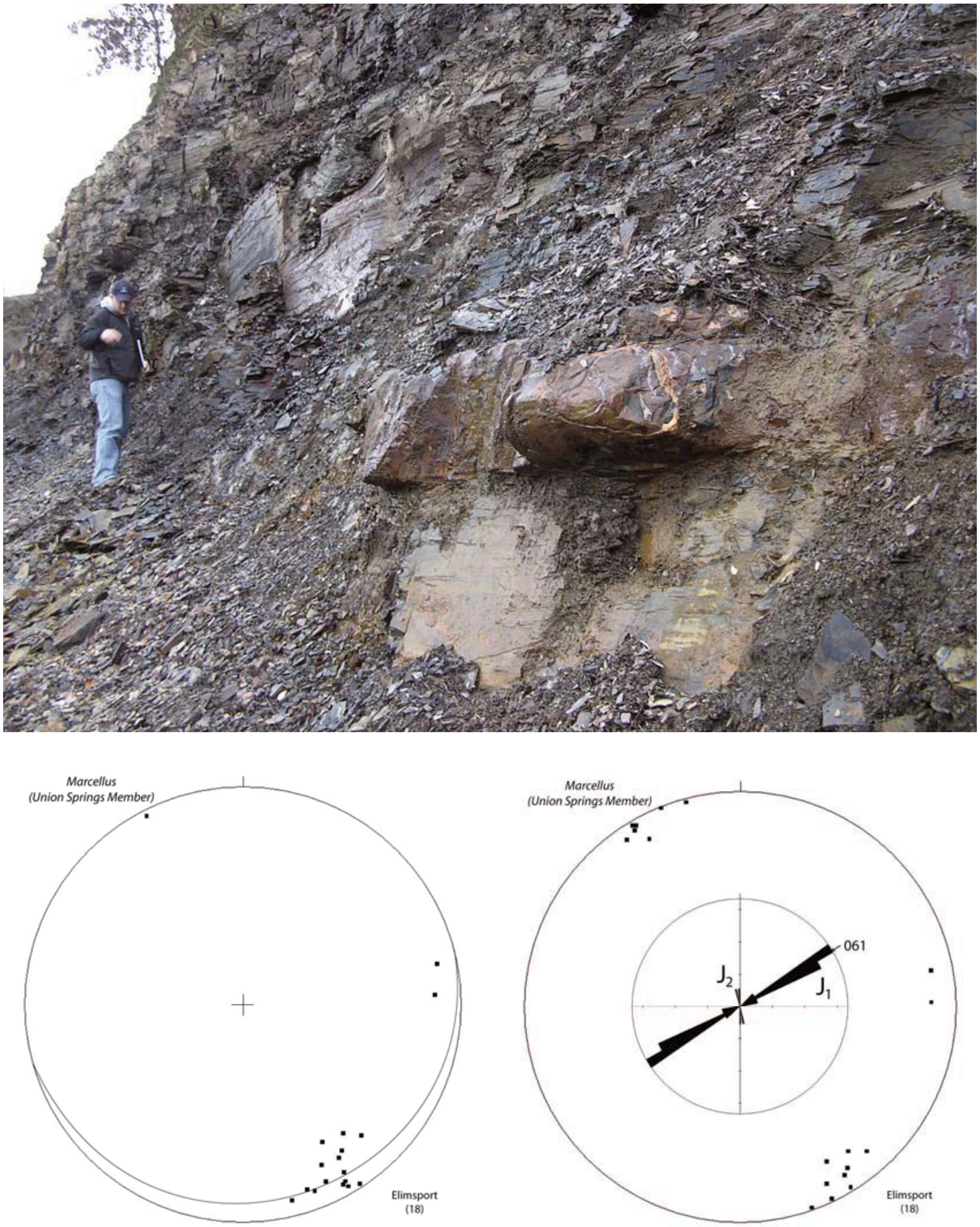

Figure 12. Examples of joint development in the Union Springs Member of the Marcellus at the Delmar Finck quarry along Pikes Peak Road off of Route 44 east northeast of Elimsport, Pennsylvania. Bedding is 075°/10°. Joints plotted in present coordinates (left) and rotated to their position with horizontal bedding using a fold axis plunging 05° toward 075° with a rotation of 10° (right).

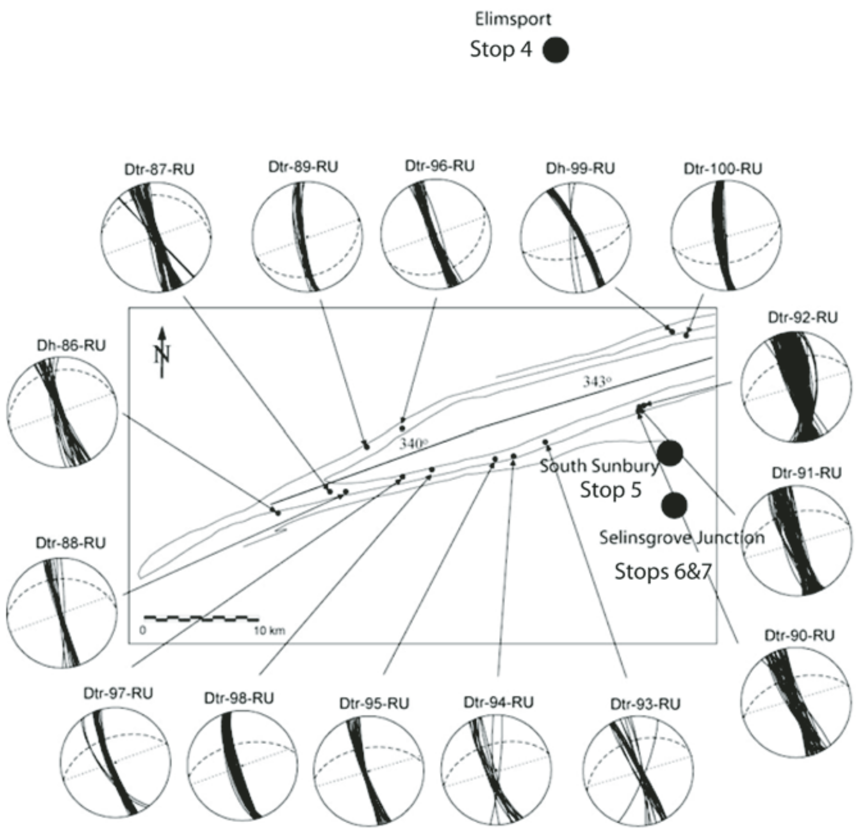

Figure 13. Present orientation of cross-fold joints in the vicinity of the Selinsgrove Syncline. Equal-area net projection. Dbh—Brallier and Harrel Formations undivided; Dh—Hamilton Group; dashed line—outcrop bedding; dotted line—local fold axis trend. The Berwick Anticline structural front passes just north of the Selinsgrove Syncline. Adapted from Engelder et al. (2009).

Observations: Two shale pits in the Union Springs Member of the Marcellus Formation are located on the east side of State Route 147. Beds in these pits dip to the NNW. The top portion of the Selinsgrove Limestone (i.e., the Onondaga Limestone of the Appalachian Plateau) is exposed in a road cut just to the south of the southern pit (Fig. 15). Disjunctive cleavage in this limestone is consistent with LPS on the south side of the Jacks Mountain–Berwick Anticline structural front.

The north shale pit exhibits a thin cleavage duplex dipping to the north. The duplex represents considerable shear strain in the form of a sigmoidal cleavage with a sense of vergence (i.e., thrusting) toward the Appalachian foreland to the NNW (Figs. 16 and 17). The sigmoidal cleavage terminates abruptly against the floor and roof thrusts at strong strain discontinuities (Fig. 18). Such cleavage duplexes are common in both outcrops and core of the Marcellus within the Valley and Ridge. We will see another example at Stop 9. These would be detachments with far greater displacement than seen on bedding surfaces exhibiting fibrous growths of slickensides indicative of flexural-slip folding.

No cleavage or other evidence of LPS is evident in overlying or underlying shale although it must be present as indicated by the extent to which the underlying limestone is cleaved without evidence of detachment from the shale.

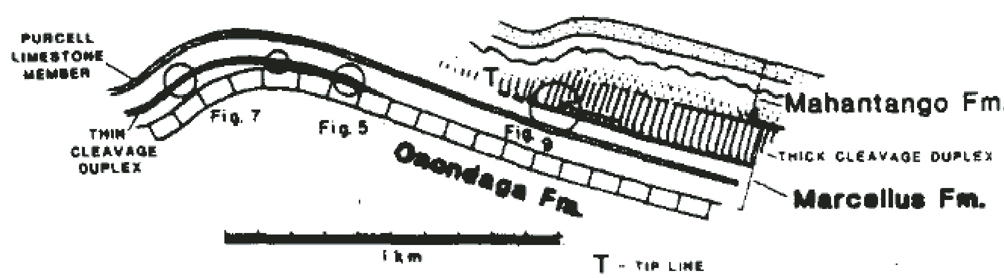

Figure 14. The Selinsgrove Junction second order anticline, showing the stratigraphic setting in the thin and thick cleavage duplexes. Stop 5 will be equivalent to the region marked Figure 9, which is above the Purcell Limestone. Stop 6 is the area marked Figure 7 with a north-dipping thin cleavage duplex. Adapted from Nickelsen (1986).

TABLE 4. SAMPLES SENT TO HUMBLE LABS FOR TOTAL ORGANIC CARBON AND ROCK-EVAL MEASUREMENTS

	TOC	S1	S2	S3	T_{max}	R_o (calc)
Oatka Creek (Stop 7)	0.78	0.07	0.04	0.02	*	?
Union Springs (Stop 6)	3.19	0.03	0.03	0.45	*	?
Cleavage duplexes (Stop 6)	1.59	0.01	0.02	1.42	*	?

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

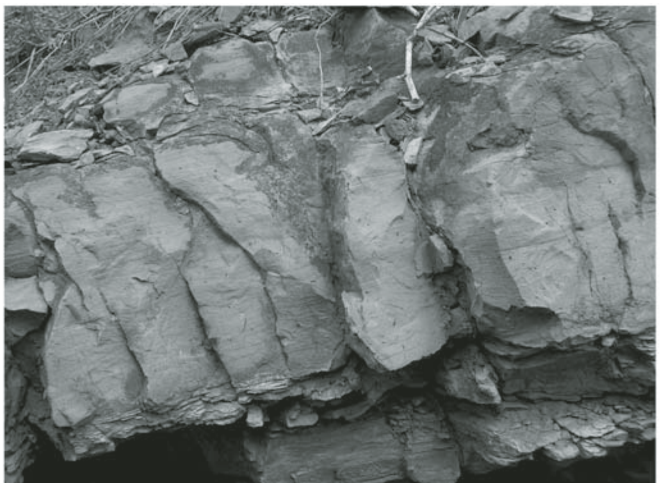

Figure 15. Disjunctive cleavage in a 20-cm-thick bed in the upper portion of the Onondaga Limestone (i.e., the Selinsgrove Limestone) at Selinsgrove Junction.

Like the Marcellus at Stop 7, few joints have developed in this rock. The Marcellus outcrops near Stop 9 and at Stop 11 have a well developed J_2 joint set. The reason why neither J_1 nor J_2 joints are better developed in the area of Selinsgrove Junction remains a mystery.

Thermal maturity of organic-rich rocks in the anthracite district of Pennsylvania is so mature that estimates of T_{max} and R_o are not possible (Table 4).

STOP 7. OATKA CREEK MEMBER CONTAINING A HIGH ANGLE FAULT WITH A TRANSFER ZONE

Oatka Creek Member of the Marcellus Formation of the Hamilton Group

Series (Eur. Stage): Middle Devonian (Eifelian)
Location: Sunbury, Pennsylvania (road cut at the intersection of Route 147 and State Highway 4018 SH)
Coordinates: 40.834580° by –76.809977°

Observations: Stop 7 is a thick section located in the Oatka Creek Member of the Marcellus black shale (Fig. 19). Here, neither J_1 nor J_2 joints 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

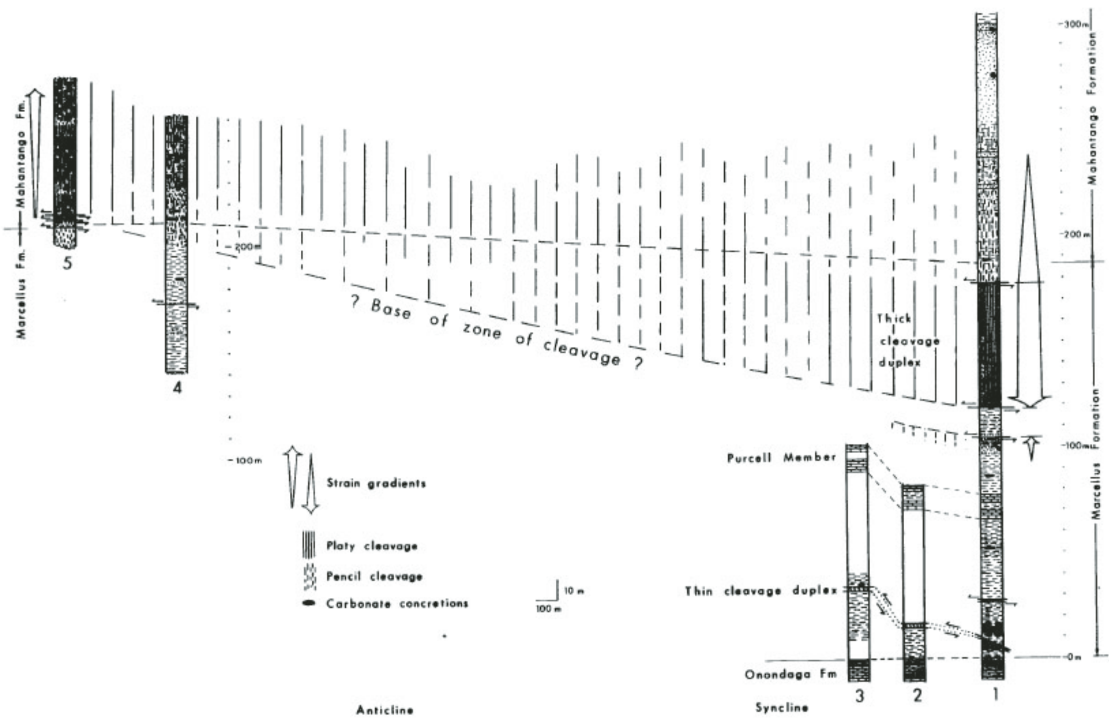

Figure 16. Correlated stratigraphic sections showing cleavage duplexes, thrust faults, and strain gradients. Section 3 is Stop 6. Section 4 is Stop 7. Section 5 is Stop 5. Adapted from Nickelsen (1986).

Figure 17. Cleavage duplex at Selinsgrove Junction. Looking to the east with tectonic transport toward the foreland (left). See Nickelsen (1986).

Figure 18. A major slip surface between the cleavage duplex, above and more weakly strained Union Springs shale, below.

fold axis and believed to have formed as a consequence of layer-parallel stretching as the local fold developed near a high angle fault exhibiting a transfer zone (Fig. 20).

Penn State's Appalachian Basin Black Shale Group (ABBSG) sampled the Marcellus in two core holes within 3 km to the east of this outcrop. In core, the evidence of LPS is particularly strong in the Purcell Limestone, the middle member of the Marcellus Formation (Fig. 21). With these structures we have seen the manifestation of LPS in the limy portion of the basal Mahantango (Stop 5), the top of the Selinsgrove Limestone (Stop 6) and in the Purcell Limestone.

STOP 8. TIGHTLY FOLDED SYNCLINE IN THE UNION SPRINGS MEMBER OF THE MARCELLUS

Union Springs Member of the Marcellus Formation of the Hamilton Group

Series (Eur. Stage): Middle Devonian (Eifelian)
Location: Lewistown, Pennsylvania (road cut along the 522 bypass west southwest of Lewistown)
Coordinates: 40.581116° by –77.626651°

Observations: 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 (Fig. 23). Iron ore (secondary limonite and jarosite) was mined along the contact between the Selinsgrove 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 shaly rocks prone to slumping, and covering over the carbon-rich black shales that produce acid drainage. Not all of the revegetation 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 Onondaga Formation. As one progresses uphill to the west, faulting juxtaposes the Ridgley Sandstone and Needmore Shale units as well as the upper Onondaga 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 Selinsgrove Limestone in a tight overturned syncline (Fig. 22). 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 23, with the axis of the overturned syncline in the center of the black band (Marcellus Shale).

The Union Springs Member of the Marcellus Shale at Stop 8 is a highly fissile, dark gray to black shale with very fine grained framboidal pyrite, generally disseminated throughout, but more abundant near the base; tightly folded lenses, 5–10 cm thick, of framboidal 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 is 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. 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 Fig. 24), 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%. Trace elements with elevated concentration (V, Ni, Cu, Cr, Mn, Ag, Au, etc.,) are consistent with those of black shale deposits.

The tight syncline is a third-order fold with numerous faults and fourth-order folds within it. The syncline is overturned and

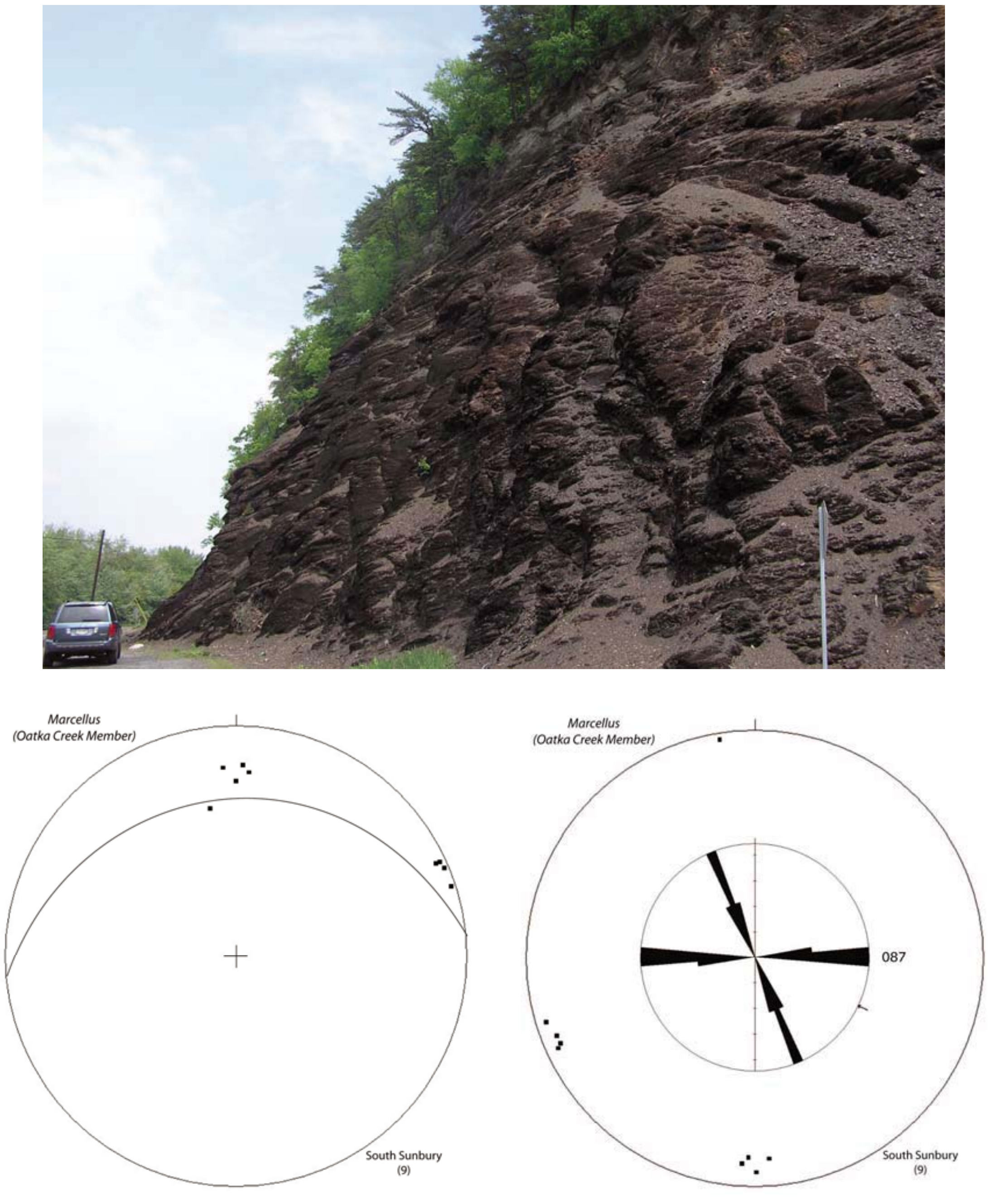

Figure 19. Oatka Creek Member of the Marcellus along Route 147 south of Sunbury, Pennsylvania. Joints plotted in present coordinates (left) and rotated to their position with horizontal bedding using a fold axis plunging 00° toward 265° with a rotation of 32° (right). E-W joints are interpreted as fold-related, whereas J_2 joints are well developed near the top of the Oatka Creek and up into the cleaved limy beds of the Mahantango Formation.

Figure 20. High-angle fault with a transfer zone.

faulted with beds dipping 60°–80°. The syncline plunges out approximately1.5 km to the west of Stop 8. The fault is interpreted as a back thrust (south vergent). Along the westbound exit ramp, a complete section of the footwall may be sampled, including the Needmore and Selinsgrove Members of the Onondaga Limestone, the Ridgley Sandstone, 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 5).

TABLE 5. SAMPLES SENT TO HUMBLE LABS FOR TOTAL ORGANIC CARBON 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 21. Core from the Purcell Member of the Marcellus showing a vertical extension of pyrite nodules, cleavage about a carbonate concretion, and calcite veins filling a cleavage duplex. This core comes from the Handiboe well located less than 2 km to the east of Stop 7.

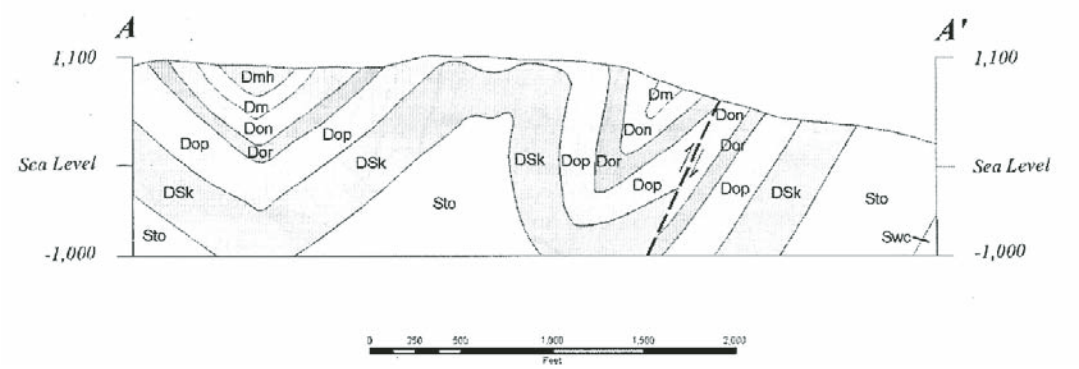

Figure 22. Structural cross section at Stop 7. View looking ENE. See Figure 1. Key to some formation names: Dop—Old Port; DSk—Keyser; Sto—Tonoloway.

Figure 23. Union Springs Member of the Marcellus Formation along the Route 522 bypass west southwest of Lewistown, Pennsylvania. (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 uncharted 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.)

STOP 9. FOLDED UNION SPRINGS MEMBER OF THE MARCELLUS WITH A TIOGA ASH BED, CLEAVAGE DUPLEX, AND SMALL-SCALE BUCKLE FOLDS

Union Springs Member of the Marcellus Group of the Hamilton Group
Series (Eur. Stage): Middle Devonian (Eifelian)
Location: Newton-Hamilton, Pennsylvania (Forgy quarry along Ferguson Valley Road east of Newton-Hamilton)
Coordinates: 40.397553° by –77.825627°

Background: 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 (Fig. 25). 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. The transition between the Onondaga Limestone and the Marcellus is particularly impressive (Fig. 26). Here, the Onondaga is an interlayered carbonate and shale, which is why it has a gamma ray signature that fluctuates with an API (American Petroleum Institute) 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. The Purcell is intensely cleaved. The Oatka Creek is a dark gray shale with local gray-black layers of higher organic content. The J_2 joint set is well developed in the Union Springs Member. (See also Table 6.)

TABLE 6. SAMPLES SENT TO HUMBLE LABS FOR TOTAL ORGANIC CARBON 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.

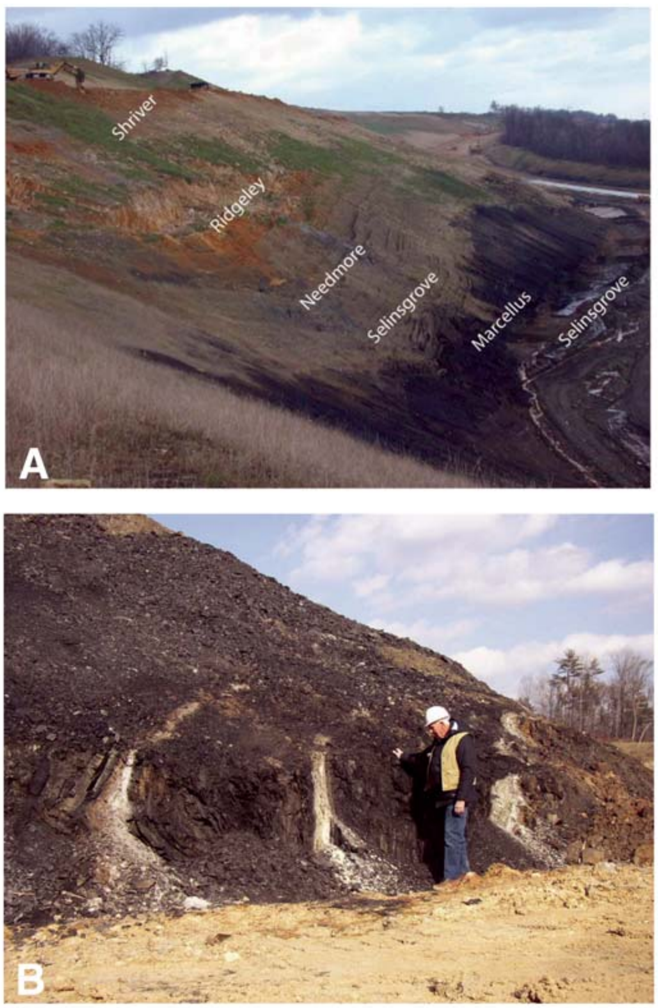

Figure 24. (A) View to northeast along the axis of the overturned syncline in center of black shale band. Beds of Selinsgrove Limestone were exposed at the road bed level below (upright) and in the slope above (overturned) the black band. (Photograph by Tom McElroy.) (B) View to northeast of three ash beds (meta-bentonites) in the Marcellus Shale at road-level during construction. (Photograph by D.P. Gold. Hugh Barnes for scale.)

Observations: The Forgy Quarry carries one bentonite which is a 4 cm layer of crystalline tuff with biotite (Fig. 27B). 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 m section that Penn State graduate student Reed Bracht has mapped (Fig. 28). 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 the transition zone is several meters thick with shale layers thickening as the limestone layers thin. These layers are not scraggy carbonates like those at the top of the Union Springs. 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 (Fig. 27A). This is thickest of several cleavage duplexes in the Forgy quarry.

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.

STOP 10. WELL-DEVELOPED J_2 JOINTS IN THE BRALLIER SILTSTONES

Brallier Formation of the Genesee Group
Series (Eur. Stage): Middle Devonian (Givetian)
Location: Huntingdon, Pennsylvania (road cut along Penn Street off Route 22 in Huntingdon)
Coordinates: 40.477211° by –77.997870°

Background: The major driving mechanism for joint propagation in the Middle Devonian section of the Appalachian Basin is natural hydraulic fracturing (Lacazette and Engelder, 1992; McConaughy and Engelder, 1999). Because the pressure for this drive develops during the maturation of hydrocarbons in source rocks, it is expected that source rocks should be most heavily fractured. The affinity between jointing and black shales is manifest by a decreasing joint density with thickness of section above the black shales (Fig. 29). Throughout the Appalachian Basin, the non-source rock that carries the most completely developed joint set is found right above black shales. This stop is an example of joint development above a black shale, the Burket/Geneseo.

Observations: The Brallier Formation is a clastic unit with distal turbidites and shale interbedded immediately over the Burket black shale. This unit is often called the undivided Brallier-Harrell where the Burket is the black shale member of the Harrell. Like portions of Mahantango above the Marcellus, this unit has a significant number 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 (the Ithaca Formation), gradually becomes more thickly bedded up section. At Stop 1 where the lower portion of the Brallier is 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 this stop where the earliest joints are mineralized J_2 joints. In this outcrop, there is no evidence for J_1 joints which favor black shales of the Appalachian Basin.

At this stop, 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 consists of strike joints with either unmineralized surfaces or coated with a delicate pattern of microscopic crystals of unknown composition. Statistical analysis indicates that the third episode of jointing is a late-stage J_2 joint set behaving like cross joints (Ruf et al., 1998). Certainly, the later J_2 joints abut strike joints more commonly than the other way around (Fig. 30). It is, however, common to see these cross joints (late J_2 orientation) cross cut the strike joints in the Brallier (Fig. 30). The strike joints are tilted slightly relative to bedding, a sign of fold-related joint growth (Engelder and Peacock, 2001).

The development of surface morphology on the joints of the Brallier siltstones is magnificent. Two sets of systematic joints cutting the same bed may exhibit different rupture styles (Engelder, 2004). Joints oriented parallel to the strike of bedding formed prior to dip-parallel joints, as inferred from cross-cutting relationships. The strike joints typically have a surface morphology consistent with that of a short blade crack, whereas the dip joints exhibit a more complex morphology (Fig. 30). 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

Figure 25. Google Earth™ image of the Kistler railroad cut. Penn State students are actively involved in a number of projects involving the Kistler section, including studying the effect of weathering on the Marcellus.

(<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 (Savalli and Engelder, 2005). 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 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 this outcrop, the frosty-window morphology is interpreted as indicative of the slow growth of cross joints during exhumation.

In Devonian clastic sections dominated by interlayered siltstones and shales, joint initiation usually starts in the siltstone layer (McConaughy and Engelder, 2001). During NHF propagation, 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 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,

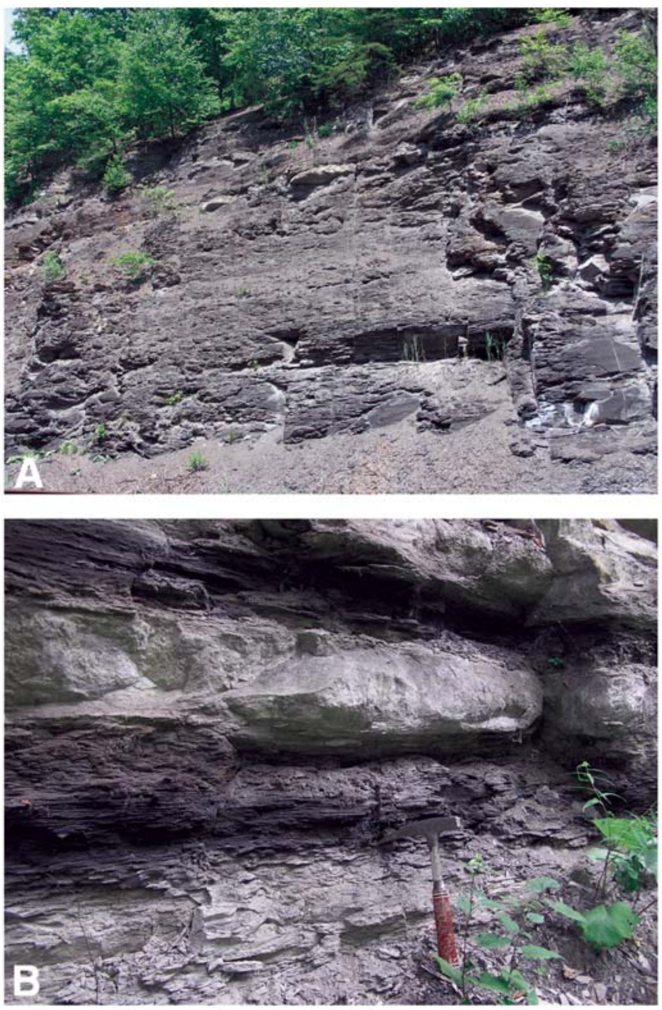

Figure 26. Top and bottom portions of the Union Springs Member of the Marcellus along the Conrail railroad cut at Kistler, Pennsylvania. (A) The top portion showing scraggy lime layers that mark the transition between the Purcell Member (above) and Union Springs Member (below). (B) The bottom transition to the Onondaga Limestone.

Figure 27. 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.

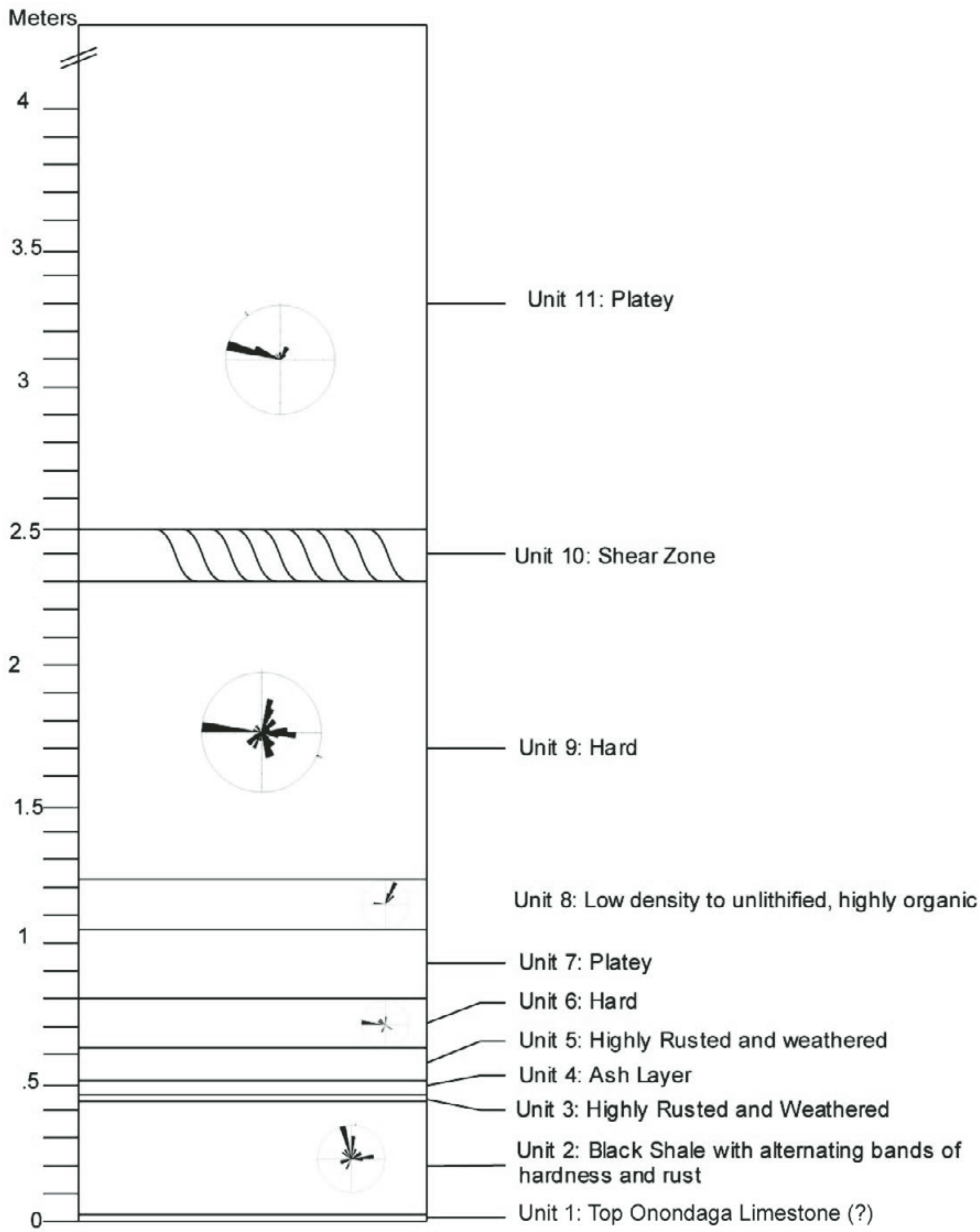

Figure 28. A 4-m stratigraphic column of the Union Springs Member of the Marcellus black shale at the Forgy quarry, Newton-Hamilton, Pennsylvania. Mapped by Penn State graduate student Reed Bracht. The rose diagrams given here are in the form of half-strike plots.

higher fluid pressures will drive en echelon cracks (i.e., fringe cracks) into bounding shale beds (Pollard et al., 1982; Carter, et al., 2001; Younes and Engelder, 1999).

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, 1991; Srivastava and Engelder, 1991). The Braillier also has the same NHF pattern as found in the Ithaca Formation with fringe cracks being driven from the interface of a parent joint (Fig. 31).

STOP 11. DIPPING OATKA CREEK MEMBER OF THE MARCELLUS WITH J_1 AND J_2 MUTUALLY CROSS CUTTING

Oatka Creek Member of the Marcellus Formation of the Hamilton Group
Series (Eur. Stage): Middle Devonian (Eifelian)
Location: Huntingdon, Pennsylvania (Cold Springs Road ~1 miles off of Route 26 to State College)
Coordinates: 40.554403° by –77.963796°

Background: One of the fundamental rules of joint propagation is that rupture is perpendicular to the plane of least principal stress (σ_3). As σ_3 occupies only one orientation, particularly in a static state, it is a physical impossibility for simultaneous crack growth in more than one orientation. Hence, when an outcrop contains multiple joint sets, there have been at least two propagation events with a rotation of stress between the events. During dynamic rupture, the stress field can be very complicated on a local basis, but with the joints observed during this field trip, static fracture mechanics governs propagation.

Abutting is a manifestation of the later joint set. However, in gas shales it is common to observe cross cutting joint sets (Fig. 32). The mechanism for cross cutting versus abutting is based on the projection of the crack-tip stress field in front of the later joints as they propagate. For deeply buried joints, the normal stress on early joints is large enough that a frictional contact between the walls of the early joint allows for an elastic distortion in the vicinity of the crack-tip cross over to the other side of the early joint. If the crack-tip distortion crosses an early joint, then the rupture of a later joint can cross the earlier joint. If the early joint is open and not in frictional contact, the elastic distortion of the crack tip from the propagation of the later joint is not transmitted across the early joint. In this case, the later joint will arrest at the earlier joint, thus abutting but not crossing the early joint.

Observations: 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 cross cutting J_1-J_2 joint sets development found in the Valley and Ridge Marcellus (Fig. 33). 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. The Hootenanny quarry is what the outcrop of Marcellus featured in Figure 32 might look like in cross section. The intersection of

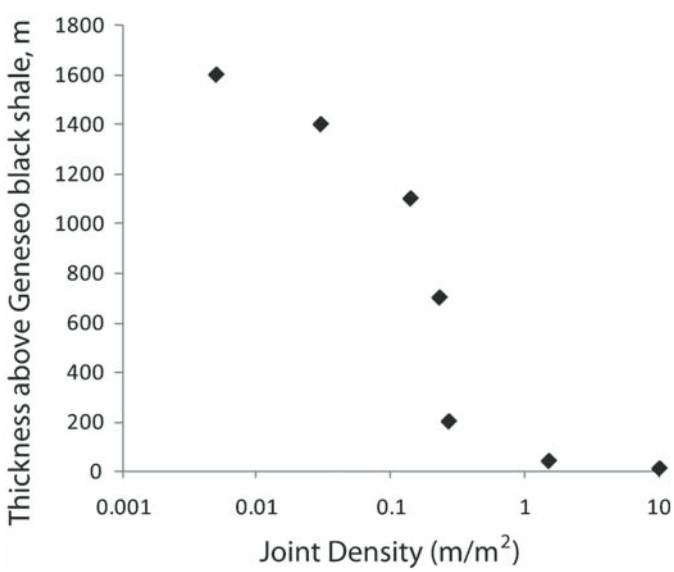

Figure 29. Joint density of J_2 joints in 2-D as measured in a series of outcrops along Route 15 between Williamsport, Pennsylvania and the New York–Pennsylvania border. Joint density was measured in cross section as cumulative joint length intersecting an area of 100 m^2 as viewed along strike of joints.

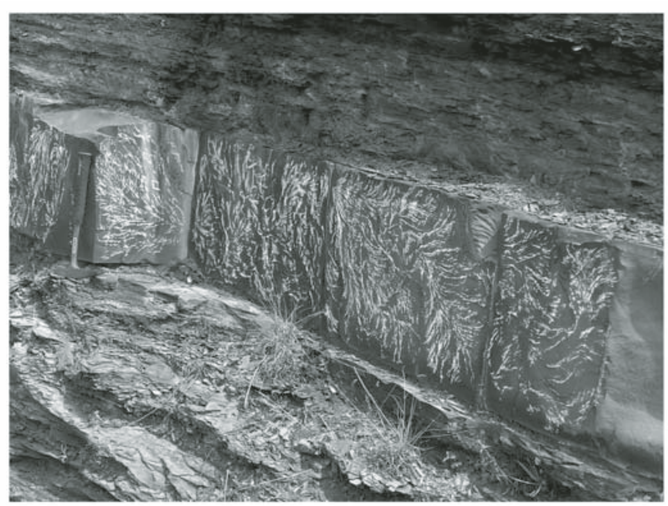

Figure 30. Joints in interbedded siltstone of the Brallier Formation in a road cut along Penn Street off Route 22 in Huntingdon, Pennsylvania (Ruf et al., 1998). Late-stage J_2 joints (chalk on two different joint surfaces with a hammer leaning against one of these) abutting a strike joint (joint propagating toward hammer).

joints in the Hootenanny quarry is at a smaller acute angle than joints at the Oatka Creek outcrop in Figure 32.

As a general rule of thumb, J_1 joints are better developed in black shales of the Appalachian Plateau. This is the case in the outcrop of the Oatka Creek (Fig. 32). Gray shale immediately over black shale has a better developed J_2 joint set. This is true for the Brallier throughout the area covered by Day 2 of this field trip (Fig. 34).

STOP 12. DIPPING UNION SPRINGS MEMBER OF THE MARCELLUS WITH INTERNAL LIMESTONE BEDS

Union Springs Member of the Marcellus Group of the Hamilton Group

Series (Eur. Stage): Middle Devonian (Eifelian)

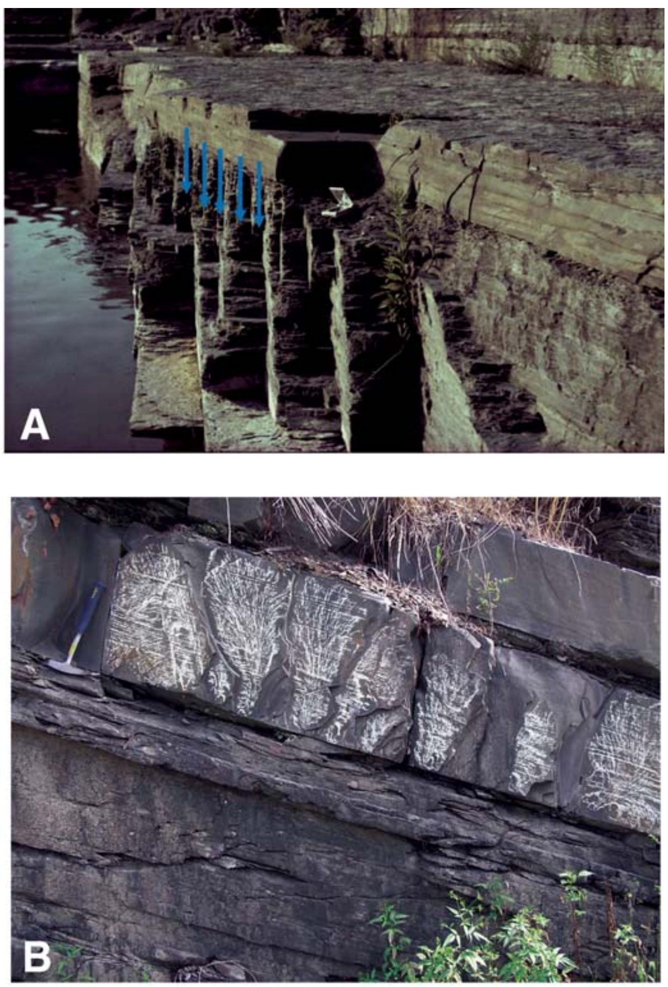

Figure 31. (A) J_2 joints in the Ithaca Formation at Taughannock Falls State Park where multiple en echelon cracks propagate down into shale from a siltstone-shale interface (Younes and Engelder, 1999). The parent joint cuts a siltstone. (B) J_2 joints in the Brallier Formation in Huntingdon, Pennsylvania, with multiple en echelon cracks propagating upward into a siltstone. The parent joint cuts a silty shale.

Location: Frankstown, Pennsylvania (New Enterprise quarry off Locke Mountain Road in Frankstown)
Coordinates: 40.435286° by −78.342129°

Background: Up to 80 or more Lower and Middle Devonian (Lochkovian to Eifelian) K-bentonites in the Appalachian Basin are distributed through the succession as four major clusters of 8–15 closely spaced beds or as scattered multiple to single beds (ver Straeten, 2004). The most prominent cluster is known as the Tioga A through G ash beds/K-bentonites.

Observations: The Union Springs Member of the Marcellus at the New Enterprise quarry in Frankstown is in the same structural position as the Finck quarry in Elimsport (Stop 4),

Figure 32. Cross cutting J_1 and J_2 joints. J_1 joints strike left to right and J_2 joints strike back to front.

Figure 33. 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.

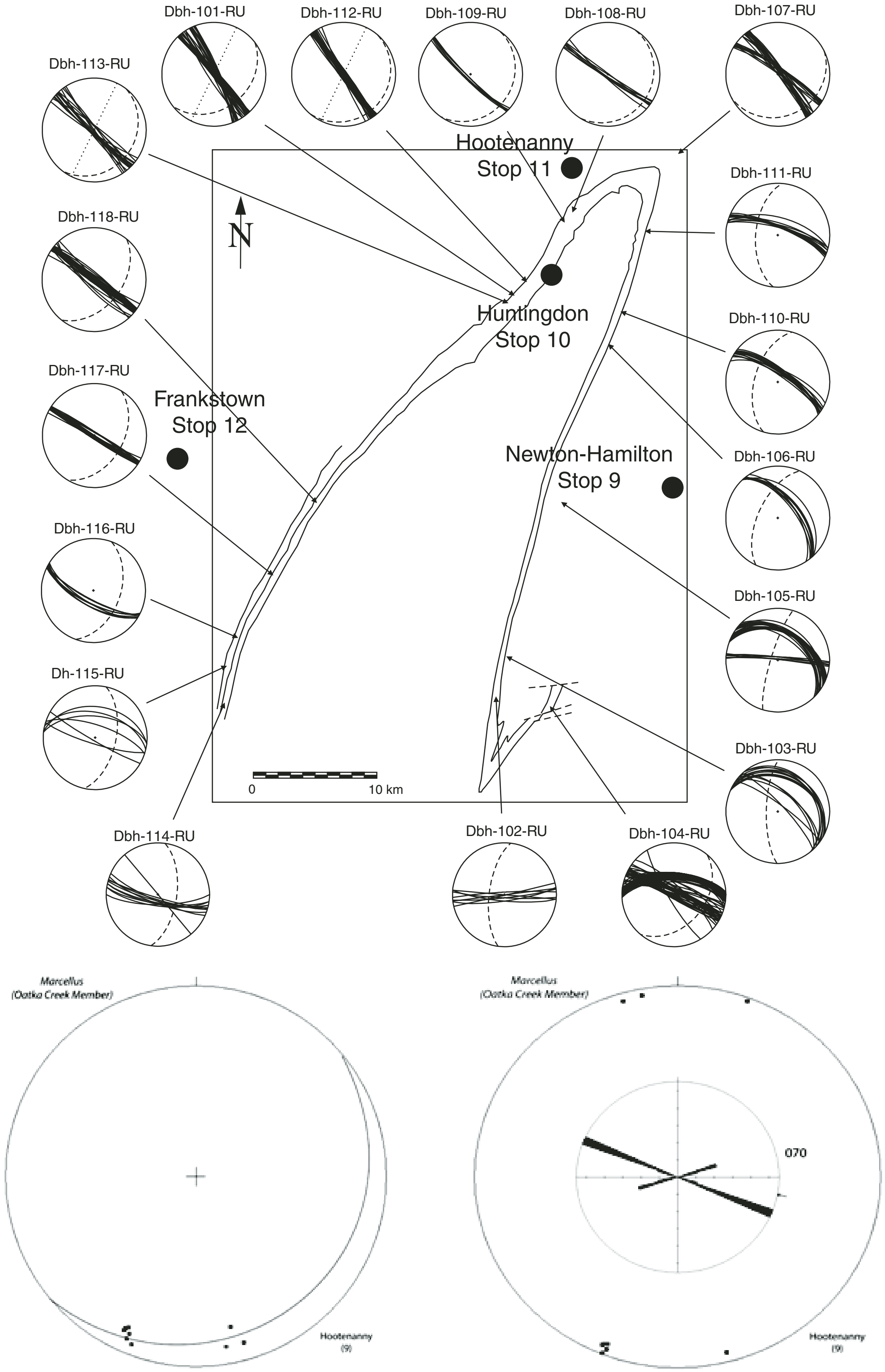

Figure 34. Present orientation of cross-fold joints in the vicinity of the Broadtop Syncline. Equal-area net projection. Dbh—Brallier and Harrell Formations undivided; Dh—Hamilton Group; dashed line—outcrop bedding; dotted line—local fold axis trend. Joints at Hootenanny quarry plotted in present coordinates (left) and rotated to their position with horizontal bedding using a fold axis plunging 00° toward 050° with a rotation of 16° (right).

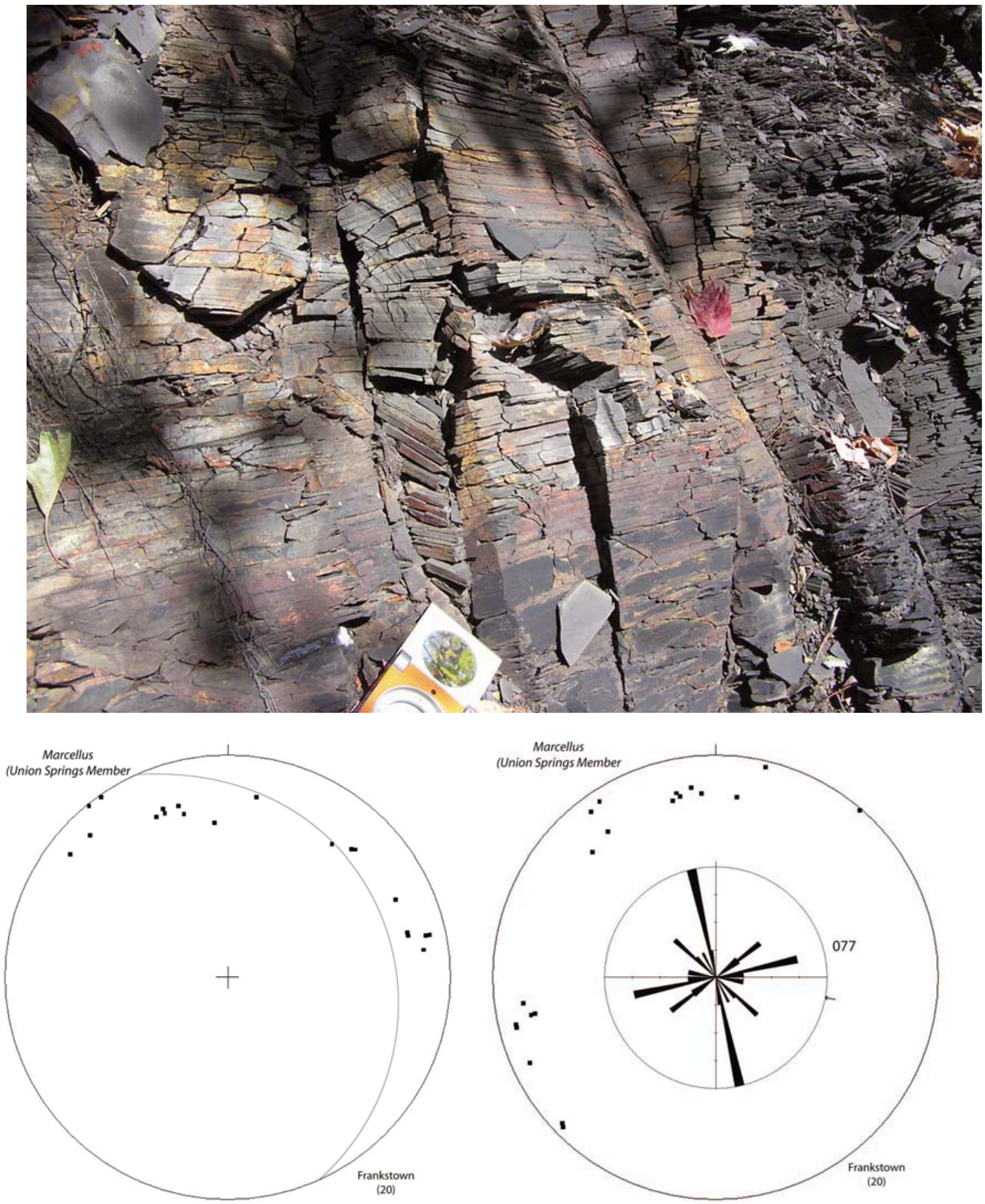

Figure 35. Examples of joint development in the Union Springs Member of the Marcellus at the New Enterprise quarry off Locke Mountain Road in Frankstown, Pennsylvania. Bedding is 336°/27°. Joints plotted in present coordinates (right) and rotated to their position with horizontal bedding.

Figure 36. Ash bed with low density, high total organic carbon shale at Frankstown, Pennsylvania.

Figure 37. Lingula found in the Union Springs Member of the Marcellus at Frankstown, Pennsylvania.

which is to say that this location is on the hinterland side of the Nittany Anticlinorium but to the foreland of the Jacks Mountain–Berwick Anticline structural front. The thermal maturation of the rock at Stops 4 and 12 is also similar and in both cases maturation has crossed into the non-prospective realm (compare Tables 3 and 7).

Joints in this section of Union Springs are less well clustered than their counterpart along the Newton-Hamilton railroad cut. The strong N-S joint trend resembles that seen at Newton-Hamilton railroad cut, but its significance is unknown (Fig. 35).

Marcellus in the New Enterprise quarry carries three ash beds which are interpreted to be the Tioga E-, F- and G-ash beds of Way et al. (1986) (Fig. 36). An unusual bed of Lingula occurs toward the base of the Union Springs (Fig. 37). The top of the Onondaga Limestone is seen at the base of the exposure. Exposures of the Oriskany Sandstone are seen on the western wall of the quarry.

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TABLE 7. SAMPLES SENT TO HUMBLE LABS FOR TOTAL ORGANIC CARBON 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.

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