The Pennsylvania State University

The Graduate School

REVISITING THE HUBBERT-RUBEY HYPOTHESIS FOR OVERTHRUST FAULTING: INFERENCES FROM PROGRESSIVE MINERALIZATION ON BEDDING SLIP SURFACES DURING FLEXURAL SLIP FOLDING OF DEVONIAN SHALE, THE APPALACHIAN BASIN, USA

A Thesis in
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by
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ABSTRACT

Both bedding-parallel slickensides and cleavage duplexes are abundant in core taken within black and gray Devonian shales of the Appalachian Basin. Slickensides are more abundant on the limbs of folds relative to hinge lines, an indication of flexural slip folding. The abundance and the orientation of slickensides in black shale relative to gray shale show that bedding-parallel slip during flexural-slip folding favored reduced effective normal stress. This reduction in effective stress is inferred to occur during the buildup of maturation-related pore pressure. Morphology of slickensides is dependent on the minerals decorating the slip surface. Chlorite rich films show mirror-like morphology polish but posses ridge-in-groove striations on microscopic scale. Quartz and calcite fibers are covered with ridge-in-groove type of striation on mesoscopic scale as well. Slip surfaces are characteristic of three internal detachment zones in the Appalachian foreland, all cutting black. The interpretation is that the Hubbert-Rubey model for low effective stress favors that development of these detachment zones rather than the inherent weakness of the shale. Since slip surfaces are natural fractures and the gas production from the low permeable rocks highly depended on finding pathways, this study can be useful for the industry.

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1. INTRODUCTION

The value of black shale as an unconventional reservoir for natural gas in many basins of the world has kindled interest in deformation mechanisms associated with the generation of high pore pressure during the thermal maturation of source rocks. Elevated pore pressure can affect black shale in two ways: it can exceed least compressive stress to drive natural hydraulic fractures and it can lower the effective normal stress across bedding surfaces to promote differential slip. Structures that are a manifestation of these two processes are common in the Appalachian Basin where natural hydraulic fracturing affects each of the black shales (Engelder et al., 2009) and slickensides arising from bedding-parallel slip slice through these same shales (Evans, 1994). If reduced effective normal stress is common during maturation of black shale, then these shales might also preferentially host detachment planes under regional thrust sheets (Hubbert and Rubey, 1959). This leads to the possibility that detachment of thrust sheets foreland fold-thrust belts is more likely in shale subject to a reduction in effective stress during the buildup of maturation-related pore pressure within the shear or a reduction in effective stress associated with pore collapse in organic material if organic material makes black shale inherently weaker. A reduced-effective-stress hypothesis is testable in foreland settings that have both gray and black shale. With equivalent strengths, bedding-parallel slip focused in black shale should be a robust witness to the role of maturation-related pore pressure generation. One of the places to assess the distribution of bedding-parallel slip is in the foreland portion of fold-thrust belts where slip is intimately tied to flexural-slip folding (Tanner, 1989).

Aside from testing the reduced-effective-stress hypothesis, an objective of this study is to examine bedding-parallel slip surfaces with an eye toward identifying those features that classic papers on slickensides may have overlooked (Means, 1987: Doblas, 1998). In particular, none of the classic papers describes the mirror-like surfaces that are common to bedding-parallel slip in the Devonian section of the Appalachian Basin. The Devonian section is rich in both clastic and carbonate beds deposited in an outer shelf to slope environments where distal turbidites are common. This basin setting provides an opportunity to understand the distribution of slip as a function of lithology. One process to be on the lookout for is the mineralization of slip surfaces as a function of the mineralogy of the substrate host rock. Finally, details of the mineralization will give clues about active processes during slip, be they congruent or incongruent pressure solution (Fry, 1982), diffusion to be pressure shadows which allow fiber growth (Durney and Ramsay, 1973), or outright transport in a fluid to some host elsewhere in the section.

A study of bedding-parallel slip has several practical applications in the shale gas industry. While natural hydraulic fracturing provides channels that serve to enhance production of natural gas from a rock of very low permeability, slickensides often become mineralized which may reduce cross-bedding flow in an otherwise low permeability rock. Such internal structural laminations may also further increase the mechanical and seismic anisotropy of gas shales. The same rock properties may be affected by larger scale detachment pervading black shale. For these reasons industry will benefit from an enhanced understanding of the development of effective-stress related bedding-parallel slip or larger scale detachment when making decisions during completion of and production from unconventional reservoirs in black shale.

1.1 Flexural-slip folding and interbed slip

Chevron (i.e., kink) folds populate several scales of folding in Appalachian foreland (Faill, 1973). This fold geometry is the basis for the theory of fault-bend folding which requires bed-parallel shear to maintain compatibility of deformation (Suppe, 1983). In the Appalachian foreland the most common mechanism for bed-parallel shear is flexural slip on bedding interfaces. One of the characteristic properties of flexural slip is maintenance of bed thickness during folding (Donath and Parker, 1964). Of course this creates compatibility problems in the sharp hinges of chevron folds (Figure 1). When bed parallel slip is not confined to an interface the general term, movement horizon, applies (Tanner, 1989). Compatibility in the hinge region is not a problem if flexural-slip folding is cylindrical in nature. Not every bedding interface within a flexural-slip fold is a movement horizon and the spacing between movement horizons varies with limb dip, lithology, and tectonic setting (Tanner, 1989). In this study, the term “flexural-slip folding” applies to both chevron and cylindrical folds along with the term “slip surface” for bedding interfaces that are decorated with less than a cm of slip-related material. Slip displacement varies with position in a flexural-slip fold and ideally no slip takes place at the hinge line (Donath and Parker, 1964; Tanner, 1989). The mechanical anisotropy of bedding interfaces plays a critical role in flexural-slip folding (Donath and Parker, 1964). Anisotropy depends on the relative ductility of the rock layers and the cohesion between layers and flexural slip is common in a rock sequence with low mean ductility.

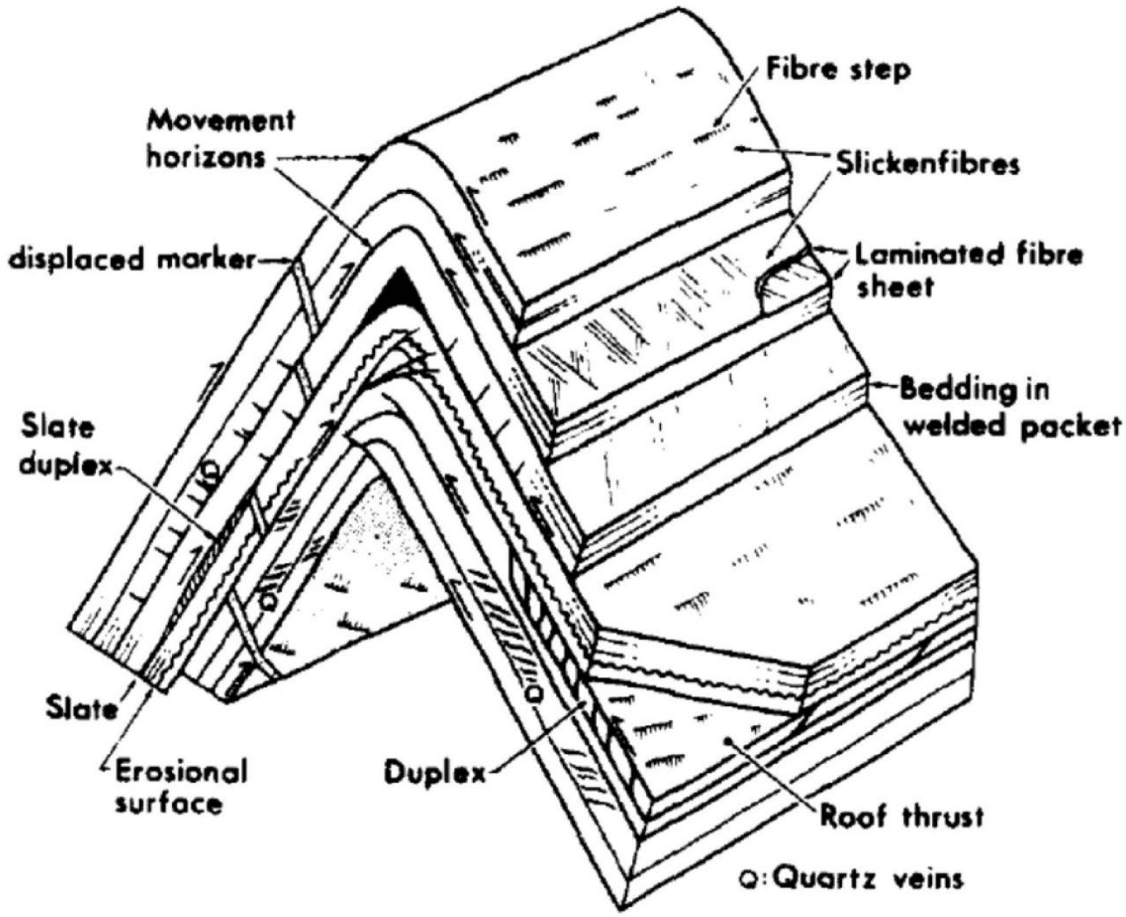


Figure 1. Features that are found on a flexural-slip fold model (Tanner, 1989).

The most common structure indicative of flexural slip is the slickenside, a class of fault that is either rough on a fine scale with fibers and grooves or polished into shiny surfaces (e.g. Means 1987; Lin and Williams 1992). Both fibers and grooves constitute a slip lineation indicative of the direction and sense of slip. Depending on the extent of fiber growth, the term, slickolite applies (Bretz, 1940). Classification of slickensides reflect the rich variety of small scale structures that can populate these slip surfaces (Figure 2). A relatively simple classification shows 6 different types of slickenside surfaces, whereas slickensides may have up to 61 kinematic indicators (Means, 1987; Petit, 1987; Doblas, 1998). The extent to which slickensides represent either brittle or ductile behavior is debatable. Flexural slip is believed to take place under brittle or moderately brittle conditions where mean ductility is low (Donath and Parker, 1964). However, slickensides are believed to be an indicator of inductile slip when the slickenside consist of a ridge-in-groove striation (Means, 1987; Lin and Williams, 1992; Lin et al., 2007). To avoid possible ambiguity arising from the usage of the terms that might imply either brittle or ductile slip, the term, slip surface is preferred because it incorporates all surfaces regardless of the extent of polish or fibrous growth.

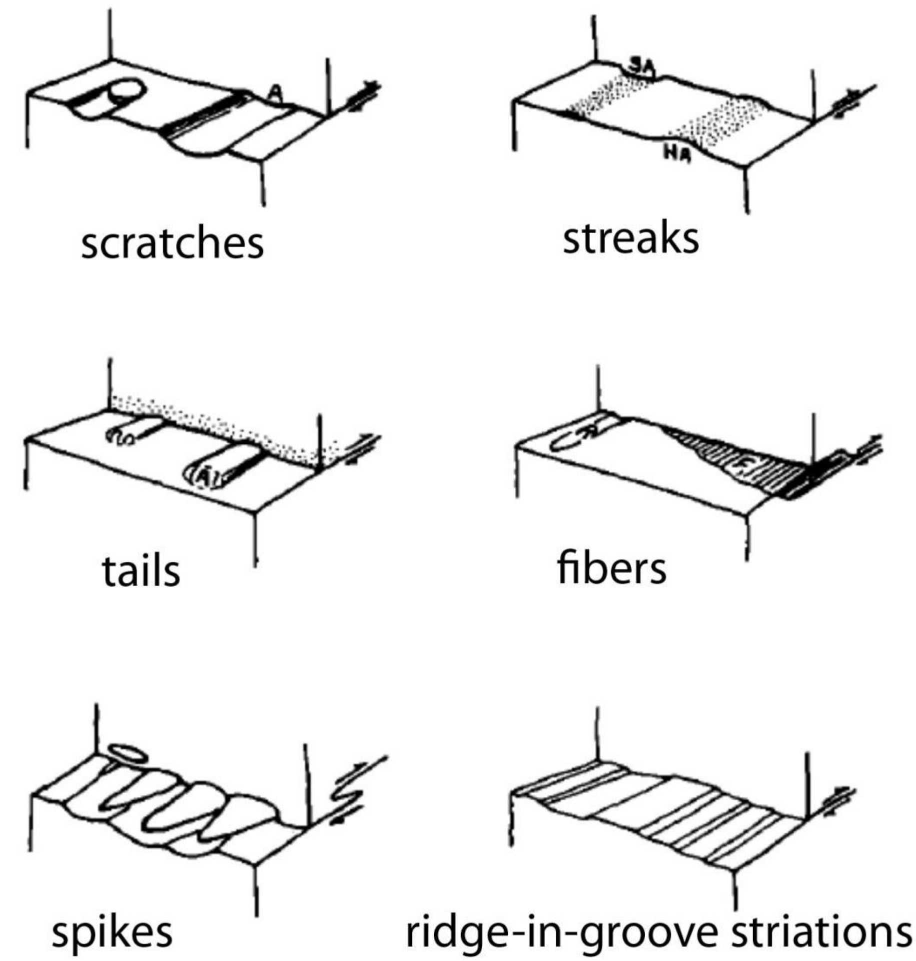


Figure 2. Types of linear structures on slip surfaces (Means, 1987).

1.2 Devonian section of the Appalachian Basin

This paper examines slip surfaces within three formations of the Middle and Upper Devonian section of the Appalachian Basin: The Marcellus, Mahantango and Lock Haven Formations (Figure 3). In Pennsylvania the Hamilton Group is divided into the Marcellus Formation, Mahantango Formation, and the Tully Limestone. The Brallier and Lock Haven Formations are part of the overlying Genesee Group. Although these units straddle 3rd order sequences of the Appalachian Basin, taken as a group these three formations represent coarsening upward sequence. The Marcellus Formation is a black to gray shale that may contain limestone interbeds. The formation is subdivided into two black shale members separated by a limestone (Cooper, 1930). The lowermost member is called the Union Springs Member, which is organic rich black shale. The Purcell Member is a limestone with interbeds of shale and siltstone (Clarke, 1903). The Oatka Creek Member is the upper black shale. The Mahantango Formation consists of gray, brown siltstone and shale and it is conformably overlies the Marcellus Formation. The Tully Limestone and another black shale, the Geneseo/Burket overlie the Mahantango. Above these are the Brallier and Lock Haven, units characterized by distal turbidites.

Flexural slip folding of the Marcellus, Mahantango, and Brallier is Alleghanian in age. A great deal is known about the tectonic overprint of the Alleghanian Orogeny including fracturing (Engelder and Geiser, 1980), folding (Srivastava and Engelder, 1990) layer-

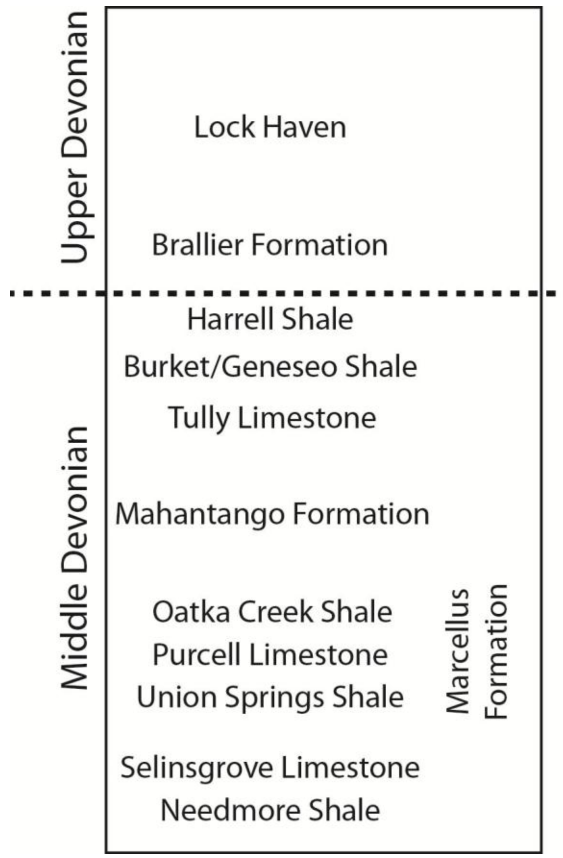


Figure 3. Basic stratigraphic column of the Middle and Upper Devonian section in the Appalachian Basin, PA.

parallel shortening fabrics (Engelder and Engelder, 1977; Engelder and Geiser, 1979) and more.   To date, the study of slip surfaces has been limited to analyses in core of black shale recovered from the Eastern Gas Shale Project (Evans, 1994; 1995).

Black –shale focused décollement was suggested at least indirectly twice in the literature. First, the famous outcrop displaying cleavage duplexes at Selinsgrove Junction are found in the basal portion of the Union Springs Member of the Marcellus (Nickelsen, 1986). Second, the core recovered during the Eastern Gas Shale Project (EGSP) displayed slip surfaces concentrated within the black shale of the Appalachian Basin (Figure 4). In the EGSP study, no distinction was drawn between slip within the cleavage duplexes and isolated bed-parallel slip (Evans, 1994). Bed-parallel slip was incorporated as the D surface and isolated bed-parallel slip. The present paper distinguishes bedding-parallel slip from the slip surfaces of cleavage duplexes that cut the host rock at an angle to bedding.

2. DATA GATHERING

Although examples of flexural-slip folding are found throughout the Valley and Ridge of Pennsylvania, outcrop quality is often subpar, particularly those of both the Mahantango and Marcellus shales. Consequently, core drilling was necessary for collecting samples of pristine slip surfaces. Outcrops of the Lock Haven Formation, a bedded distal turbidite did yield slip surfaces of high enough quality that they were useful for study. In total, flexural -slip folding was documented at six localities in Central PA (Figure 4).

2.1 Outcrops

One example of flexural-slip folding is found in the Lock Haven Formation along Route 15 just north of Williamsport PA. Sandstone beds of a distal turbidite sequence roll through a train of several anticline-syncline pairs. Some of the folds are chevron in character with monoclonal limbs and others have rounded limbs (Figure 5a). Outcrops of the Marcellus are weathered to the extent that only cleavage duplexes are apparent.

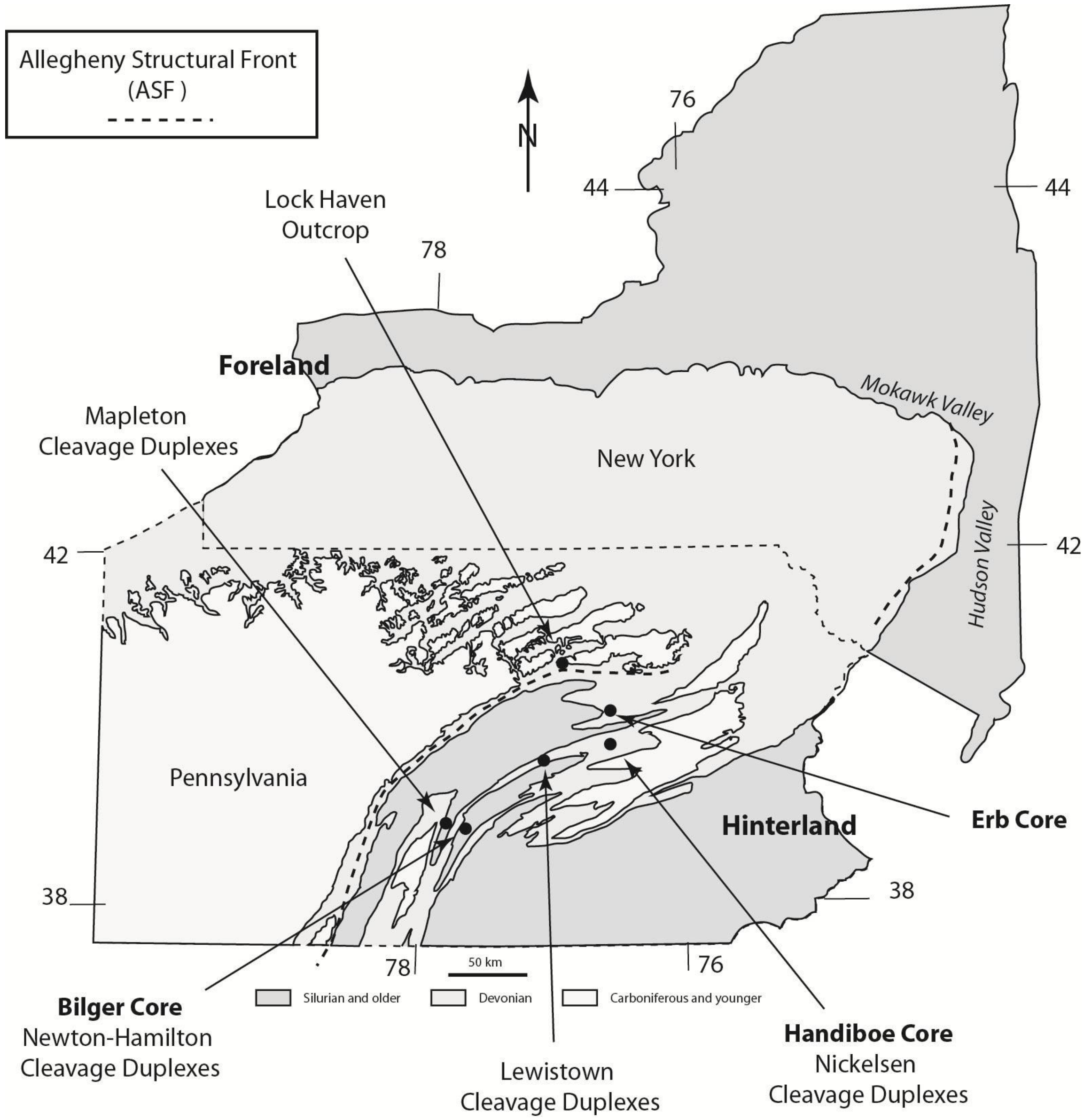


Figure 4. Geological map of the Central Appalachian Mountains showing the sample locations for three Marcellus cores and four Marcellus cleavage duplexes. The Alleghney Structural Front divides the Appalachian Plateau to the NW and the Appalachian Valley and Ridge to the SE. Outcrops of the Marcellus occur near that contact between the Silurian and Devonian rocks within both the Plateau and Valley and Ridge.

2.1.1 Bedding Slip Surfaces in outcrop

The Lock Haven Formation is package of gray to green fine-grained sandstones, siltstone, and shale interlayers. The sands and silts have >10% matrix indicative of a greywacke. Bedding thickness varies from several cm to up to a meter. Bed-parallel slip surfaces occur between coarser-grained beds, often when very little shale fills the bedding interface (Figure 5b). Slip surfaces show different degrees of mineralization and a variety of morphologies from mirror-like smooth to flat fibrous slip surfaces to more irregular surfaces with thick mineralization (Figure 6).

Minerals on the slip surfaces are green (chlorite), and milky white to a brown-gray (quartz). When chlorite builds up on thick fibers of milky-white quartz, the chlorite is a bright olive green. Chlorite on surfaces that are underlain by a greywacke matrix appears to have the color of the matrix largely because the slip surface is thin enough to transmit light on the dark substrate (Figure 6b, c).

2.1.2 Cleavage Duplexes

Cleavage duplexes were observed in four outcrops of the Marcellus Formation where they are most common in the basal portion of the Union Springs Member of the Marcellus (Figure 4). Duplexes can vary from a few cm to over a meter in thickness. These features have the geometry of a shear zone with the 'cleavage planes' tilted

Figure 5. (a) An example of a flexural-slip fold in the Lock Haven Formation along Route 15 north of Williamsport, PA. (b) A slip surface showing ridge-in-groove striations from a flexural –slip fold within the Lock Haven Formation north of Williamsport.

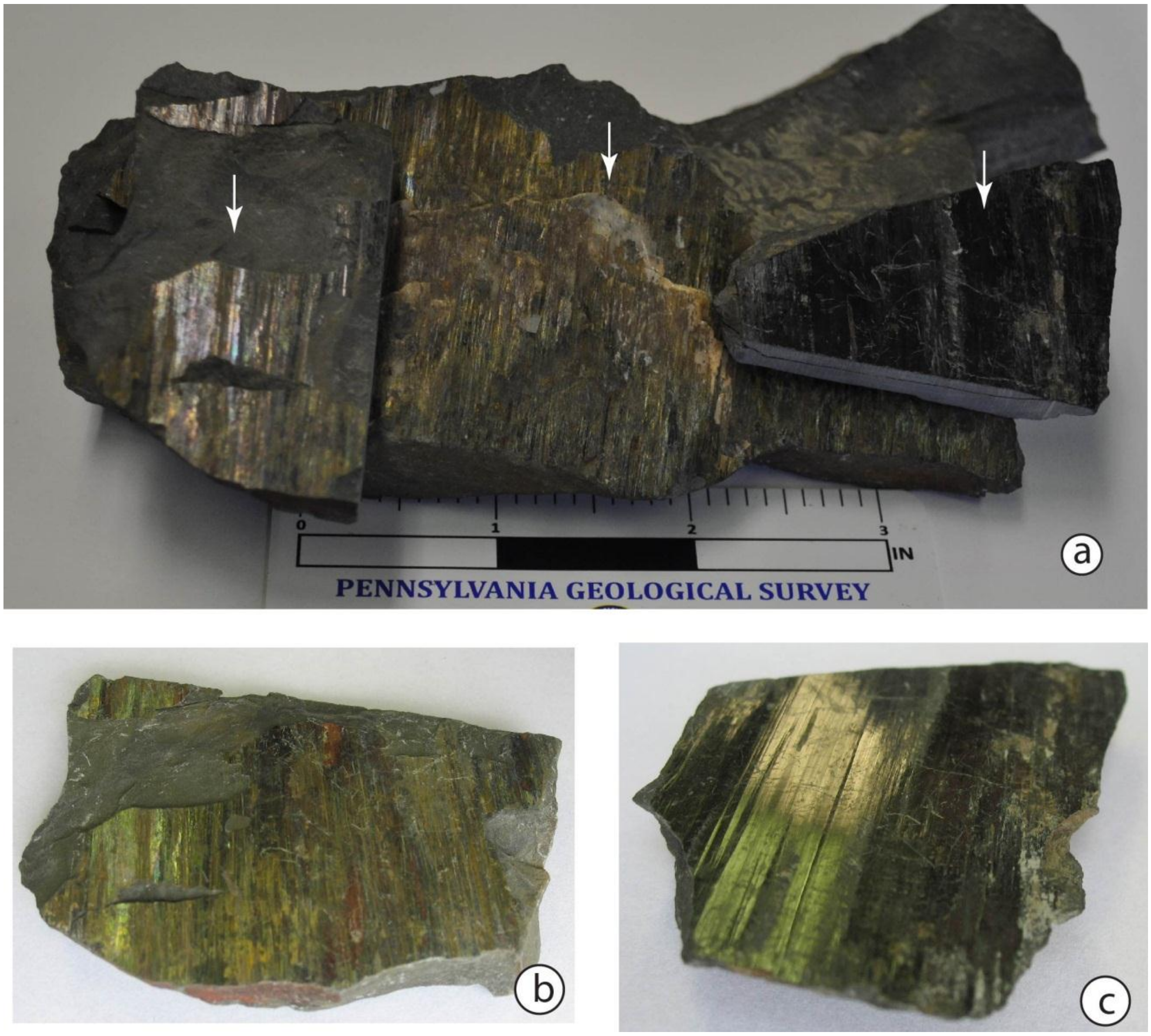


Figure 6. Samples from bedding-parallel slip surfaces in the Lock Haven Formation north of Williamsport, PA. (a) Arrows from left to right show a mirror slip surface, chlorite over quartz on ridge-in-groove striation, and a mirror slip surface that appears black when light is not reflecting from the mirror. (b) Ridge-in-groove striation on bedding slip surface in Lock Haven Formation showing the olive green color of a chlorite film on quartz fibers. (c) Mirror slip surface of a chlorite film on a greywacke matrix. Olive green light reflects off the mirror.

toward the transport direction (Figure 7). Deformation within the duplex completely overprints bedding. The transport direction is generally towards the foreland no matter where the cleavage duplex is found relative to the nearest anticlinal hinge. The duplex-bedding contact is often very sharp and mineralized in a manner that suggests concentrated slip along the duplex-bedding interface. 'Cleavage planes' have a higher reflectivity than the shale matrix, thus resembling a polish, unlike the clay surface of an insoluble residue from an ordinary cleaved rock. This inventory of cleavage duplexes includes those at Selinsgrove Junction (Nickelsen, 1986).

2.2 Cores

Penn State's Appalachian Basin Black Shale Group (ABBSG) funded the sampling of the Marcellus black shale by core drilling where the Marcellus is found in the shallow subsurface. The ABBSG core lab has nearly 2000 meters of core from eight shallow wells. Of these three cores were selected for detailed study from the Bilger, Erb and Hanidboe wells. Each core includes the lower portion of the Mahantango gray shale, the entire Marcellus section, and a portion of the underlying Selinsgrove limestone (Figure 3). Each core was examined for both bedding-parallel slip surfaces and cleavage duplexes. The location of each slip surface and duplex was recorded relative to the top of the Selinsgrove (Onondaga) Limestone which was used as the stratigraphic marker to correlate both outcrops and wells. The morphology and mineralogy of the surfaces

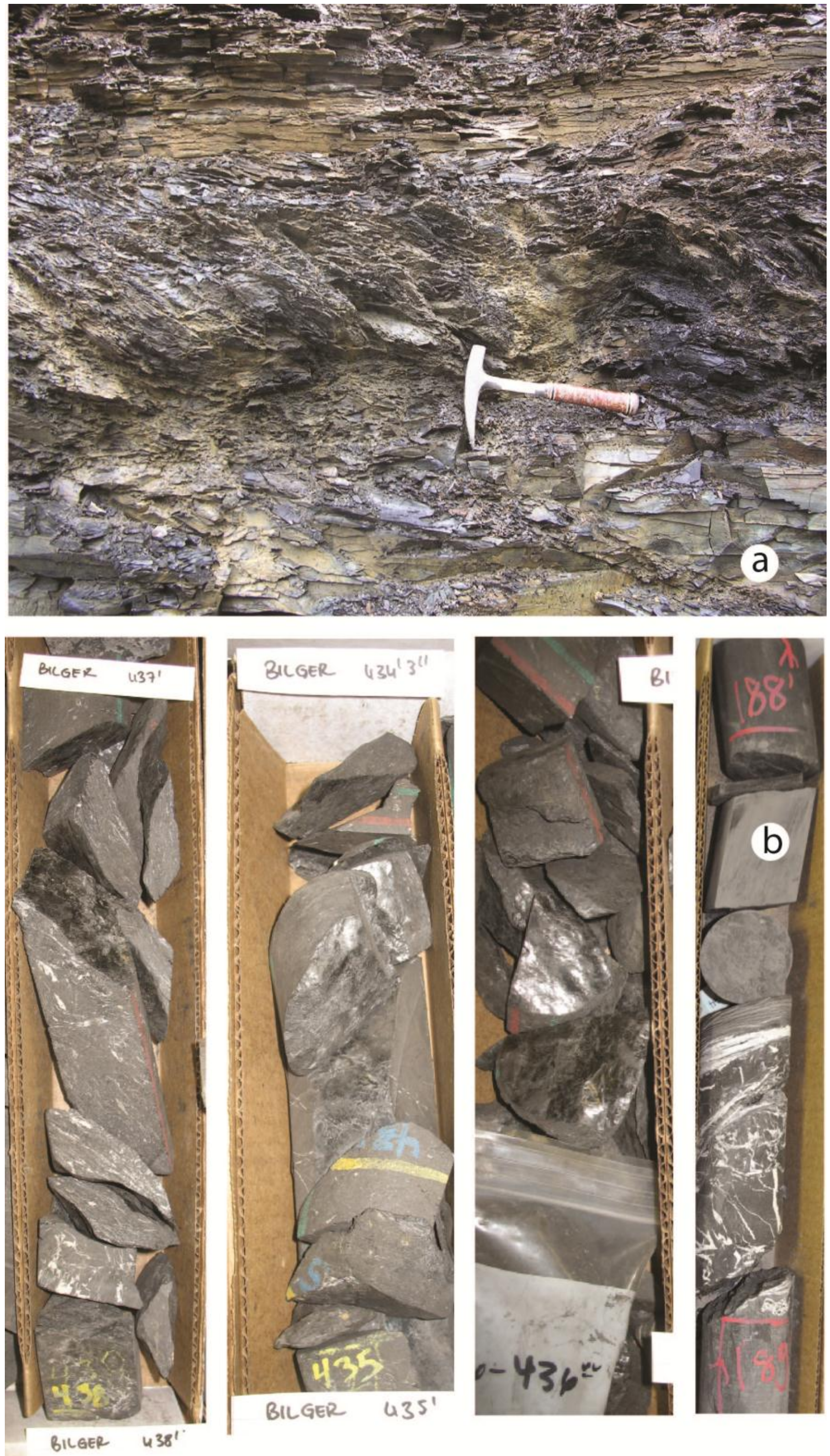


Figure 7. Cleavage duplexes. (a) 53 cm thick cleavage duplex 2 m above the Selinsgrove Limestone in the Marcellus Formation at Newtown Hamilton. (b) Cleavage duplexes in core: Bilger well (left three boxes) 2 m to 6 m (by core) above the Selinsgrove Limestone; Handiboe well (right box) 112 m (by core) above the Selinsgrove Limestone.

were described and the direction of slip relative bedding strike was noted. Samples of the mineral growth along slip surfaces were carefully separated from the matrix for XRD analysis.

2.2.1 Dip versus Slip

One of the most striking features of the bedding slip surfaces is that the lineations record a complex slip history that was neither coaxial with local folding nor consistent in dip direction. On a single bedding surface slip direction can vary as much as 10^{o}. This reflects the complexity of local folding sampled in a single core such as that from the Bilger well where bedding dips range between 19^{o} and 25^{o} in 150 m of core. First order folds in the PA Valley and Ridge appear to have monoclinal panels but within these panels thick shale sections such as the Marcellus-Mahantango deform as drag folds within the limbs of the first order folds.

The general orientation of slip surfaces in the Bilger Core is N69^{o}E, dipping 20^{o}SSE. However, the rake of the slip lineation on surfaces is rarely 90° (Figure 8). In a number of instances slip lineations overprint indicating a range of slip directions up to 10° on a single surface.

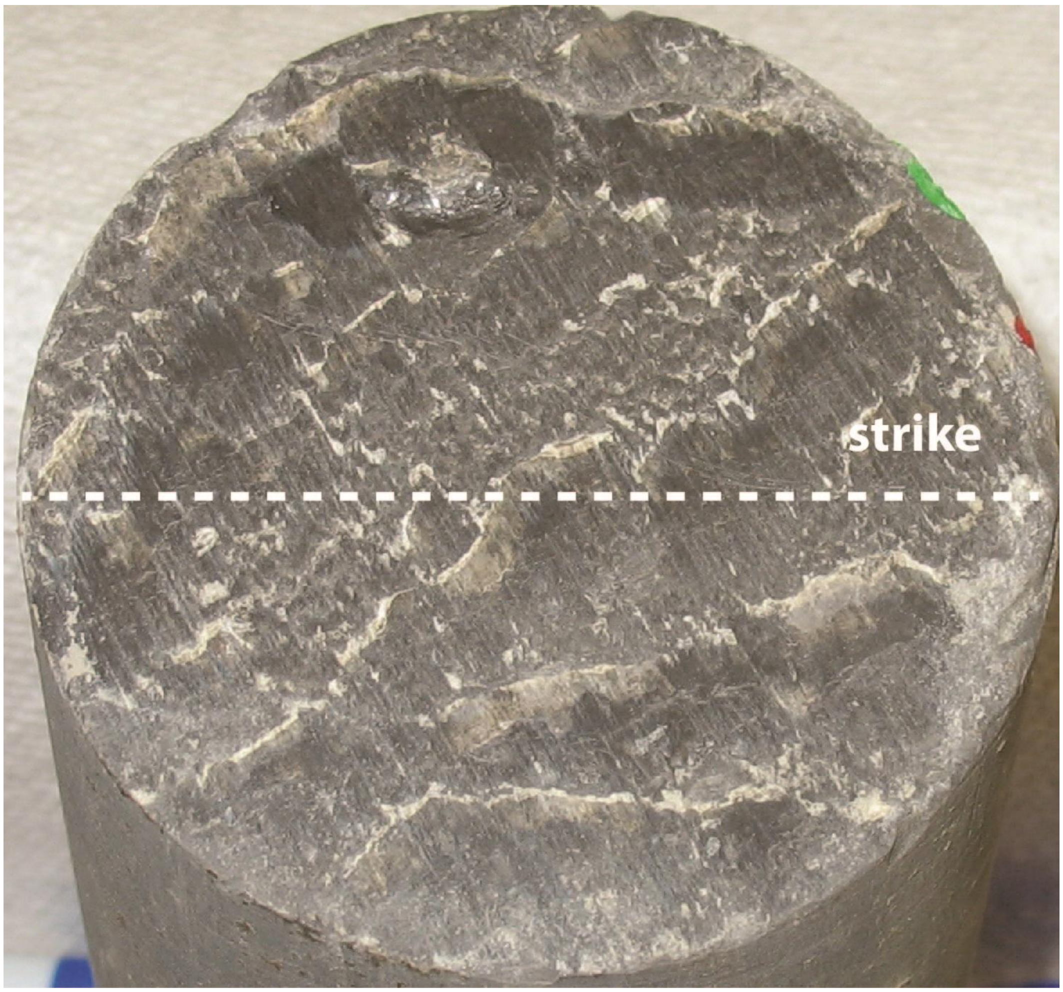


Figure 8. Footwall sample of a slip surface showing fiber growth in the Mahantango Formation 122 m (by core) above the Selinsgrove Formation in the Bilger well. Core is oriented so that bedding strike is E-W and dip direction is toward the bottom of the photo . The angle between slip and dip is 30^{o}.

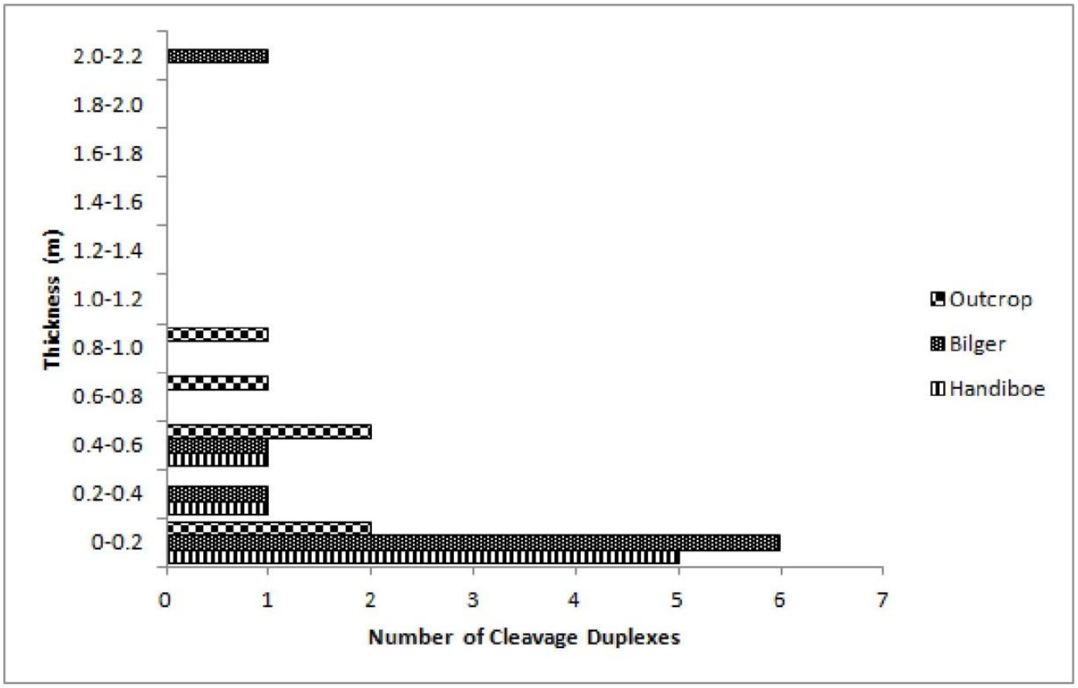
The orientation of slip vector was calculated using the formula below:

$$d=\begin{pmatrix} cos\lambda\; cos\Phi + \; sin\lambda\; cos\delta\; sin\phi \\ -cos\lambda\; sin\phi + sin\lambda\; cos\delta\; cos\phi \\ sin\lambda\; sin\delta \end{pmatrix}$$

where λ is the slip angle, Φ is the strike angle, and δ is the dip angle. In the Bilger core the rake of slip lineations varies a great deal falling in a range between 66° and 90° with the slip lineation distributed on either side of the dip direction.

2.2.2 Distribution of cleavage duplexes

A number of cleavage duplexes were observed in the Bilger and Handiboe cores (Figure 7). Like their counterparts in outcrop, cleavage duplexes in core are most common within the Marcellus and most densely developed within 10 m of the top of the Selinsgrove limestone (Figure 9). The thickest cleavage duplex is found in the Union Springs Member of the Bilger cores. Cleavage duplexes show distinctive structures in the cores. They exhibit many internal slip surfaces that are exposed when the shale is further broken. These internal surfaces are mirror-like but, unlike the mirror surfaces for bedding-parallel slip, the duplex surfaces are quite irregular. A great number of calcite veins cut cleavage duplexes, particularly within 10 m of the Selinsgrove Limestone. In some instances, the calcite filling of cleavage duplexes concentrates along bed-parallel slip surfaces giving the same impression as seen in outcrop that slip evolves from a diffuse zone (i.e., the duplex) to a few thin surfaces of concentrated slip.



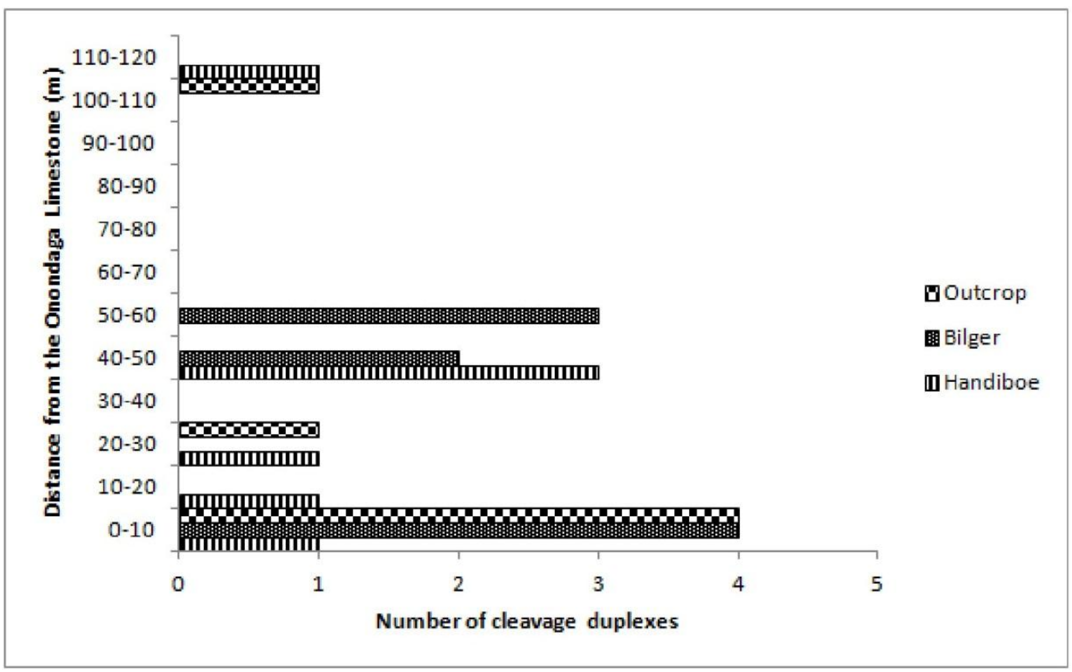


Figure 9. Thickness of cleavage duplexes binned in 20 cm intervals (top) and height of cleavage duplexes binned in 10 m intervals above the Selinsgrove Limestone (bottom).

3. SLIP SURFACES

The extent to which bed-parallel slip surfaces populate the Marcellus black shale and its overlying counterpart, the Mahantango gray shale is striking. Core from three wells contained at least 1260 bed-parallel slip surfaces and this does not count the thousands of slip surfaces concentrated in cleavage duplexes. The presence of slip surfaces in three cores presents an opportunity to document the evolution of slip surfaces through a section of clastic rocks of different grain size and mineralogical composition as well as structural position.

3.1 Distribution

The distribution of slip surfaces varies from one formation to another and within the same formation. One meaningful way to understand development of bed-parallel slip is to count density per unit length of core (Figure 10). Bed-parallel slip is not uniformly developed in any of the three cores. In zones of the Mahantango (Bilger well) shale splits into as many as 72 slip surfaces per m. In the same well (n = 861) two zones in the Marcellus have nearly as many slip surfaces per m. Density of slip surfaces is lower in the Handiboe core (n = 289) and lowest in the Erb core (n = 110).

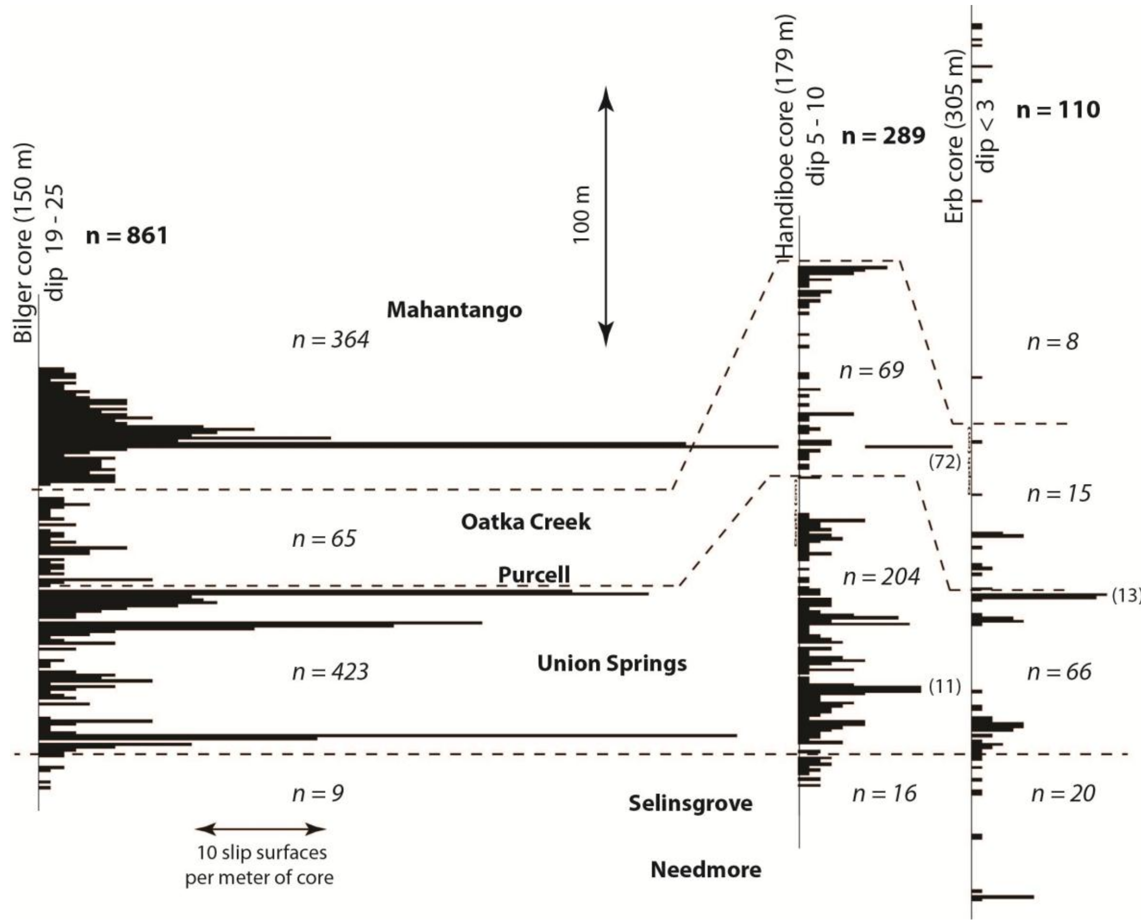


Figure 10. The distribution of slip surfaces within the three ABBSG cores. The data are binned in one meter intervals with the maximum of (72) slip surfaces in one bin in the Bilger core. Bedding dip varies in all three wells to such an extent that correction for true bed thickness was not attempted. The result is that the cored interval in the Bilger well is less than 10% thicker than it really is. The horizontal datum is set at the Selinsgrove-Marcellus contact (dashed line). The Marcellus Mahantango contact indicated by second dashed line.

Slip surface development is striking at two positions within the Marcellus core (Figure 10). First, the bottom 10-20 meters of the Union Springs Member in all three cores carries a well-developed set of slip surfaces. Of course, the absolute number of slip surfaces scales with the sum of the slip surfaces in a particular core. Second, the Union Springs Member just below the Purcell Limstone as a well-developed set of slip surfaces in both the Bilger and Erb cores. Third, most of the Oatka Creek Member in all three cores carries fewer slip surfaces than its mate below, the Union Springs Member. Fourth, the Mahantango in the Bilger core carries a large number of slip surfaces whereas the Erb core has very few.

3.1.1. Structural Position

The number of slip surfaces in the Marcellus correlates with bed dip: Bilger (dip 19° – 25° v. n = 488); Handiboe (dip 5° – 10° v. n = 273); Erb (dip < 3° v. n = 81) (Figure 10). The same can be said for the Union Springs Member: Bilger (dip 19° – 25° v. n = 423); Handiboe (dip 5° – 10° v. n = 204); Erb (dip < 3° v. n = 66). While Mahantango is missing from the Handiboe core, the number of slip surfaces in the other two core is the same as for the Marcellus: : Bilger (dip 19° – 25° v. n = 264); Erb (dip < 3° v. n = 8).

3.1.2 Organic Content

Industry uses the gamma ray count as an approximate measure of organic content in various rocks. In the three ABBSG wells, gray shale has a gamma ray API value between 150 and 180 (Figure 11). Limestone is indicated by an API value < 100 and black shale is indicated by an APR value > 180. The Union Springs Member in the Handiboe and Erb wells is clearly a black shale with the basal portion having a maximum API value approaching 500. The maximum API in the three ABBSG wells is close to 600 in the Bilger well.

The development of slip surfaces best correlates with the organic content of the black shale in the Erb and Handiboe wells (Figure 11). The density of slip surfaces is so much higher in the Bilger well that there is no clear correlation between organic content and slip surfaces.

3.2 Morphology

The distribution of slip surfaces with both organic content and structural position suggests that there may be a difference in the surface morphology within and among the ABBSG cores. Morphology was examined on the mm to cm scale by direct observation. The morphology was then examined on a much finer scale using reflected light and scanning electron microscopy.

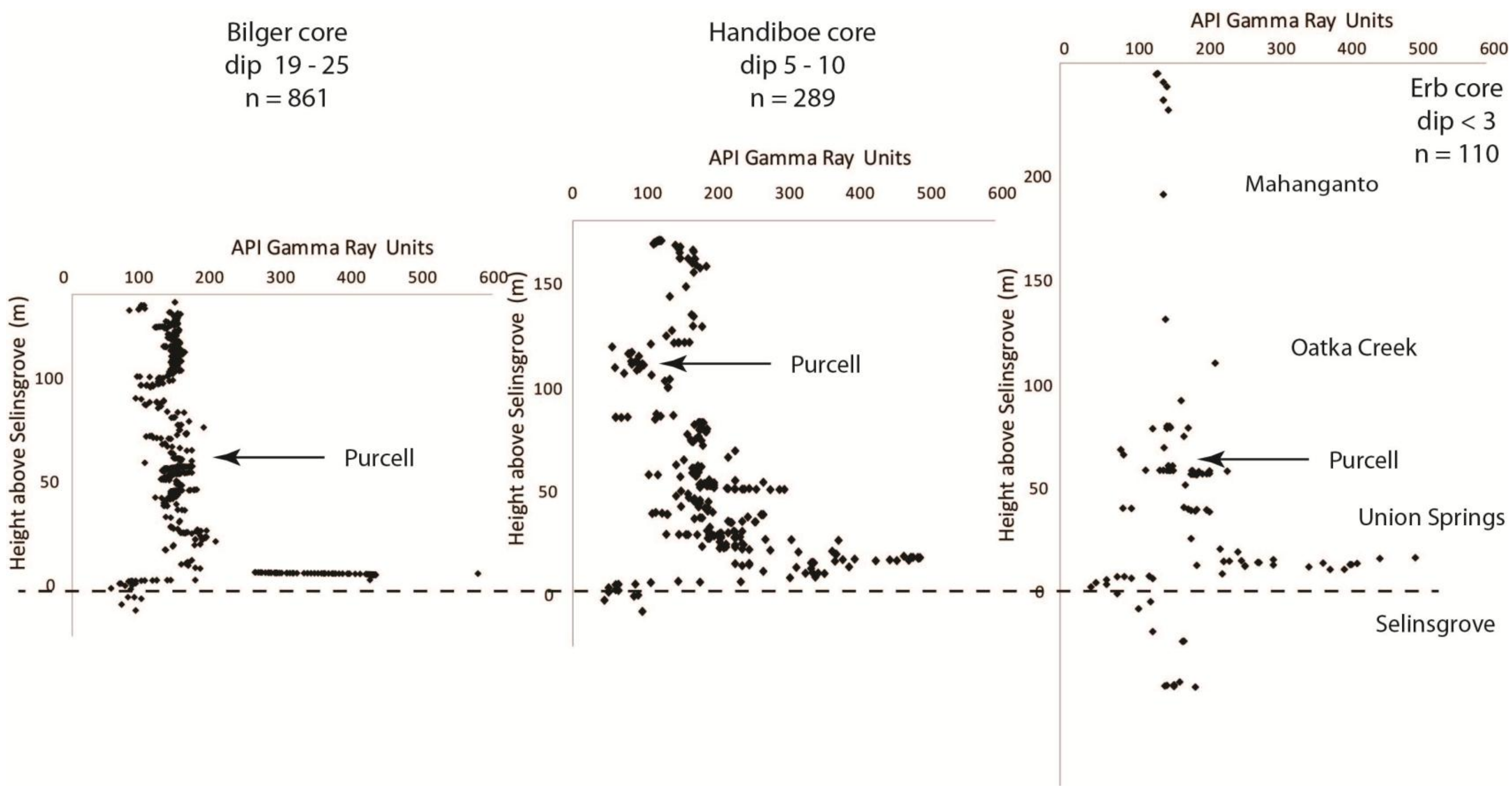


Figure 11. API gamma ray units for rock matrix on which each slip surface sits. Note that one datum in the Bilger well approaches 600 API units. Number of slip surfaces in each well is indicated by n. Like Figure 13, the height above the Selinsgrove is a vertical distance in a well bore. The horizontal datum is set at the Selinsgrove-Marcellus contact (dashed line).

3.2.1 Direct Observation

Slip surfaces the Marcellus-Mahantango vary from mirror planes to slightly irregular surfaces carrying either fibers or ridge-in-groove striations (Figure 12). Fibers develop by growth of elongate crystals parallel to the displacement direction (Figure 8). Often ridge-in-groove striations overprint the fiber growth. Asperity ploughing ,the result of a protuberance moving with one side of a pair of shearing surfaces while being plucked from the other side (Figure 12b). Fibers commonly step with risers facing the slip direction of the opposite wall of the slickenside. Ridge-in-groove striations step at right angles to the slip direction. As a general observation, mirror smooth surfaces were more common in the Mahantango section. Also, fiber growth with irregular steps is more common in the Mahantango-Oatka Creek section of the ABBSG cores (Figure 12a, b) whereas the ridge-in-groove striations on slip surfaces are more common in the Union Springs-Selinsgrove section of the ABBSG core (Figure 12c, d).

The most common minerals on slip surfaces are chlorite, quartz, pyrite, and calcite. Although, when it is not easy to determine the difference between the fibrous calcite and quartz, the dilute hydrochloric acid test was applied on slip surfaces (Figure 13a,b,c,d). As a general observation, calcite was rare in the Mahantango section and very common in the Union Springs-Selinsgrove section. The mirror surfaces were often a thin coat of chlorite sitting on a dark matrix. Pyrite was commonly entrained in the chlorite. Pyrite was also common in the quartz fibers well up into the Mahantango

Figure 12. The morphology of slip surfaces in the Mahantango-Marcellus section ranging from fibers (a and b) to ridge-in-groove striations (c and d).

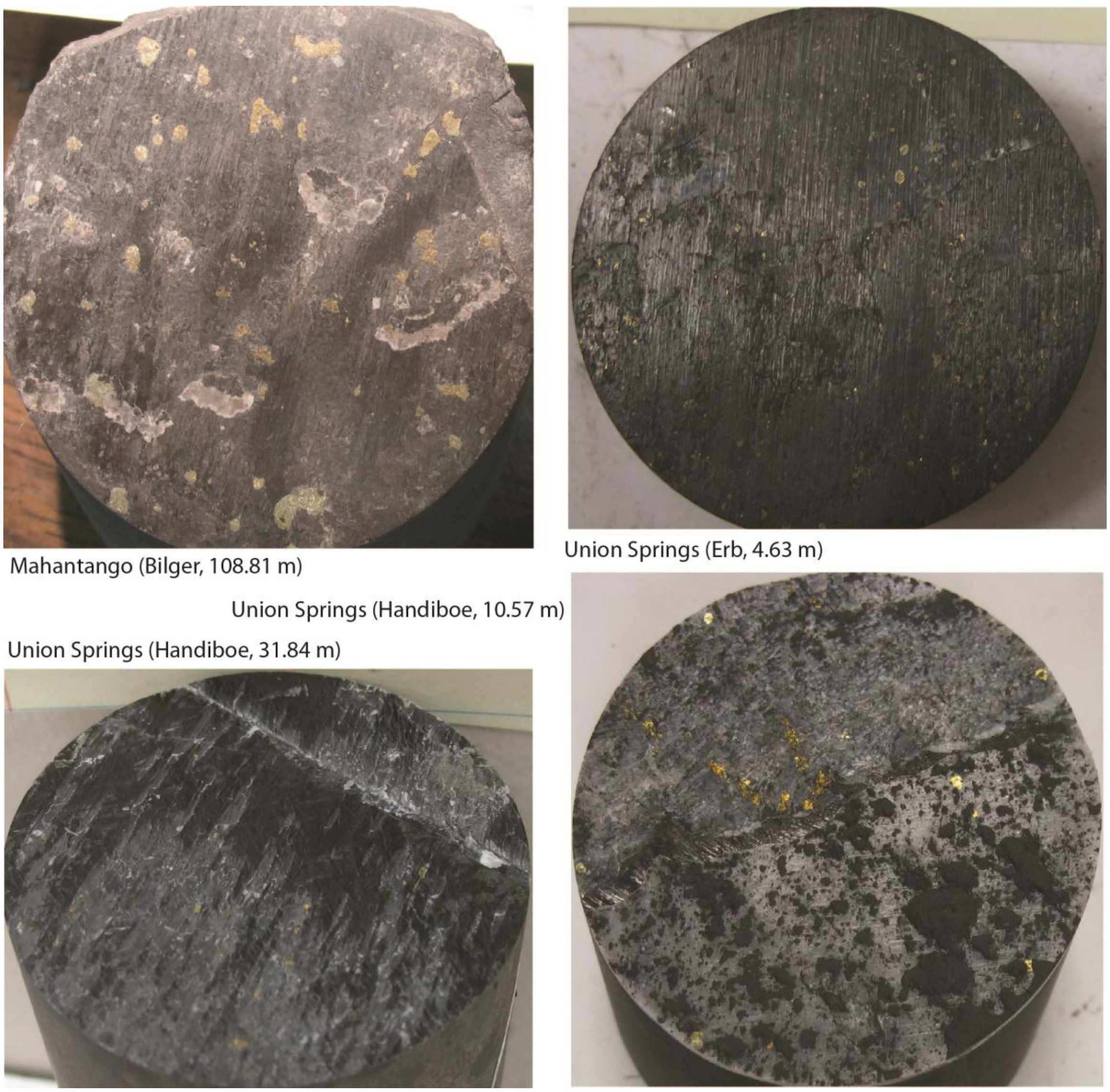


Figure 13. Progressive mineral development on slip surfaces. (a) Pyrite and quartz entrained in fibers. (b) Pyrite entrained in a ridge-in-grove striations of chlorite. (c) Calcite and chlorite entrained in a mirror surface. (d) A matrix breccia entrained in calcite fibers.

section. The best-developed ridge-in-groove striations are found in calcite which was much more common the Union Springs-Selinsgrove section.

3.2.2 Microscopy

A reflected-light and scanning electron microscopes were used for a closer look at the minerals and the surface morphology (Figure 14).   Even mirror surfaces have a rich texture when the scale of the picture is decreased from reflected light to SEM.   Pyrite and calcite are particularly interesting when viewed up close because they both carry microscopic ridge-in-groove striations.   Pyrite appears to clump on the sliding surface without the crystal faces characteristic of framboidal pyrite or other pyrite growing from solution (Figure 14a, b, c). Edges of the pyrite clumps appear to mate to the underlying matrix much like a bead of solder. The ridge-in-groove striations indicate intimate contact with an opposite slip surface.   Fibers of calcite display multiple thin layers of mineral coating that build up on an otherwise polished slip surface.   Even at the finest scale calcite accumulates as true fibers in comparison to pyrite which does not appear to be layered.

3.3 Progressive Mineralization

Slip surfaces that appear to be polished to a mirror plane are of particular interest because they have received little attention in the literature on slickensides.

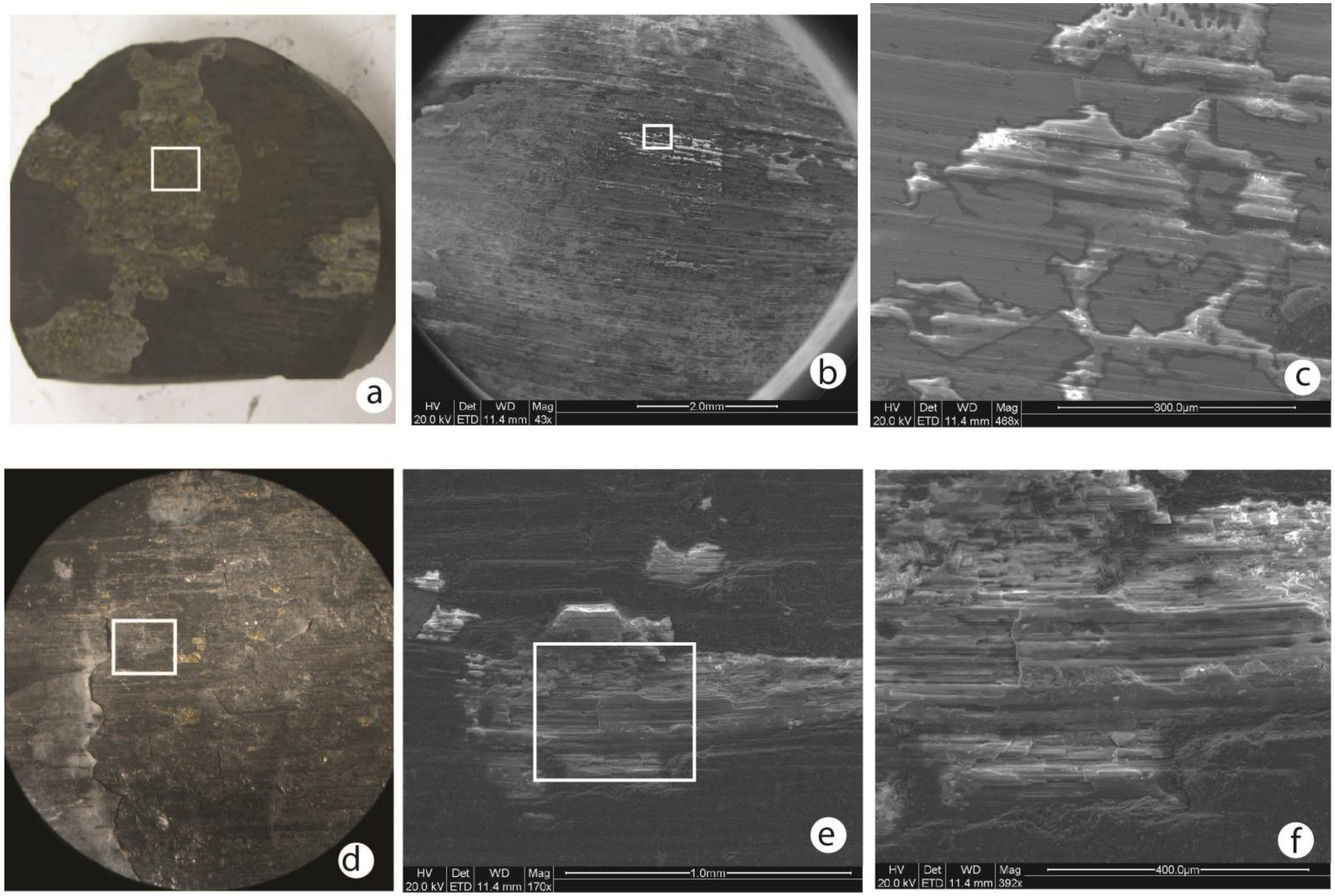


Figure 14. Slip lineations at different scales. (a) Ridge-in-groove striation on Marcellus 7 m above the Selinsgrove Limestone in the Erb well. (b) Pyrite lineation in the form of ridge-in-groove striation. (c) Pyrite with a positive relief while still carrying ridge-in-groove striations. (d) Fibers of calcite on Marcellus 5 m above the Selinsgrove Limestone in the Erb well. (e) Fibers of calcite. (f) Layering of calcite fibers with ridge-in-groove striations.

To understand these surfaces, the mineralogy (using XRD) of the mirror was measured for comparison to the matrix substrate to which the mirror film was attached. These results were then compared with the mineralogy of the classic fiber growth and ridge-in-groove striations.

Scintag 2 was used for XRD measurements. The source was a Cu-α normal focus glass tube and the scintillation counter was a Ge solid state detector, liquid N_2 cooled. The goniometer was a vertical sample mount with powder held in place by Van der Wals forces. Diffraction peaks were identified using a JADE 8.2 software package by MDI, Inc.

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3.3.1 Calibration

An adequate quantitative measure of the mineral components along slip surfaces requires calibration of XRD detector using minerals of interest. Of particular interest were the peak intensities of three minerals: quartz, calcite, and chlorite. Each mineral shows a different pattern in terms of two-theta and intensity. Muscovite was used as a proxy for chlorite. The calibration took several steps.

In this study, calibration has been made for quartz, calcite, muscovite and different ratios between them. Samples were run several times by reloading the goniometer mount to define range of intensities simply due to the loading process. The precision of this technique was surprisingly poor in terms of intensity for reasons that were not clear (Figure 15).

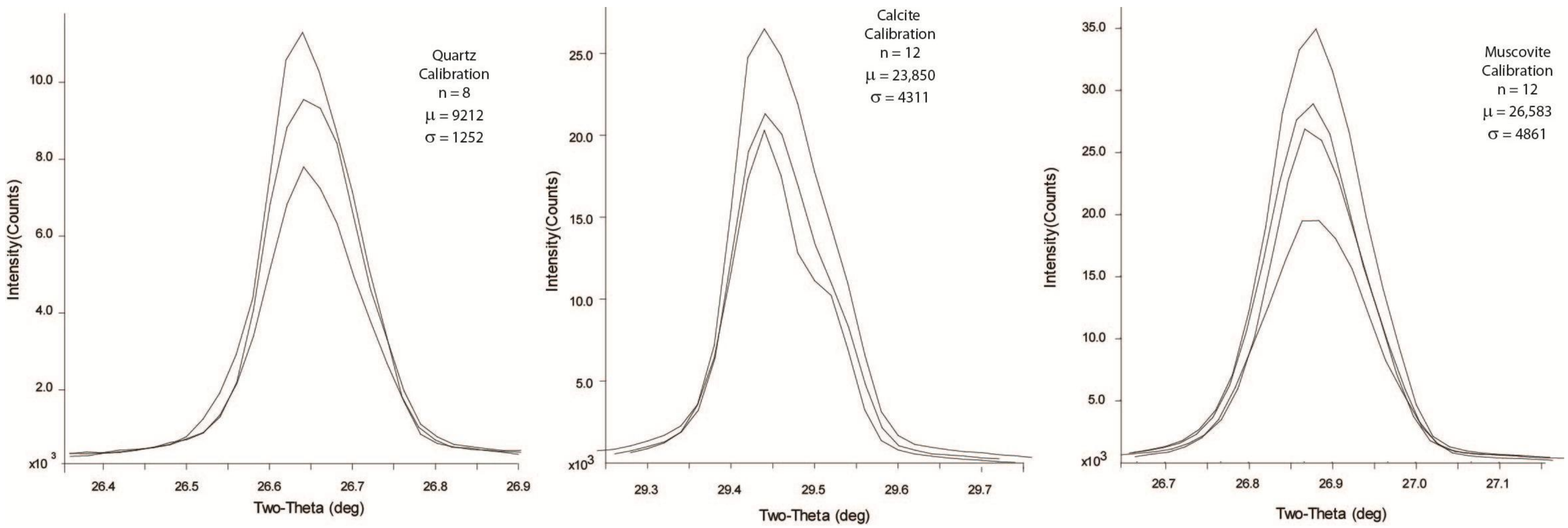


Figure 15. XRD calibration of quartz, calcite, and muscovite. Each example shows three of eight to twelve individual traverses through the most intense peak for each mineral.

The mean intensity counts that were measured for quartz (9212), calcite (23850), and muscovite (26583) (Figure 15). Two-theta angles of quartz and muscovite are close to each other. Therefore, experiments were run in a narrow interval using 3:1 weight ratio experiments of quartz/muscovite (Figure 16a). Again, reloading powder into the goniometer mount gave a range of intensities relative to a calculated reduction in intensity based on a 3:1 ratio of pure end-member minerals. This was done to understand the reliability of peak intensities when it came to quantitative measures of volume of natural samples. Experiments of the 1:1 weight mixture of calcite and muscovite show the variety of different intensities as well (Figure 16b).

3.3.2 Flexural slip in the Lock Haven Formation

Slip surface samples of Lock Haven Formation were collected from Williamsport, Pennsylvania. Two samples of slip surfaces and matrixes were powdered for mineral analysis. XRD results from slip surface and its corresponded matrix show that chlorite, quartz and illite are present. However, the abundance of these minerals is different on slip surface and matrix. During slip chlorite intensity is concentrated on the surfaces relative to quartz and illite (Figure 17).

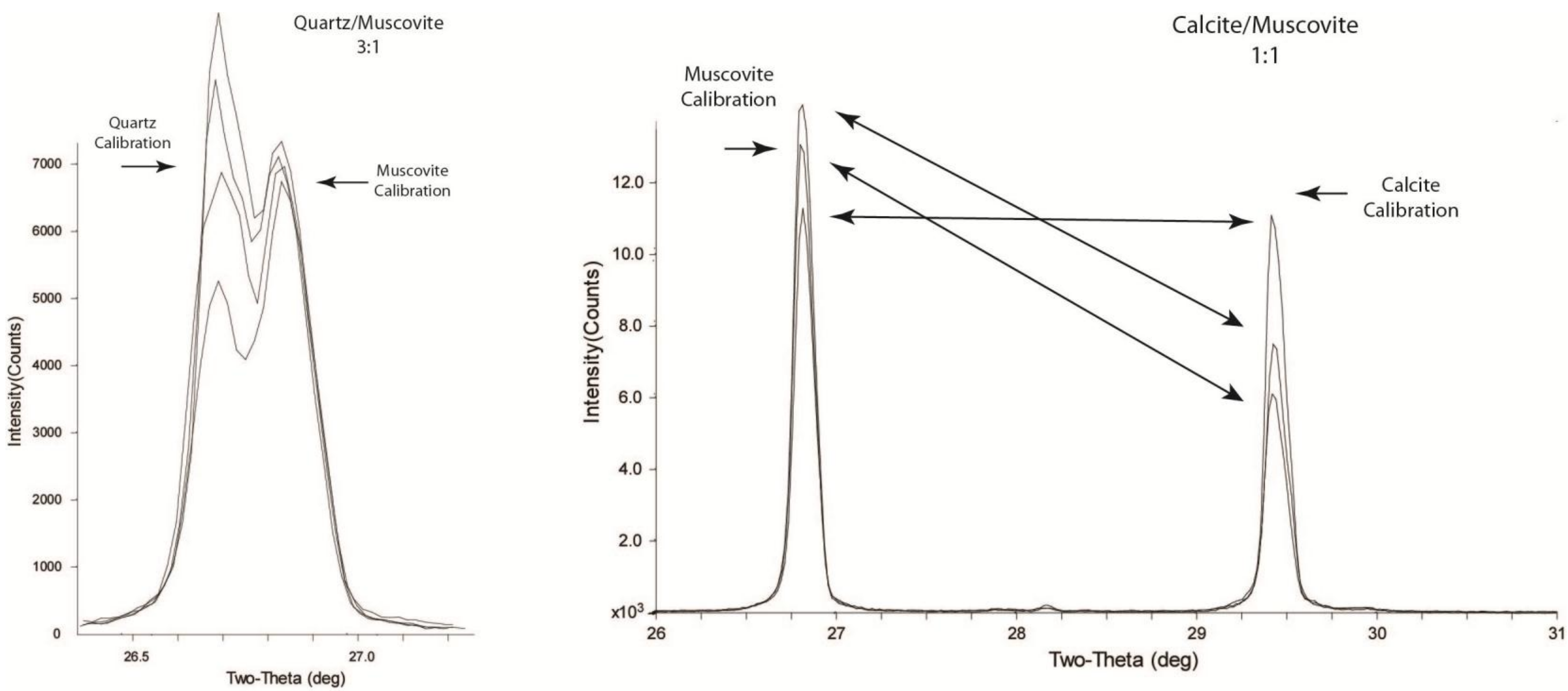


Figure 16. XRD runs for mixtures of minerals by volume: 3:1 for quartz to muscovite and 1:1 for calcite to muscovite. The sample was prepared anew for each run.

3.3.3 Flexural slip in the Mahantango Formation

Mineral analysis of the Mahantango Formation comes from the Bilger core, 96.18 m above the Onondaga Limestone. XRD patterns show that quartz, chlorite, ankerite, illite, and pyrite are present both on surfaces and matrix. Re-runs of the powdered samples show similar intensities (Figure 18a). Quartz is rich in the matrix compare to slip surface. The same concentration of chlorite is present on slip surfaces as was seen on slip surfaces in the Lock Haven Formation (Figure 18b).

3.3.4 Flexural slip in the Marcellus Formation

Calcite filling along slip surfaces in the Marcellus Formation is a common phenomenon compared with slip surfaces of chlorite and quartz in the Lock Haven and Mahantango Formations. Cleavage duplexes at the base of the Union Springs contain calcite veins with a stockwork around fragments of the black shale (Figure 19a). A traverse of samples through this cleavage duplex 2 – 6 m above the Selinsgrove suggests that quartz and calcite occupy approximately 33% of the volume of the Union Springs at this depth. Volume composition logs are consistent with this assessment with mica (chlorite and Illite) filling about 33% of the volume of the rock and organic matter and pore space taking up about 33% of the rock. The exchange of calcite for quartz follows a calibration in for a mixture of pure quartz and calcite except the natural Qtz-Cal line indicates that these minerals occupy about 33% of the volume of the natural rock.

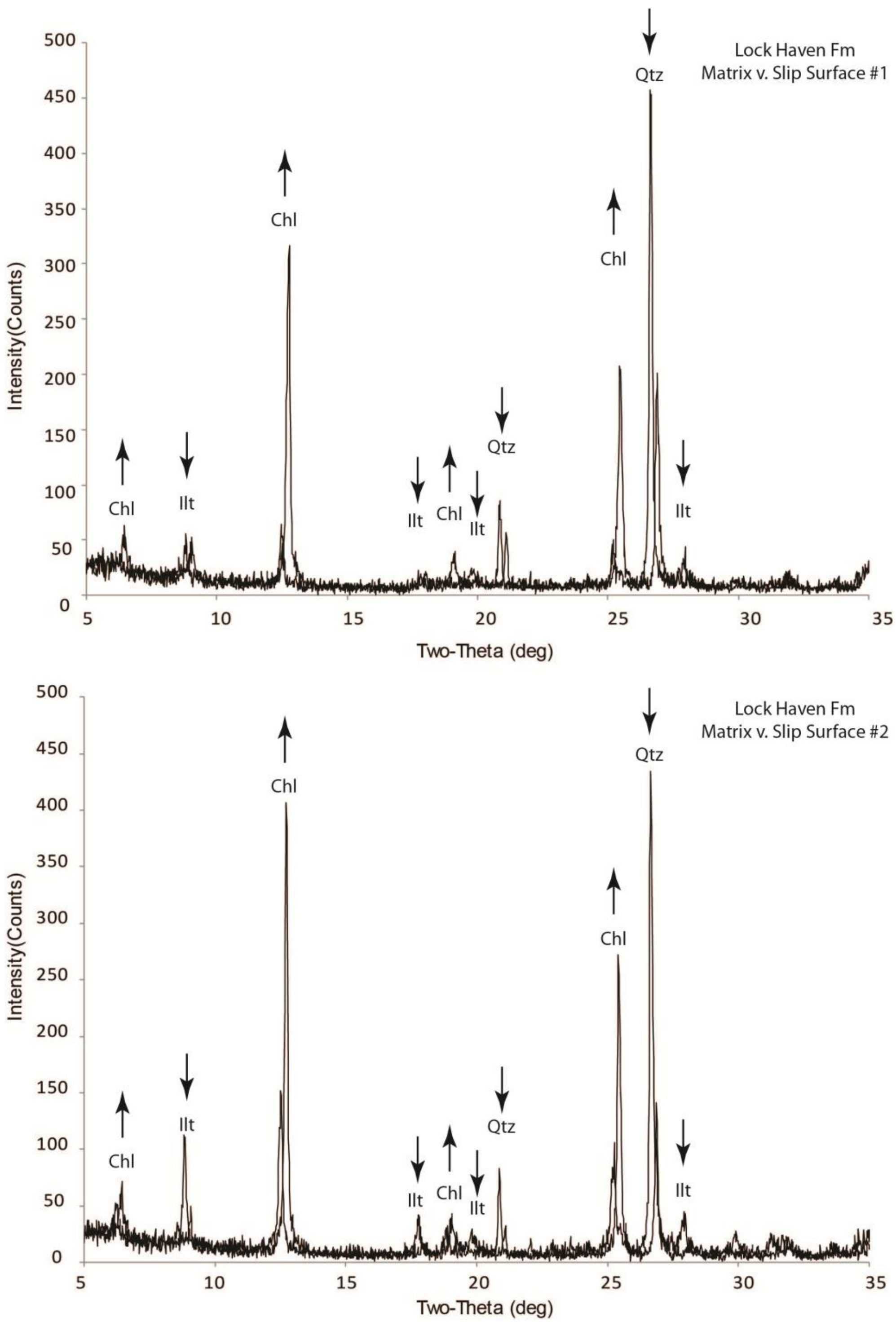
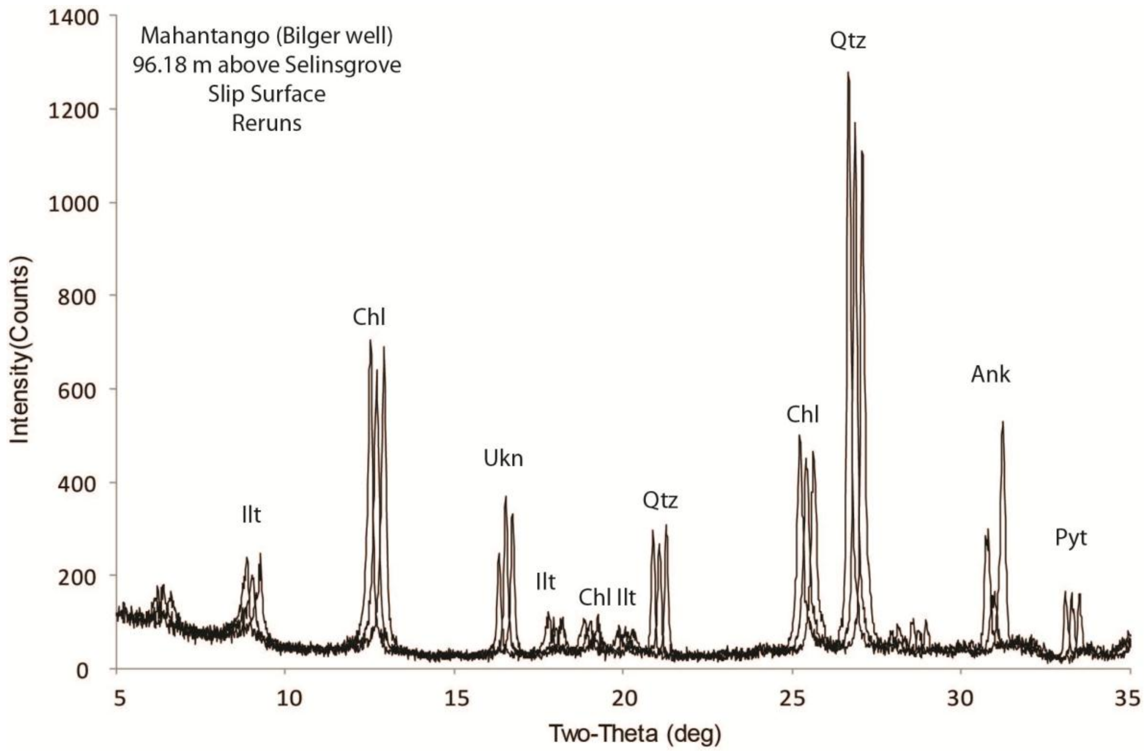


Figure 17. XRD diffraction patterns from two slip surfaces in the Lock Haven Formation, Williamsport, PA. In each diagram the slip surface pattern is displaced to the right by 0.2° to allow for better comparison of the patterns. Arrows show which minerals increase and which decrease from the matrix to the slip surface. Qtz – quartz; Ilt – illite; Chl – chlorite.



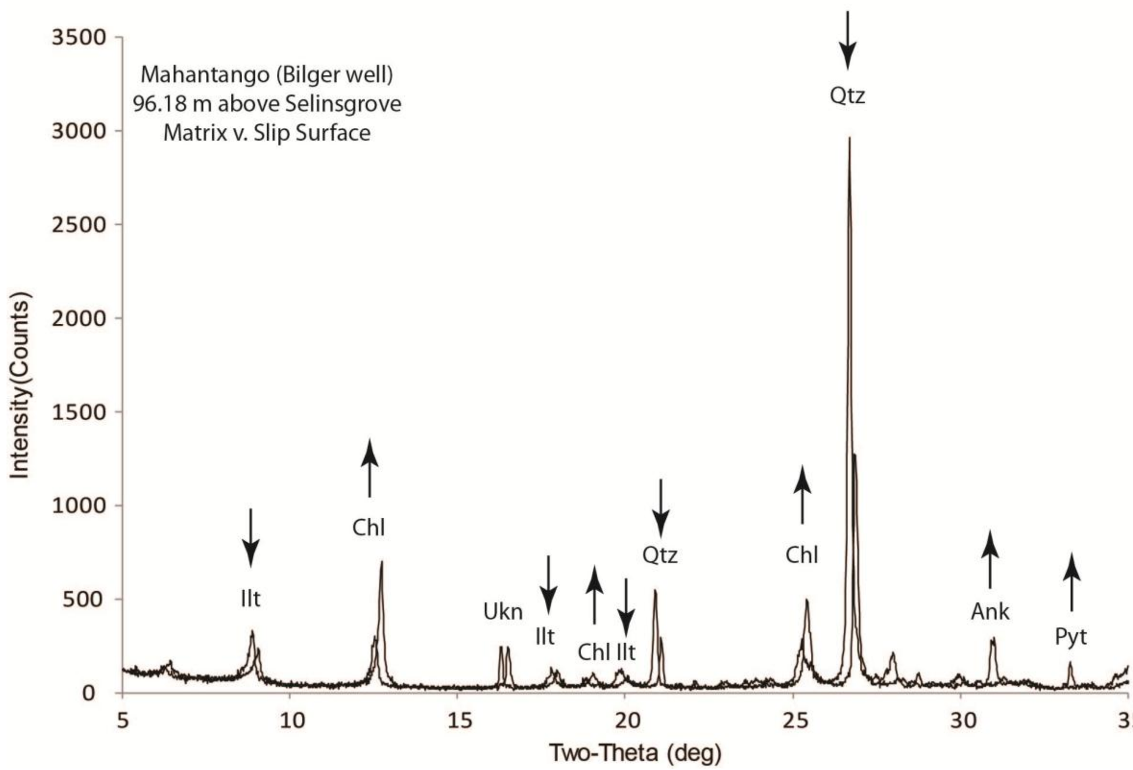


Figure 18. XRD diffraction patterns from the Mahantango Formation, Bilger well. (a) three different runs of the same powdered slip surface. (b) slip surface compared with matrix. Arrows show which minerals increase and which decrease from the matrix to the slip surface. Qtz – quartz; Ilt – illite; Chl – chlorite; Ank – Ankerite; Pyt – Pyrite; Unk – Unknown.

The core box shown in Figure 19 (a) demonstrates the organic rich part (based on the gamma ray values in Figure 19 (b)) of the Marcellus Formation. The thickest cleavage duplex is located in this part of the section. Additionally, calcite fillings in veins and in the cleavage duplex can be seen in Figure 20 (a). The mineral composition log (Figure 20 (b)) shows that quartz has the more than 40% volume in the section.

Since quartz is the significant mineral for the matrix and calcite is significant for the fracture surfaces, quartz-calcite calibration was necessary to be able make a correct comparison. XRD analyses of different amounts of quartz- calcite samples linear calibration line (Figure 19c). The Qtz-Cal mixture of both the cleavage duplex and the calibration line are parallel which suggests that calcite and quartz occur in the rock in about the same ratio. The calcite is preserved in the matrix as very thin slip surfaces of the cleavage duplex. Slip surface mineral line follows the same trend with the calibration cure with lower intensities.

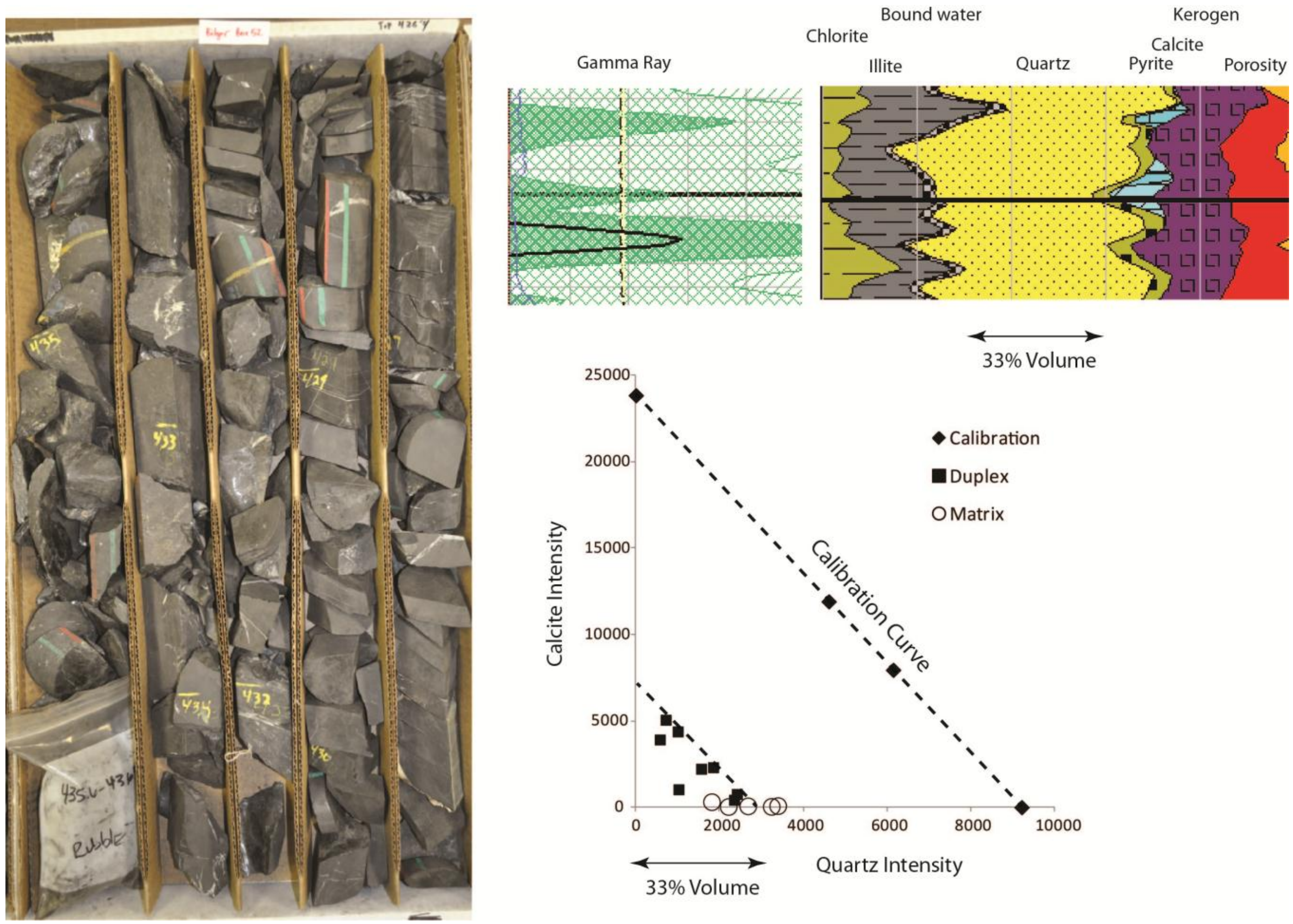


Figure 19. (a) A box Marcellus core (1 m to 4 m above the Selinsgrove) from the Bilger well showing part of a cleavage duplex (left three slots) and other slip surfaces (right two slots). (b) XRD analyses for eight slip surfaces through a cleavage duplex within the Marcellus between 2 m and 6 m above the Selinsgrove. Data are plotted as a ratio of quartz to calcite along with a calibration curve for mixtures of pure quartz and calcite. (c) a gamma ray (0 – 150 API) and a volume % composition log from a Marcellus well.

4. DISCUSSION

This paper has two objectives. First was a test of the hypothesis that both bedding-parallel slip and larger-scale detachment in black shales were manifestations of the reduction in effective stress during the buildup of maturation-related pore pressure. While a complete test is not possible because maturation took place long ago, a concentration of bedding-parallel slip and larger-scale detachment in black shale is an affirmation of the hypothesis. The second objective was to study slickensides, particularly those with a mirror polish, in hopes of finding clues about the evolution of these surfaces which have not been well documented in the literature.

4.1 Pore pressure generation in black shale

Abnormal pore pressure comes about in the Earth by a number of mechanisms roughly divided into three types of processes including increases in compressive stress (e.g., compaction disequilibrium), changes in volume of fluid (e.g., thermal maturation of kerogen), and fluid movement or buoyancy (e.g., pressure at the top of a gas column) (Osbourne and Swarbrick, 1997). The Marcellus is presently overpressured in the northern half of the Appalachian Basin where operators in Lycoming Cty, PA, report pressure above 90% of the vertical stress. While the mechanism leading to this high pressure is not clear, one of the most likely possibilities is generation during thermal maturation in a rock that has very low matrix permeability. Evidence of paleo-overpressure is preserved within fluid inclusions of veins cutting the Marcellus (Evans, 1994; 1995). Natural hydraulic fractures are also concentrated within the black shales, another manifestation of high fluid pressures at some point in the burial history of the Marcellus (Lacazette and Engelder, 1992; McConauaghy and Engelder, 1999; Lash and Engelder, 2007; Engelder et al., 2009).

The concentration of both slickensides and cleavage duplexes in the lower, most organic rich portion of the Union Springs Member is striking (Figures 9, 10). In general, the Union Springs Member is more organic rich, an indication that maturation-related pressure generation is more effective in this portion of the Marcellus relative to the overlying Oatka Creek (Figure 11). At least in the Erb well, the Marcellus black shale is slickenside rich relative to the Mahantango gray shale, again pointing toward a connection with maturation-related pore pressure generation. The association between bedding-parallel slip and black shale is consistent with the notion that slip is favored under lower effective stress, a condition found in the Marcellus black shale to this day. The high trapping pressure of fluid inclusions in slickenside fibers on bedding-parallel slip surfaces in black shale of the Appalachian Plateau is further evidence of the presence of low effective stress during slip (Evans, 1995).

4.2 Transport direction of the cleavage duplexes – a larger scale detachment predating folding

Appalachian Valley and Ridge tectonics is characterized by two mechanical packages, the underlying, stiff Cambrian-Ordovician carbonate section and the overlying ductile Silurian through Carboniferous clastic section (Hatcher et al., 1989). Major detachment surfaces defining these packages include a basal detachment in the Cambrian Waynesboro shale and a roof thrust detachment in the Ordovician Reedsville/Utica Shale. Appalachian Plateau tectonics is defined by a single detachment within the Silurian Salina salts (Davis and Engelder, 1985). Other detachment horizons are recognized within shales of the clastic section including one at the base of the Hamilton Group which is within the Marcellus (Hatcher et al, 1989; Scanlin and Engelder, 2003).

Experiments on the evolution of fault zones indicate the slip evolves through a series of steps from a broad zone to surface of concentrated slip (Engelder, et al., 1975). Field observations confirm this process of the gradual concentration of slip from a zone to a single surface (Abroleya and Engelder, 1995). Cleavage duplexes within the Marcellus follow the same rule with slip starting across a zone of distributed shear and then narrowing into a concentrated slip surface usually at the contact between the duplex and the country rock.

While the mechanism for development of cleavage duplexes is uncertain, several observations are important. First, they are concentrated within the richest layers of the Union Springs Member (Figure 9). Second, cleavage duplexes resemble the classic shear zone as expressed in an s-c mylonite with the tip of the acute angle defined by s-c structure pointing in the direction of the transport. Third, with very few exceptions the direction of transport indicated by cleavage duplexes in the Marcellus is toward the foreland thus indicating the NNW motion of the hanging wall regardless of the dip direction of the local fold limb. This indicates that duplexes are not a manifestation of local folding and may have developed before fold amplification. Fourth, some of the larger duplexes develop a thin zone of concentrated slip at the contact between duplex and country rock, a step toward a more regional detachment.

Cleavage duplexes resemble the scaly fabrics found in the imbricate fan which typically develops at the toes of an accretionary prisms (Fisher, 1996). The scaly fabrics consists of an anastomosing web-like array of polished, striated surfaces (Moore et al., 1986). The difference between cleavage duplexes in the Marcellus and the toe of an accretionary prism is based on the extent of lithification, sediments characterize accretionary prisms whereas we presume that the Marcellus was lithified during the development of its cleavage duplex. The growth of cleavage duplexes may be similar to the thickening of a mélange in accreting sediments, however (Moore and Byrne, 1987). The model for thickening of mélanges is that slip surfaces are abandoned in favor of the development of new slip surfaces as a consequence of strain hardening. In the Marcellus strain hardening may occur if the duplexes favor the collapse of pore space in the organic material of the richest portion of the Marcellus. If the slip surfaces provide a conduit for gas escape from the collapsing pores, pore pressure may dissipate temporarily, thus further hardening the local rock to drive slip into undisturbed rock.

While sample statistics for cleavage duplexes is low (n = 18), their distribution does suggest that there is a correlation between duplex development and organic richness. It is reasonable to infer that generation of maturation-related pore pressure was most effective within the organically richest beds of the Marcellus. Effective normal stress would have been the lowest in these same beds, thus creating the most favorable conditions for the development of regional detachment faults, regardless of the specific slip mechanism. In sum, these observations indicated that detachment of the hanging wall depends on low effective normal stress but that slip is not automatically concentrated along one surface within the shale.

4.3 Mirror-like slip surfaces

The connection between bedding-parallel slip and low effective pore pressure is apparent. Despite low effective stress along slip surfaces, pressure solution is still an active mechanism during slip. XRD analyses show that chlorite, quartz, and illite are the most abundant minerals in both slickensides and host rock samples taken above the Marcellus. However, the abundance of these minerals is altered by pressure solution which concentrates chlorite preferentially along slip surfaces. The idea is that a chlorite film forms as a thin but very planar layer, not because of deposition by diffusion mass transfer but rather as a clay selvage much like a standard disjunctive cleavage residue. The classic mechanism for the formation of disjunctive cleavage is the preferential dissolution of quartz relative to clay (chlorite). Diffusion mass transfer is responsible for preferentially transporting quartz away from the local slip surface to be deposited elsewhere as slickenside fibers. The mirror is not so much a polish of concentrated chlorite as it is a manifestation of slip localization where the zone of localization is so thin that a mirror is the product of that slip (e.g., Engelder et al., 1975; Arboleya and Engelder, 1995). It may be presumed that grains are aligned but these grains of chlorite cannot be resolved under high magnification SEM (Figure 14). Evidence of frictional wear is not seen at any scale. Chlorite is also deposited on a substrate of quartz fibers but in this case the fibers tend to be irregular rather than smooth, thus muting the mirror-like behavior of chlorite when the slip surface is a substrate of rock matrix (Figure 6). In summary, mirror-like slip surfaces that are found in Devonian Shales of the Appalachian Basin are a result of chlorite concentration and quartz mineral dissolution.

4.4 Ridge-in-groove striations

Ridge-in-groove striations are common at all scales down to microscopic grooves that are part of the mirror-like slip surfaces. On the mesoscopic scale ridge-in-groove striations appear to overprint both quartz (i.e., Lock Haven and Mahantango) and calcite (i.e., Marcellus) fibers. Such striations are seen on all minerals including pyrite and chlorite. In fact, they may not be a separate structure as implied by Means (1987) but rather a feature of all slickenside surfaces on which there has been little to no brittle frictional wear. Ridge-in-groove structures are also the manifestation of concentrated slip even when the slip surface is not planar. For example, they occur where the slip cuts through a homogeneous and continuous material as might be found within a fiberous growth of a finite thickness. The slip surface is irregular at right angles to the slip direction but in the direction of slip it is a true lineation. Ridge-in-groove is a 1-D mirror that grows as a consequence of pressure solution in a mono-mineralic material. In a sense, it appears that ridge-in-groove is scale independent and a manifestation of slip when the slip is not cataclastic (Figure 14).

4.5 Distribution of bed-parallel slips surfaces

The abundance of slip surfaces along bedding planes in both outcrops and cores is an indicator that slip has occurred between layers. Non-evolving bed thickness across the fold indicates that the deformation mechanism was flexural slip. The regional distribution of slip surfaces in core suggests that slip displacement is not the same at every point on the fold. As it was mentioned before, in a basic flexural slip model no displacement takes place on the hinge line. Therefore, our interpretation of slip distribution in the Erb core suggests that, the well was drilled close to the hinge line of a fold. The proximity to a hinge line is indicated by the very shallow dip of bedding at Erb and orientations of slip surfaces in Erb core are sub-horizontal.

On the other hand, slip surfaces within the Bilger core are more concentrated. In the Mahantango Formation and Union Springs Member spacing between slip surfaces gets less than 1 cm. In addition, the average dip angle of slip surfaces is 20^{o} indicating that the Bilger core was drilled from a fold limb (Figure 20).

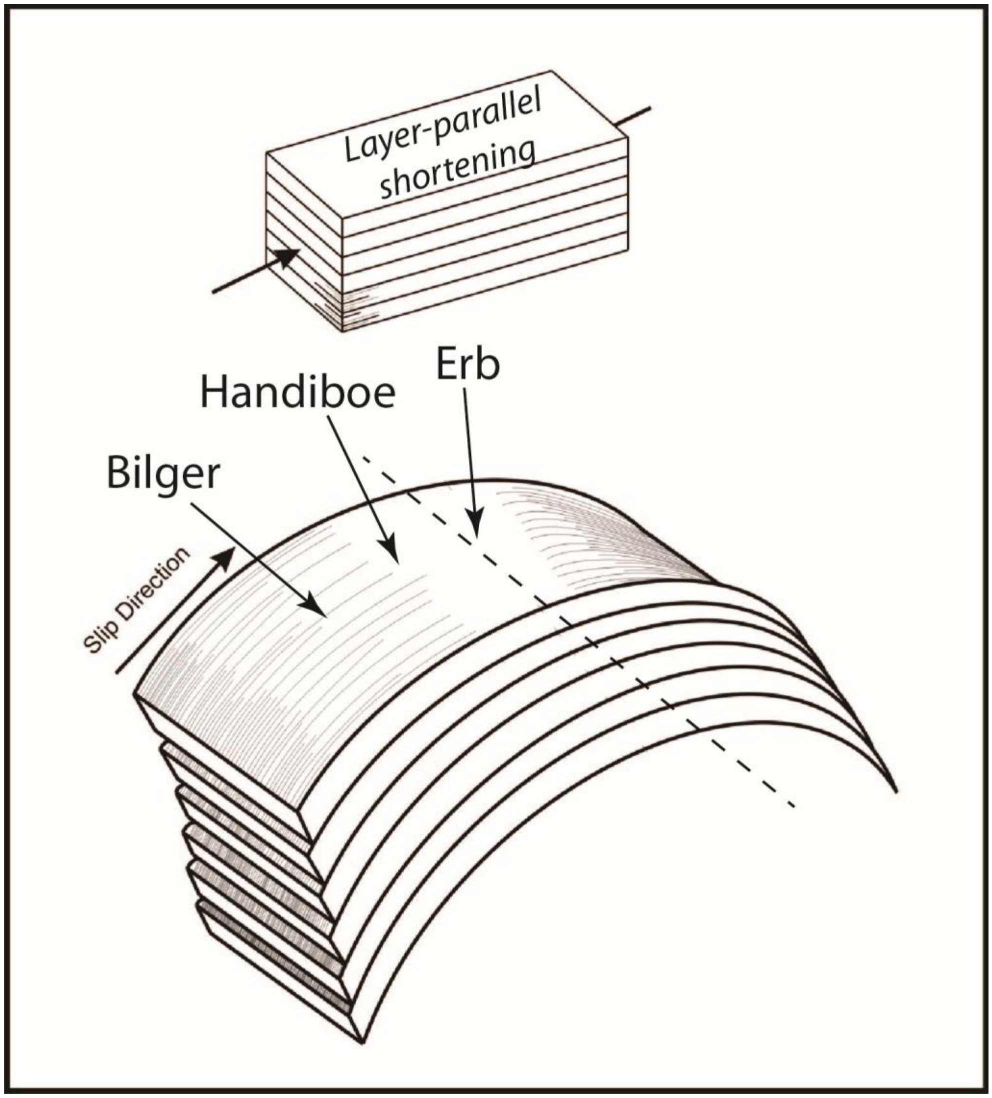


Figure 20. Schematic diagram showing the structural position of the Erb, Handiboe, and Bilger cores relative to a flexural-slip fold.

4.6 The Hubbert-Rubey hypothesis

The overthrust faulting in foreland basins is made possible by three mechanisms, each of which is governed by the frictional properties of rock along the regional décollement. First, the décollement layer can be very weak as is the case for the Silurian salt under the Appalachian Plateau detachment sheet (Rodgers, 1963; Wiltschko and Chapple, 1977; Scanlin and Engelder, 2003). Second, the décollement layer can be subject of pore pressure that reduces the effective normal stress across the detachment surface towards zero (Hubbert and Rubey, 1959; Gretner, 1972). Third, if the décollement layer is of normal strength and not subject to abnormal pore pressure, then stress within the thrust sheet is supported by developing a wedge against the hinterland load (Davis, et al., 1983). A transition from a wedge to weak detachment occurs at the Allegheny Front of the Appalachian Foreland where the basal detachment jumps from the Cambrian Waynesboro shale below the Valley and Ridge to the Silurian Salina salt below the Appalachian Plateau (Davis and Engelder, 1985). The Appalachian detachment sheets have a number of internal detachment zones of which the most prominent three are the Ordovician Utica/Stone River black shale zone, Silurian Rochester black shale zone, and the basal Hamilton Group zone (i.e., the Marcellus black shale) (Hatcher et al., 1989). The perception is that these internal detachments in shale are ‘weak’ zones.

The debate over the origin of detachments in strong versus weak shale goes back to whether or not bedding planes have a cohesive strength (Hsu, 1969; Hubbert and Rubey, 1969). The argument was that pore pressure was not so important if the cohesive strength of the detachment surface was negligible (i.e., shale is weak). Mechanical weakness is addressed in two parameters in the Coulomb Envelope: cohesive strength and friction, be it internal or sliding (Handin, 1969). Experiments on sliding friction address the question of the frictional strength of shale with the statement that "minerals such as chlorite, kaolinite and halloysite, which are normally considered to be very weak, have about the same friction as initially clear surfaces of very strong rocks such as granite" (Byerlee, 1978). Under large overburden the cohesion term in a Coulomb material is a small enough fraction of the total strength that cohesion does not matter. Both gray (i.e., the Mahantango) and black (i.e., the Marcellus) shale in the Appalachian basin is a mixture of chlorite, illite, and quartz with calcite in some instances. It is a mudstone with minerals possessing standard frictional strengths. The component that distinguishes black shale is organic matter in the form of kerogen, which while weak is matrix supported in many cases. It is the rock capable of self-generating abnormal pore pressure.

Slip, both cleavage duplexes and bedding-parallel slickensides, in ABBSG core is concentrated in the black shale interval in two places: in the basal organic-rich zone of the Union Springs Member and just below the Purcell Limestone where the organic richness of the Union Springs is the minimum (Figure 10). Presuming that the Purcell Limestone acts as a seal, slip is maximum where the most gas is generated and where gas is most likely to be trapped. This distribution of slip supports the contention that low effective stress is more important for promoting slip than weakness of the shale, particularly when Mahantango and Marcellus are arranged continuously from top to bottom of a section. The three major internal detachment zone in the Appalachian Basin thrust sheets are all within black shale. The association between black shale and detachment during Alleghanian tectonics leads to the conclusion that maturation-related reduction of effective stress was crucial for the development of regional detachments. The famous Hubbert-Rubey model for overthrust tectonics demands a detachment surface charged with abnormal pore pressure. While an external source for that pore pressure was hard to explain, a detachment zone that self-generates an abnormal pressure seems like a simple solution to the age-old problem of discovering the source for the Hubbert-Rubey pore pressure.

4.7 The importance of slip surfaces for natural gas production

Since the Devonian Shales of the Appalachian Basin present low permeability, the intensity of natural fractures needs to be known to predict potentially productive permeable zones. Slip surfaces are natural fractures. Therefore, knowing the distribution of slip surfaces may become important for the natural gas production. Highly fractured units may lead gas to flow to surface easier if there is a seal to prevent the gas. On the other hand, if there is no seal to prevent the gas, highly fractured units may allow the gas to migrate.

5. CONCLUSION

Measurement of gas pressure in contemporary wells, fluid inclusions within veins cutting the Marcellus black shale and concentrated natural hydraulic fractures within the shale all witness the generation of high pore pressure.   While there are several mechanisms for generating abnormal pore pressure, the only mechanism focused within black shale is the generation of pressure during the thermal maturation. The concentration of slickensides and cleavage duplexes in the organic rich portion of the Marcellus Shale witnesses the role that maturation-related pressure generation played in forming these structures.

Cleavage duplexes in the Marcellus Shale are zones of gradual concentration of slip. As mentioned above, the correlation between the concentration of cleavage duplexes and the organic richness is that the generation of maturation-related pore pressure was more effective within the organically rich portions of the Marcellus Shale.

Quartz dissolution and chlorite concentration by pressure solution are the two important mechanisms that control the mirror-like morphology on slip surfaces. While quartz is dissolved as a result of pressure solution, chlorite is getting concentrated. Therefore, the slip surfaces which only mineralized that way are shinier and smoother. If quartz and other minerals are abundant on the surfaces, carried by fluid flow, then the surface looks more fibrous and less shiny. Even though surfaces show mirror-like morphology on mesoscopic scale, they present ridge-in-groove type of striation on a microscopic scale.

The correlation of distribution of slip surfaces in cores indicates that, the presence of slip surfaces is highly depended on the structural position of a formation. The Bilger core has the highest number of slip surfaces, and also slip surface are very closely spaced in the Mahantango and the Union Springs parts of the core. Slip surface distribution in the Handiboe core is more uniformed than the Bilger core. However, the abundance of slip surfaces less than the Bilger core. The interval that has the highest number slip surfaces is in the Union Springs part of the core. The Erb core has the least number of slip surfaces in these three cores. The highest number is, also in the Union Springs part of the core. The slip surface distribution difference indicates that these core were drilled different parts of the folds. The Bilger core has the highest number of slip surfaces, therefore, our interpretation is it was drilled away from the hinge line. The average dip angle which is 20o proves that. The Erb core includes the least number of slip surfaces. Thus, it was drilled close to the hinge line of a fold. In addition. The bedding and slip surfaces are almost horizontal.

Slip surfaces are characteristic of three internal detachment zones in the Appalachian foreland, all cutting black. The interpretation is that the Hubbert-Rubey model for low effective stress favors that development of these detachment zones rather than the inherent weakness of the shale.

The industry can benefit to have better knowledge about the slip surface distribution and mineralogy can be used for the industry, since the production is highly depended on the creating pathways in the low permeable shales for gas to flow into the pipes.

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