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Revisiting the Hubbert–Rubey pore pressure model for overthrust faulting: Inferences from bedding-parallel detachment surfaces within Middle Devonian gas shale, the Appalachian Basin, USA

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ABSTRACT

Both bedding-parallel slickensides and cleavage duplexes are forms of mesoscopic-scale detachment faulting populating black (Marcellus and Geneseo/Burket) and intervening gray (Mahantango) shales of the Middle Devonian, a section known for abnormal pore pressure below the Appalachian Plateau. The abundance and the orientation of slickensides and cleavage duplexes in the more organic-rich black shale relative to gray shale suggests that maturation-related abnormal pore pressure facilitates detachment, a mesoscopic manifestation of the Hubbert–Rubey pore pressure model for overthrust faulting. The former are discrete slip surfaces whereas the latter consists of nested, anastomosing slip surfaces, either cutting through bedding or on disrupted bedding surfaces stacked as mesoscopic versions of thrust duplexes. Cleavage duplexes are between a few cm and over 1 m thick with their hanging walls commonly transported toward the Appalachian foreland, regardless of local limb dip. Cleavage duplexes are most common near the stratigraphic maximum flooding surface, the organic-rich section most prone to develop maturation-related pore pressure in the Middle Devonian gas shales. Bedding-parallel slickensides are somewhat more evenly distributed in the black shale but also found in overlying gray shale. In both black and gray shales, slickensides are more abundant on the limbs of folds, an indication of pore-pressure-related flexural-slip folding. On the macroscopic scale, the Pine Mountain Block of the Southern Appalachian Mountains was enabled by a basal detachment cutting along the Upper Devonian Chattanooga black shale which has a thermal maturity sufficient for the generation of abnormal pore pressure. The Pine Mountain block is a large-scale overthrust showing little evidence of collapse of the hinterland side, a credible example of a pore-pressure-aided overthrust fault block of the type envisioned by the Hubbert–Rubey model.

1. Introduction

The Pine Mountain block of the southern Appalachian Mountains is one of the world's finest examples of a broad detachment sheet (>35 km) that did not collapse at its back end to form a tapered wedge (Fig. 1). Dave Wiltschko first showed T.E. the Pine Mountain detachment sheet during an annual field trip of the Appalachian Tectonics Study Group in the late 1980s. Following in the tracks of other giants in Appalachian geology including Wentworth, Butts, and Rich, Dave wrote several papers dealing the tectonics of the Pine Mountain block thrusting, particularly its ramp anticline (Wiltschko, 1979). Reflecting back on over a century of geological study focused on the Pine Mountain block, one of the more profound observations concerning the mechanical paradox of intact thrust blocks came from the geologist famous for the Wentworth-scale, "It is especially interesting to note that the force required to shear the block loose over the whole area is only about one-tenth of that required to produce motion against the resistance of friction." (Wentworth, 1921). At the time, Wentworth was well aware of Smoluchowski's observation that detachment sheets were too weak to support the hinterland forces necessary to drive broad detachment sheets against the resistance offered by 'dry' friction (Smoluchowski, 1909). For the past 50 years, the most popular explanation for frictional slip without hinterland collapse was to call upon abnormally high pore pressure to reduce the effective normal stress holding in place the frictional contact along the basal detachment (Hubbert and Rubey, 1959). Such normal-stress dependent strength behavior is consistent with a Coulomb

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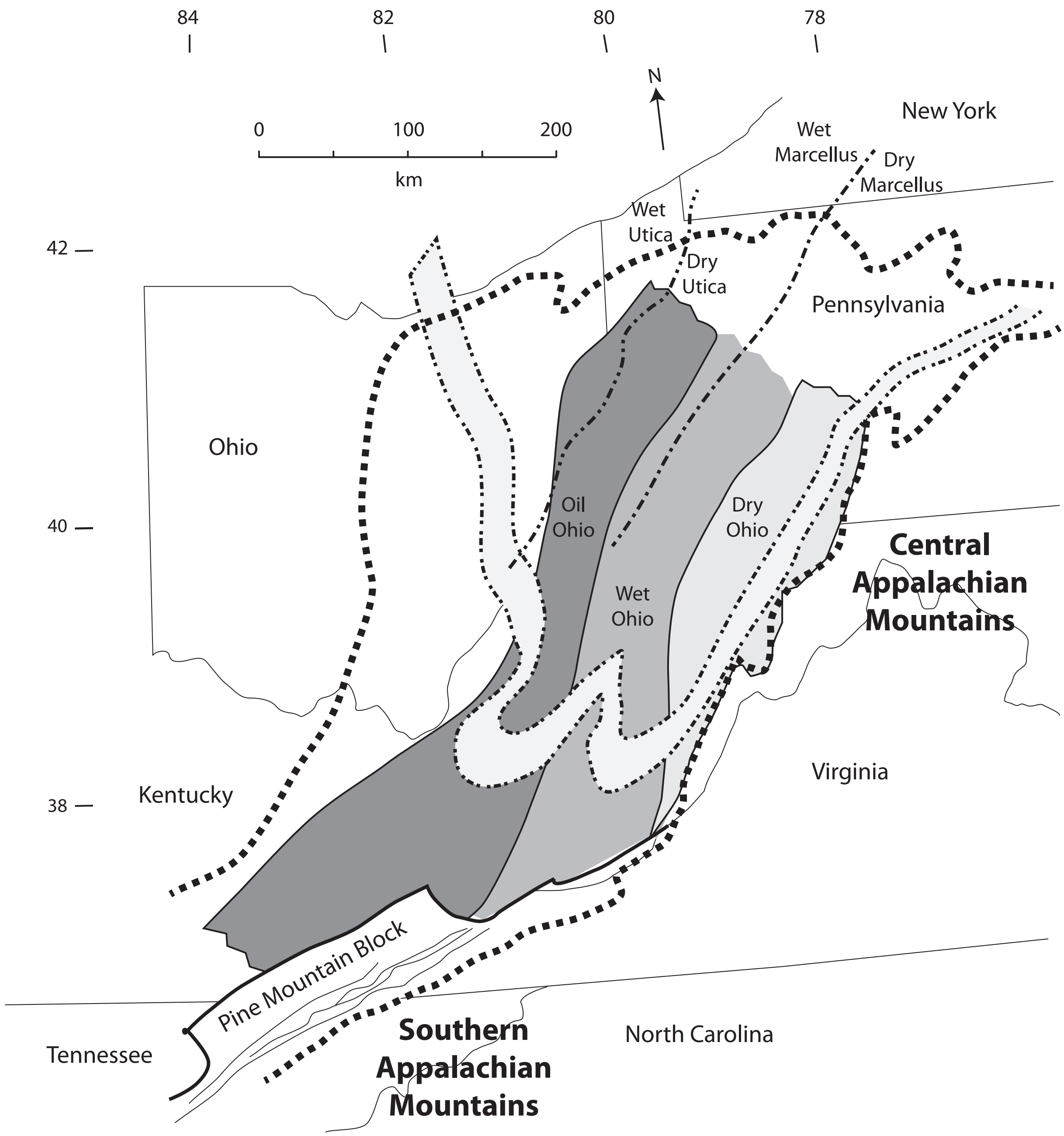

Fig. 1. The location of the Pine Mountain block relative to organic maturation levels in terms of oil and gas generation zones in the Appalachian Mountains including the Upper Devonian Ohio gas shale, the Middle Devonian Marcellus gas shale, and the Ordovician Utica gas shale as measured using vitrinite reflectance (%Ro) and other evidence for thermal maturity (adapted from Rimmer et al. (1993)). Thick dashed line is the pinchout line for the Ohio gas shale. Light gray map pattern denotes the southern extent of the Silurian Salina salt (adapted from Davis and Engelder (1985)).

material (Handin, 1969). If the Hubbert–Rubey model is applicable to the basal detachment of the Pine Mountain thrust sheet, then the detachment zone may have behaved like a Coulomb surface subject to high pore pressure during Alleghanian thrust faulting (Hatcher et al., 1989).

1.1. Questions about the Hubbert–Rubey model

The Hubbert–Rubey model for high-pore-pressure-aided regional detachment without hinterland collapse presents some questions (Gretener, 1981). The first concerns whether high pore pressure exists simultaneously over the total length (i.e., distance in the transport direction) of any thrust sheet but, in particular, the Pine Mountain detachment sheet. Second is the question of the mechanism for maintaining high pore pressure in space and time given the large areal extent and distance traveled for detachment sheets like the Pine Mountain thrust. The Hubbert–Rubey model seems plausible as long as simultaneous slip over the entire detachment surface does not cause pore pressure leakoff. If the fault slips in a series of discrete increments, it can heal and seal between slip events without pore pressure leakoff (Price, 1988). Still, one wonders how pore pressure is generated and maintained in the immediate vicinity of the detachment surface which is often a contact between different lithologies.

Because of its well-exposed slip surface, the Glarus Thrust of the Helvetic Nappes, Switzerland, is one of the more controversial examples of a large-scale detachment amenable to the Hubbert–Rubey model (Groshong et al., 1984; Heim, 1921; Schmid, 1975). However, strain localization gives rise to an alternative model based on grain boundary sliding during superplastic flow within a fine-grained calcite aggregate of the Lochseitenkalk mylonite (Schmid et al., 1977). Still, a version of the Hubbert–Rubey model for the Glarus thrust persists because evidence for the presence of water along the detachment surface leads some to suggest that cyclic pressure increases cause hydraulic fracturing accompanied by seismic slip (Badertscher and Burkhard, 2000; Sibson, 1990). The idea is that dewatering by compaction and prograde metamorphism in the footwall produced large volumes of water that escaped to the foreland along the Glarus thrust (Badertscher et al., 2002; Burkhard and Kerrich, 1988). The question is whether fluid escape promoted strain localization when present as a second phase (Burlini and Bruhn, 2005) or whether the presence of water promoted a stress-sensitive Coulomb-like behavior with the reduction of an effective normal stress as implied by the seismic pumping model (Hubbert and Rubey, 1959; Sibson et al., 1975).

Another question concerns whether, when viewing detachment surfaces or zones in the field, it is possible to decipher slip by Coulomb friction from slip by any of a number of a stress independent mechanisms including superplastic flow. Many of the world's famous detachment sheets involve shale. When shale is in the hanging wall, as is the case for the Verricano redbeds in the hanging wall of the Glarus thrust, then the shale is treated as an impermeable boundary which channels water along the detachment surface (Badertscher et al., 2002). The Pine Mountain block is another example of a large detachment sheet with shale in the hanging wall (Wentworth, 1921). In many cases, however, shale is found in the footwall including the Marias River shale under the Lewis thrust, MT (Erickson, 1994), the Sevier shale under the Holston Mountain and The Cliffs thrusts, TN (Ohlmacher and Aydin, 1995, 1997), the Chattanooga shale under the Hunter Valley thrust, VA (Harris and Milici, 1977), and even the Rome shale under the Saltville thrust, VA (House and Gray, 1982) and the Max Meadows and Blue Ridge sheets (Gibson and Gray, 1985). In some of these examples, shale appears to be deforming as a cataclastic material which is taken as evidence for stress-sensitive Coulomb behavior (Kennedy and Logan, 1998). The transition between Coulomb and plastic mechanisms is difficult to identify because both modes of slip give the appearance of strain localization (Arboleya and Engelder, 1995; Ebert et al., 2007; Engelder et al., 1975).

1.2. Foreland detachment within gas shale

The shale at the base of the Pine Mountain block is the Upper Devonian Chattanooga gas shale (Harris and Milici, 1977). The value of gas shale as an unconventional reservoir for natural gas in many basins of the world kindles interest in deformation mechanisms associated with the generation of high pore pressure during the thermal maturation of source rocks. Elevated pore pressure affects black shale in at least two important ways: pore pressure might exceed least compressive stress to drive natural hydraulic fractures (Engelder and Lacazette, 1990; Lacazette and Engelder, 1992; Secor, 1965) and pore pressure might lower effective normal stress to ease frictional slip on faults (Gretener, 1972, 1981; Hubbert and Rubey, 1959). If reduced effective normal stress is common during maturation of black shale, then these shales should preferentially host detachment planes under regional thrust sheets such as the Pine Mountain thrust block (Harris et al., 1970; Kilsdonk and Wiltschko, 1988; Mitra, 1988; Rich, 1934; Wentworth, 1921). This leads to the hypothesis that detachment faulting in black shale is a manifestation of the reduction in effective normal stress during the buildup of maturation-related pore pressure within the shale (Swarbrick et al., 2002) and not exclusively a manifestation of an inherent frictional weakness or plasticity of the shale (Kennedy and Logan, 1998; Wojtal and Mitra, 1986).

Maturation-related detachment is a relatively new idea that comes from Peter Cobbold's group at Rennes, France (Cobbold, 1999; Cobbold et al., 2004, 2013; Loseth et al., 2011). There are examples in several basins of the globe including the Niger Delta (Cobbold et al., 2009), the North Sea (Loseth et al., 2011) and in the Andes where maturation fronts and deformation fronts seem to coincide (Cobbold, 2005; Cobbold and Castro, 1997). In particular, an association between beef and detachments in source rock in the Magellan Basin is consistent with the maturation-related detachment hypothesis (Zanella et al., 2013). A reduced-effective-stress hypothesis is testable in other foreland settings such as the Appalachian Basin where there is a variation in total organic carbon content through a section that includes both rich (i.e., black) and lean (i.e., gray) shale. Assuming equivalent frictional and bulk rock strengths for shale, black and gray, detachment faulting focused in the richer source rocks should be a robust witness to the role of maturation-related generation of abnormal pore pressure. In this case, the fluid responsible for the pore pressure is not water or brine, but rather a petroleum or natural gas.

A number of structures are a manifestation of elevated pore pressure in the Appalachian Basin including natural hydraulic fracturing in several black shale units ranging from the Middle Devonian Marcellus to the Upper Devonian Dunkirk–Huron (Engelder et al., 2009; Lacazette and Engelder, 1992; McConaughy and Engelder, 1999; Sheldon, 1912), slickensides arising from bed-parallel slip through these same shales (CliffsMinerals, 1982; Evans, 1994), cleavage duplexes, particularly in the Marcellus (Bosworth, 1984; Engelder et al., 2011; Kepferle et al., 1981; Nickelsen, 1986; Wheeler, 1978), fibrous veins including beef and cone-in-cone structures (Gilman and Metzger, 1967; Taber, 1918) and other detachment surfaces found cutting several shales (Hatcher et al., 1989). To examine whether the Hubbert–Rubey model operated in shale of the foreland portion of the Appalachian fold–thrust belt because of maturation-related detachment, we document the distribution of detachment surfaces at two scales based on thickness and slip magnitude. Cleavage duplexes are a larger scale, bed-parallel structure that can range from a few cm up to over a meter thick and represent an unknown but significant amount of differential slip with the hanging wall generally but not always toward the foreland (Bosworth, 1984; Nickelsen, 1986). Bed-parallel slickenside surfaces are a smaller-scale slip surface confined to a single bed boundary and these likely represent considerably less but still unknown differential slip with hanging wall toward the anticlinal axis (Evans, 1994). The bed-parallel slip of slickensides is common during flexural-slip folding associated with the growth of fault-bend folds of the Appalachian Basin (Faill, 1973; Geiser, 1988; Suppe, 1983) with the tendency for slip surfaces to concentrate in the limbs of folds relative to their hinges (Tanner, 1989).

Aside from testing the hypothesis that foreland faulting is a manifestation of maturation-related reduced effective stress, an objective of this study is to examine bed-parallel slip surfaces with an eye toward identifying other small-scale structures that classic papers on slickensides may have overlooked (Doblas, 1998; Means, 1987). In particular, we wish to revisit the interpretation of mirror-like surfaces that, in the past, are often treated as a product of a mechanical polish by frictional wear (Engelder, 1974). Evidence presented here supports the hypothesis that these slip surfaces are controlled by a diffusion mass transfer where their development may depend on the mineralogy of the substrate host rock. Details of the mineralization will give clues about the active processes during slip, be they congruent or incongruent pressure solution (Fry, 1982), diffusion to pressure shadows which allow fiber growth (Durney and Ramsay, 1973), or outright transport in a fluid to some host elsewhere in the section (Davidson et al., 1998). If these surfaces are not a product of frictional wear, can they be incorporated in any model based on Coulomb wedge theory (Davis et al., 1983)?

Slickensides are a class of fault that is either rough on a fine scale with fibers and grooves or polished into shiny surfaces (Engelder, 1974; Lin and Williams, 1992; Means, 1987). Both fibers and grooves constitute a slip lineation indicative of the direction and sense of slip. Depending on the extent of step development with stylolite characteristics during fiber growth, the term, slickolite applies (Bretz, 1940). Classification of slickensides reflects the rich variety of small scale structures that can populate these slip surfaces (Fig. 2). A relatively simple classification shows 6 different types of slickenside surfaces, whereas slickensides may have up to 61 kinematic indicators (Doblas, 1998; Means, 1987; Petit, 1987). 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 indication of ductile slip when the slickenside consists of a ridge-in-groove striation (Lin et al., 2007; Lin and Williams, 1992; Means, 1987). 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.

1.3. The application

Finally, a study of bed-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 and increase mechanical and seismic anisotropy in an otherwise low permeability rock. The same rock properties arise during larger scale detachment pervading black shale. For these reasons industry will benefit from an enhanced understanding of the development of bed-parallel slip or larger scale detachment when making decisions during drilling into, completion of, and production from unconventional reservoirs in black shale.

We use samples from the Pennsylvania natural gas play as a proxy for samples from the basal detachment of the Pine Mountain block largely because, without industry interest in the Pine Mountain block, there is very little possibility of obtaining a comparable suite of fresh shale samples from that region. Yet, industry funding has allowed us to collect a magnificent set of samples from central PA. Some may doubt that an extrapolation can be made

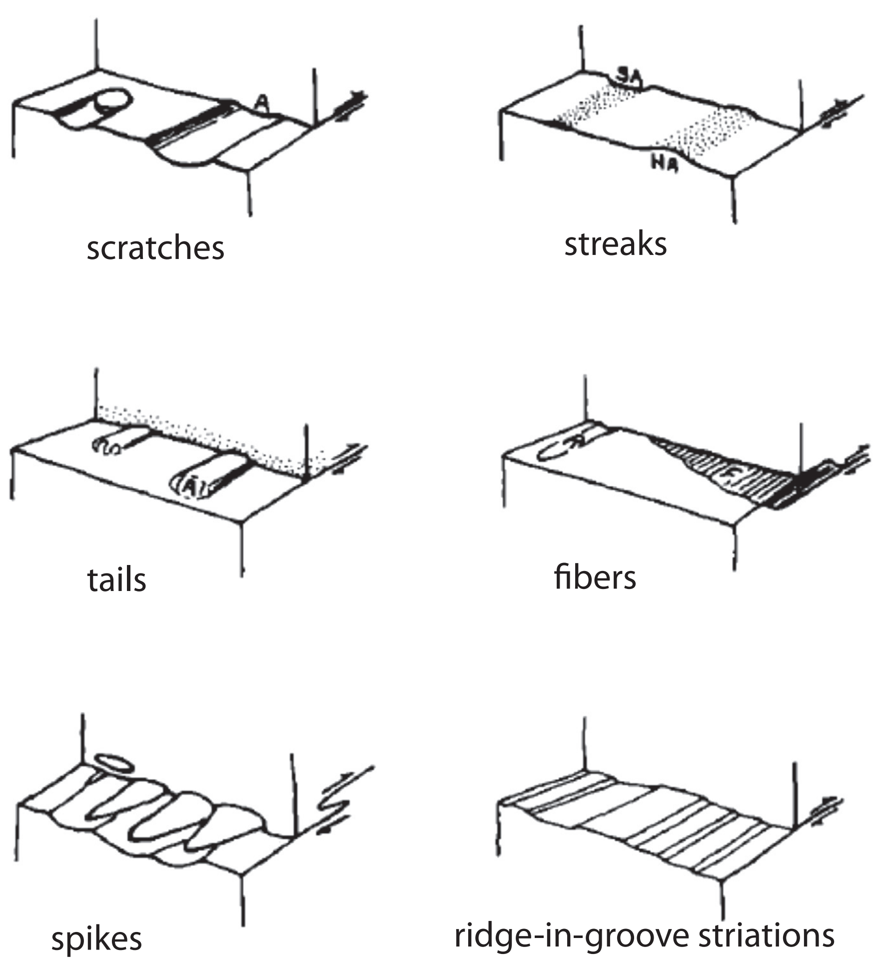

Fig. 2. Types of linear structures on slip surfaces (adapted from Means (1987)).

from the central to the southern Appalachian foreland but we think the lessons from central PA might apply to the Pine Mountain block (Fig. 1).

2. The Appalachian Basin

The Appalachian Basin was an active depocenter for more than 300 My from the rifting of Rodinia through the rifting of Pangaea (Quinlan and Beaumont, 1984; Rodgers, 1970). Several times during basin infilling conditions favored the preservation of organic matter in sufficient volumes to allow the development of economic gas shale. The most notable of these include the Ordovician Utica shale, the Middle Devonian Marcellus and Geneseo shales and several Upper Devonian shales including the Ohio–Chattanooga shale. Burial was sufficient to allow the generation of hydrocarbons within at least the hinterland parts of each of these black shales. The extent of thermal maturity in each shale is reflected in the provinces where oil, wet gas, and dry gas are produced. Boundaries between hydrocarbon provinces step progressively west with the depth of each shale in response to the higher temperature and pressure to which the deeper units were subjected (Fig. 1).

The Alleghanian Orogeny is characterized by two tectonic styles characteristic of zipper tectonics starting with a period of strike-slip between Gondwana and Laurentia followed by a period of convergence which drove the foreland fold–thrust belt of the Central and Southern Appalachians (Hatcher, 2002). During the early strike-slip tectonic phase of the Alleghanian Orogeny, burial of the Central Appalachians sufficient to expel enough gas to drive J_1 joints (Engelder and Whitaker, 2006). Full burial of the gas shales was not achieved until convergence when J_2 joints were generated during the cracking of oil to dry gas in the deeper parts of the basin. Thermal maturity in the southern Appalachian Mountains lagged where the Upper Paleozoic cover was thinner. The Pine Mountain block detached within the Ohio–Chattanooga shales when burial was sufficient to generate oil during the convergent phase of the Alleghanian Orogeny (Rimmer et al., 1993).

This paper examines slip surfaces within four formations of the Middle and Upper Devonian section of the central Appalachian Basin of PA: the Marcellus, the Mahantango, the Burket/Geneseo and the Lock Haven Formations (Fig. 3). In PA the Hamilton Group is divided into the Marcellus Formation, Mahantango Formation, and the Tully Limestone. The Burket/Geneseo, Brallier and Lock Haven Formations are part of the overlying Genesee Group. Although these units incorporate several 3rd order sequences, taken as a group these four formations straddle two 2nd order sequences of the Appalachian Basin (Johnson et al., 1985; Kohl et al., 2013; Lash and Engelder, 2011; Ver Straeten, 2007).

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

3. Bed-parallel slip in outcrop

Although examples of bed-parallel slip are found throughout the Valley and Ridge of PA, outcrop quality is often subpar because weathering obscures small-scale structures in shale. Consequently, core drilling is necessary for collecting samples with pristine slip surfaces. Outcrops of the Lock Haven Formation, a bedded distal turbidite, yields bed-parallel slip surfaces of high enough quality for study. Larger-scale cleavage duplexes in shale also survive for outcrop observation. Our study of bed-parallel slip concentrates on seven localities in Central PA (Fig. 4).

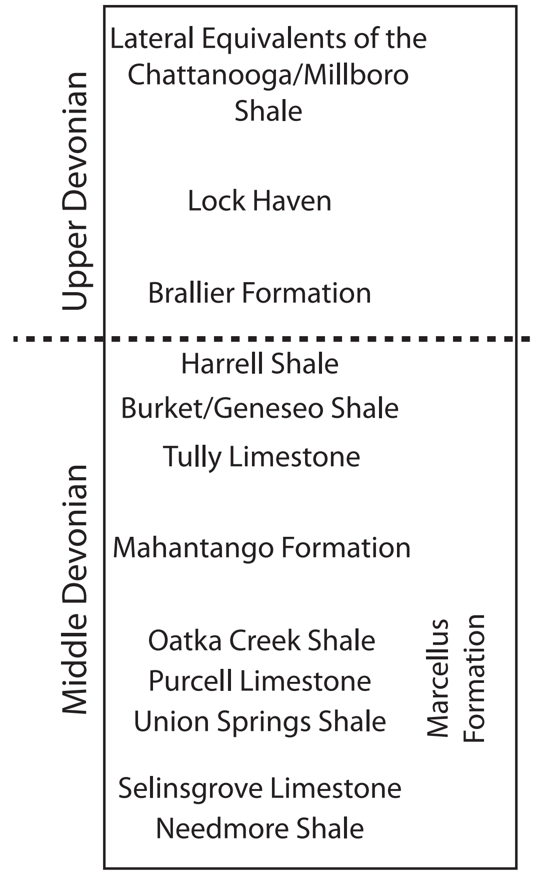

Fig. 3. Basic stratigraphic column of the Middle and Upper Devonian section in the Appalachian Basin, PA. For a more detailed breakdown of the Devonian black shale section in the Appalachian Basin see (Ettensohn, 1985).

3.1. *Cleavage duplexes*

Cleavage duplexes are most commonly found in the basal portion of the Union Springs Member of the Marcellus. This is the case for the type locality of a cleavage duplex near to Selinsgrove Junction, PA (Nickelsen, 1986). 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 toward the transport direction (Fig. 5). Deformation within the duplex completely overprints bedding. The transport direction is generally towards the foreland no matter where it is located relative to the nearest anticlinal hinge. At the type locality, the hanging wall of the cleavage duplex is heading downhill toward the foreland on the NNW limb of a local fold. This rule is true for cleavage duplexes observed in other portions of the Appalachian Basin as well (Bosworth, 1984; Kepferle et al., 1981; Wheeler, 1978). The duplex-bedding contact is often very sharp and mineralized in a manner that suggests concentrated slip along one or both duplex-bedding interfaces. ‘Cleavage planes’ have a higher reflectivity than the shale matrix, thus resembling a polish from simple shear, unlike the clay surface of an insoluble residue reflecting plane strain in an ordinary cleaved rock. The polish is, however, a pressure solution phenomena (Gratier et al., 1999).

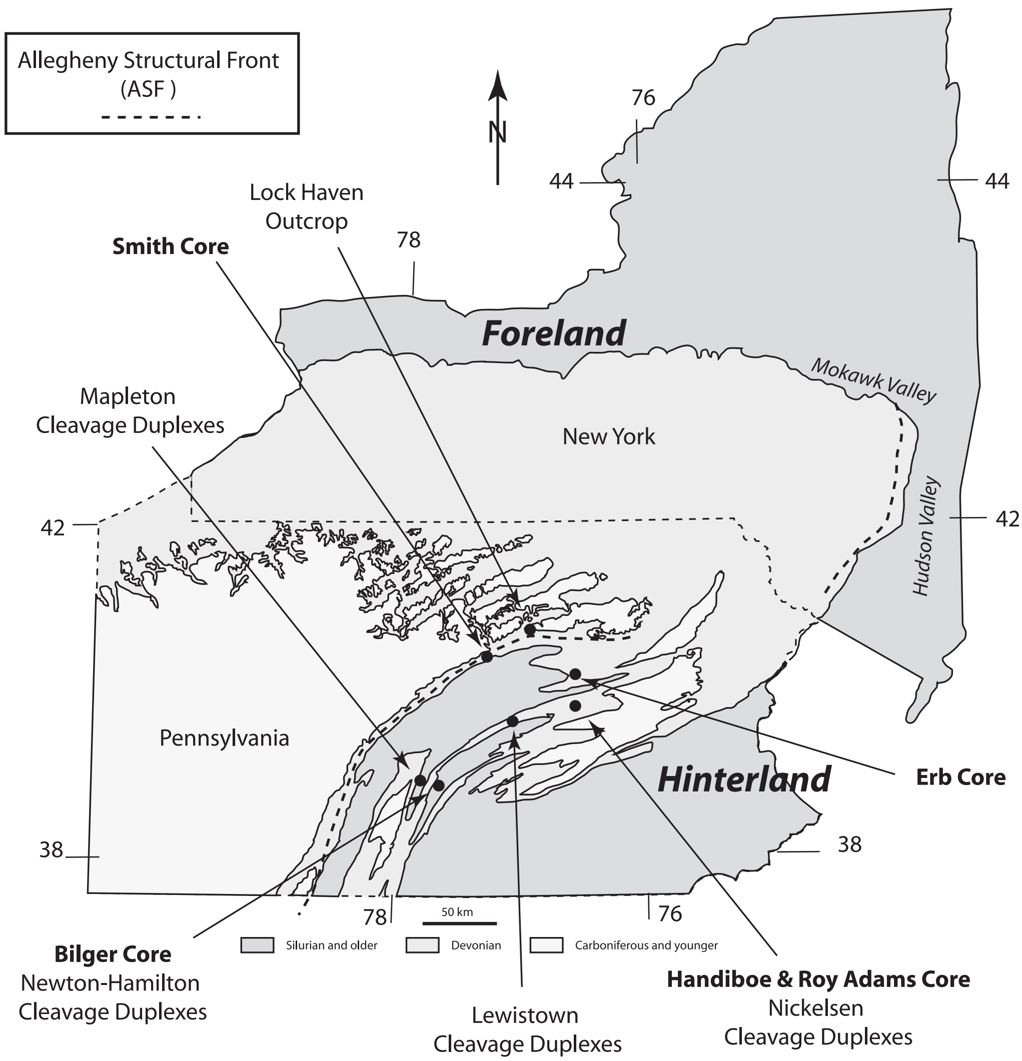

Fig. 4. Geological map of the Central Appalachian Mountains showing the sample locations for three Marcellus cores (Bilger, Erb, Handiboe), one Geneseo/Burket core (Smith) and four Marcellus cleavage duplexes in outcrop. The Allegheny Structural Front divides the Appalachian Plateau to the NW and the 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.

3.2. Slickensides

The Lock Haven Formation is a package of gray to green fine-grained greywacke and shale interlayers with bed-parallel slip surfaces between coarser-grained beds (Fig. 6a). Hanging wall toward anticlinal crests indicates that these surfaces are a manifestation of flexural-slip folding. Slip surfaces show different degrees of mineralization and a variety of morphologies from mirror-like smooth surfaces to flat fibrous slip surfaces to more irregular surfaces with thick mineralization. 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 (Fig. 6b,c).

4. Bed-parallel slip in core

Penn State's Appalachian Basin Black Shale Group (ABBSG) funded the sampling of the Marcellus black shale by core drilling where the Marcellus and Geneseo/Burket are found in the shallow subsurface. Of these, four cores with a cumulative length over 700 m were selected for detailed study including three wells through the Marcellus (i.e., the Bilger, Erb, and Handiboe) and one well through the Geneseo/Burket (i.e., the Smith). After coring, a suite of slim-hole logs was taken in each well including gamma ray and density.

Each of these Marcellus cores includes the lower portion of the Mahantango gray shale, the entire Marcellus section, and a portion of the underlying Selinsgrove limestone (Fig. 3). The Geneseo/Burket core cuts down into the Tully Limestone. Each core was examined for both bed-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 or top of the Tully Limestone. The morphology and mineralogy of the surfaces 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.

4.1. Cleavage duplexes

A number of cleavage duplexes were observed in the Bilger and Handiboe cores (Fig. 5). Like their outcrop counterparts, cleavage duplexes in core are most common within the Marcellus and most densely developed within 10 m of the top of the Selinsgrove

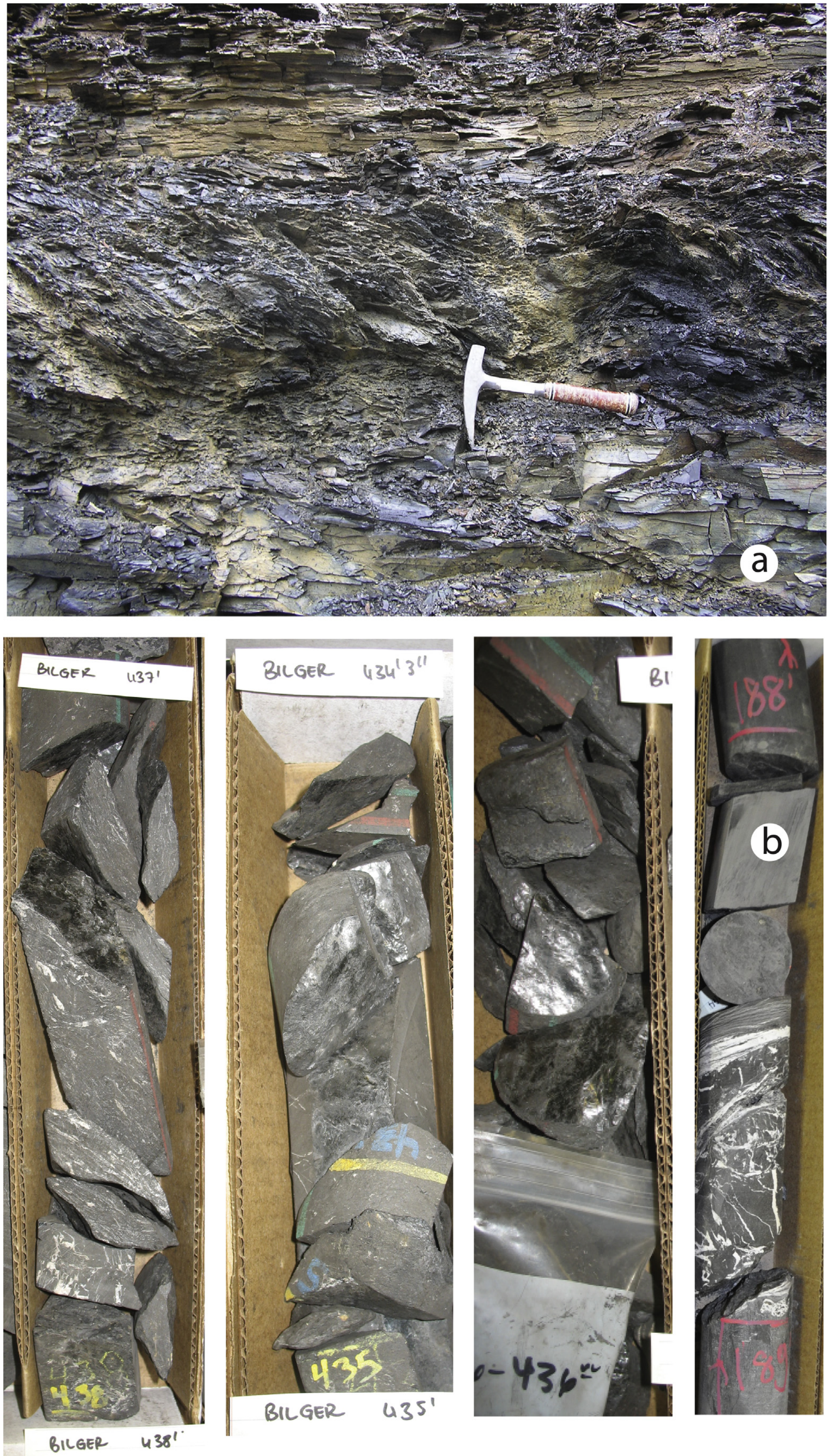

Fig. 5. Cleavage duplexes. (a) 53 cm thick cleavage duplex 2 m above the Selinsgrove Limestone in the Marcellus Formation at Newtown Hamilton showing a transport direction toward the foreland (left). (b) Cleavage duplexes in core: Bilger well (left three boxes) 2–6 m (by core) above the Selinsgrove Limestone; Handiboe well (right box) 112 m (by core) above the Selinsgrove Limestone.

Fig. 6. Samples from bed-parallel slip surfaces in the Lock Haven Formation north of Williamsport, PA. (a) A slip surface showing ridge-in-groove striations from a flexuralslip fold within the Lock Haven Formation north of Williamsport. (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.

limestone, a position close to the maximum flooding surface of the Union Springs Member (Fig. 7). A cleavage duplex in the Geneseo/Burket is in the same position relative to the Tully Limestone. 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 bed-parallel slip, the duplex surfaces are quite irregular. A great number of calcite veins cut cleavage duplexes, particularly within 10 m of the underlying 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 with concentrated slip.

4.2. Slickensides

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

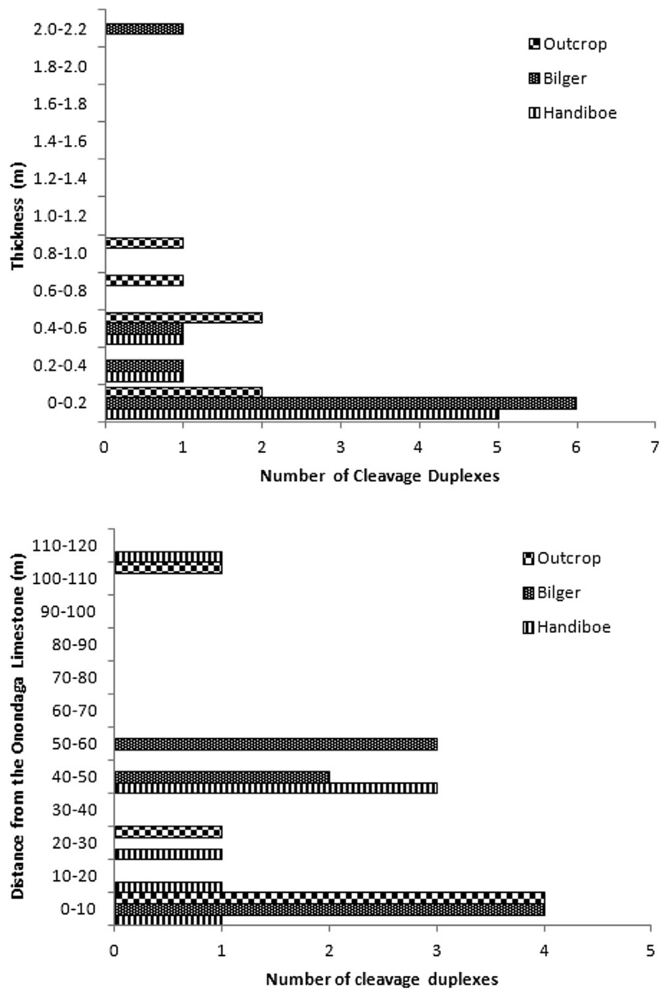

Fig. 7. For samples from both outcrop and core, the thickness of cleavage duplexes is binned in 20 cm intervals (top) and height of cleavage duplexes is binned in 10 m intervals above the Selinsgrove Limestone (bottom).

bedding surface slip direction can vary as much as 10°. 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° and 25° 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°E, dipping 20°SSE. However, the rake of the slip lineation on surfaces is rarely 90° (Fig. 8). In a number of instances slip lineations overprint indicating a range of slip directions distributed through 10° on a single surface. The sense of slip is hanging wall uphill toward anticlinal axes (Fig. 8).

4.2.1. 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 record events per unit length of core (Fig. 9). 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 ($n = 110$).

Slip surface development is striking at two positions within the Marcellus core (Fig. 9). First, the bottom 10–20 m of the Union Springs Member in all three cores carries a well-developed set of slip surfaces. Second, the Union Springs Member just below the Purcell Limestone has 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.

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. $n = 81$) (Fig. 9). 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 relative number of slip surfaces in the Mahantango of the other two core is the same as for the Marcellus: Bilger (dip 19°–25° v. $n = 264$); Erb (dip < 3° v. $n = 8$).

Industry uses a high (>180 API) gamma ray count as one but not the only indicator of organic content in various rocks (Schmoker, 1981). In the three ABBSG wells, gray shale has a gamma ray API count between 150 and 180 (Fig. 10). Limestone is indicated by an API count <100 and black shale is indicated by an APR count >180. By gamma ray proxy, the basal Union Springs Member, the maximum flooding surface, in all three wells (API > 500) is the most organic rich. The densest development of slip surfaces occurs within shale with the highest organic content in the Erb and Handiboe wells (Fig. 10). The density of slip surfaces is higher in the Bilger well so that there is no clear correlation between organic content and slip surfaces.

4.2.2. Morphology

Slip surfaces the Marcellus–Mahantango section of the Central Appalachians vary from mirror planes to slightly irregular surfaces carrying either fibers or ridge-in-groove striations (Fig. 11). Fibers develop by growth of elongate crystals parallel to the displacement direction (Fig. 8). Often ridge-and-groove striations overprint the fiber growth. Asperity plowing, the result of protuberances moving with one wall of a slip surface, is rare. 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. Mirror smooth surfaces are more common in the Mahantango section. Also, fiber growth with irregular steps appears more often in the Mahantango–Oatka Creek section of the ABBSG cores (Fig. 11a,b) whereas the ridge-in-groove striations on slip surfaces are more common in the Union Springs–Selinsgrove section (Fig. 11c,d).

Matrix minerals smeared along or growing on bedding-parallel slip surfaces include chlorite, quartz, pyrite, and calcite. Dilute hydrochloric acid test is applied on slip surfaces to determine the difference between the fibrous calcite and quartz (Fig. 12a–d). Calcite is rare in the Mahantango–Oatka Creek section and very common in the Union Springs–Selinsgrove section. The mirror surfaces are often a thin layer of chlorite coating the dark matrix of the Mahantango–Marcellus section. Recrystallized pyrite is commonly entrained in the chlorite. Pyrite was also common in the quartz fibers well up into the Mahantango section. The best-developed ridge-in-groove striations are found in calcite which was much more common in the Union Springs–Selinsgrove section.

Reflected-light and scanning electron microscopes reveal a rich texture in the minerals populating the slip surfaces (Fig. 13). Even mirror surfaces have a ridge-in-groove texture with a peak to peak distance of 10 μm or less. Pyrite and calcite carry microscopic ridge-

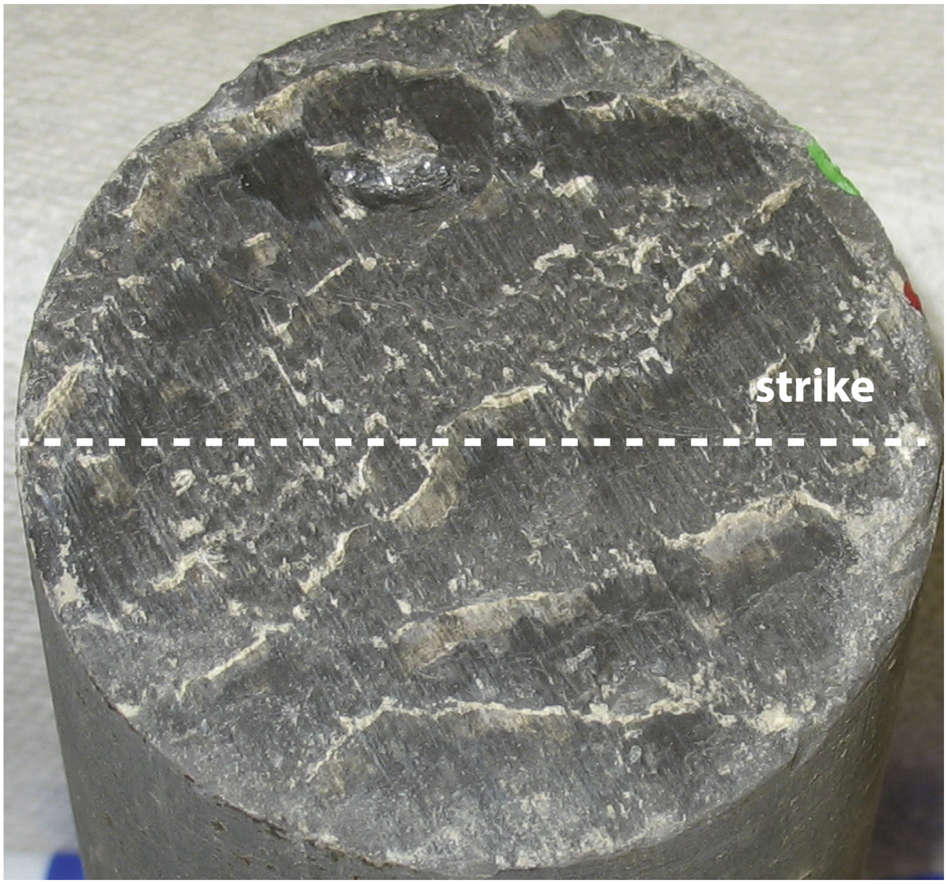

Fig. 8. Footwall sample of a slip surface showing fiber growth in the Mahantango Formation 122 m (by core) above the Selinsgrove Formation in the Bilger well. Core is oriented so that bedding strike is E–W and dip direction is toward the bottom of the photo. The angle between slip and dip is 30°.

in-groove striations that pass continuously from one mineral to the other. Pyrite appears to clump on the sliding surface without the crystal faces characteristic of framboidal pyrite or other pyrite entrained in the matrix of black shale (Fig. 13a–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 (Fig. 13c,f).

4.2.3. *Progressive mineralization*

Slip surfaces that appear to be polished to a mirror plane have received little attention in the literature on slickensides. 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. An adequate quantitative measure of the mineral components along slip surfaces requires calibration of the XRD detector using quartz, calcite, and chlorite (Aydin, 2011).

XRD analyses from slip surface of Lock Haven Formation, a greywacke, collected from Williamsport, Pennsylvania are used to provide a perspective for interpreting the evolution of slip surfaces in the Marcellus. Both the slip surfaces and their corresponding matrix are composed of chlorite, quartz and illite. However, during slip, chlorite is concentrated on the slip surfaces relative to its concentration in the quartz- and illite-rich matrix of the Lock Haven Formation (Fig. 14).

Mineral analysis of the Mahantango Formation comes from the Bilger core, 96.18 m above the Selinsgrove 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 (Fig. 14a). Quartz is rich in the matrix compared to slip surface surface. The same concentration of chlorite is present on slip surfaces of Mahantango as was seen on slip surfaces in the Lock Haven Formation (Fig. 14b).

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. 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 as much as 33% of the rock volume in the richest portion of the Union Springs (Fig. 15). The exchange of calcite for quartz follows a calibration line for a mixture of pure quartz and calcite and the natural Qtz–Cal line in the Marcellus indicates that these minerals occupy about 33% of the volume of the natural rock, a result consistent with the ELAN log of the Marcellus (Fig. 15).

The lower Union Springs Member is the organically richest part (based on the gamma ray values in Fig. 15b) of the Marcellus

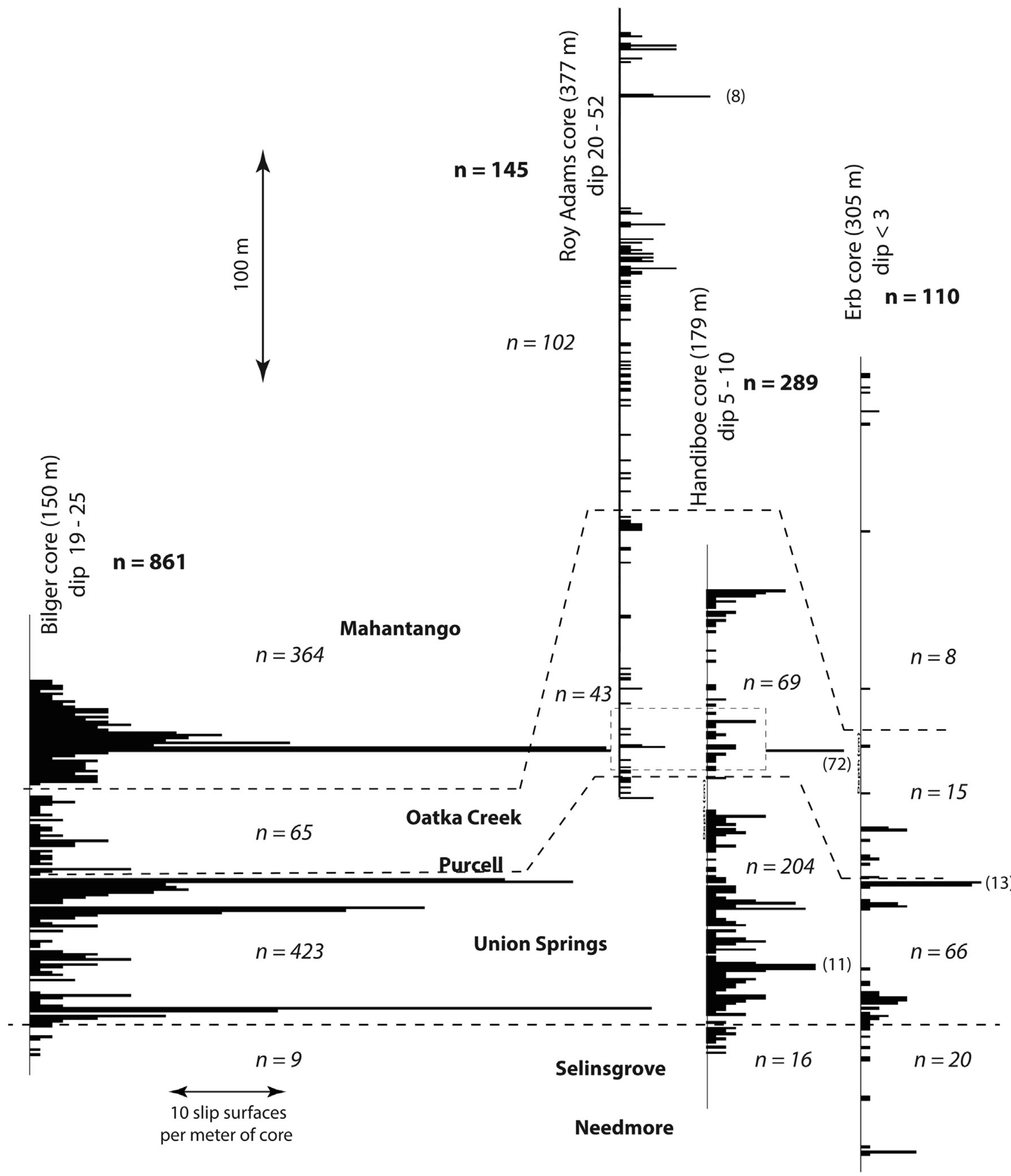

Fig. 9. The distribution of slip surfaces within the three Marcellus cores of this study. The data are binned in 1 m intervals with the maximum of (72) slip surfaces in one bin in the Bilger core. Bedding dip varies in all three wells to such an extent that correction for true bed thickness was not attempted. The result is that the cored interval in the Bilger well appears 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. The thicker Marcellus section in the Handiboe core is a true stratigraphic thickening.

Formation. The thickest cleavage duplexes are located in this part of the section. Here, calcite fillings in the form of beef also populate the cleavage duplexes (Fig. 15a). Quartz, probably biogenic, is more than 40% volume in the matrix of this portion of the Marcellus section whereas there is very little calcite in the matrix (Fig. 15c).

Since quartz is the significant mineral for the Union Springs matrix and calcite is significant for the fracture surfaces, quartz–calcite calibration helps define the volume of slip surfaces in the cleavage duplex. XRD analyses of different amounts of a pure quartz–calcite mixtures form a linear calibration line (Fig. 15c). 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. The Union Springs Qtz–Cal line is offset from the pure sample because of the clay and organic matter in the matrix. Some portions of the cleavage duplex in the Marcellus carry as much as 80% calcite beef (Fig. 15c).

5. Discussion

This paper seeks to answer three questions regarding the Hubbert–Rubey pore pressure model for overthrust faulting: 1. Can

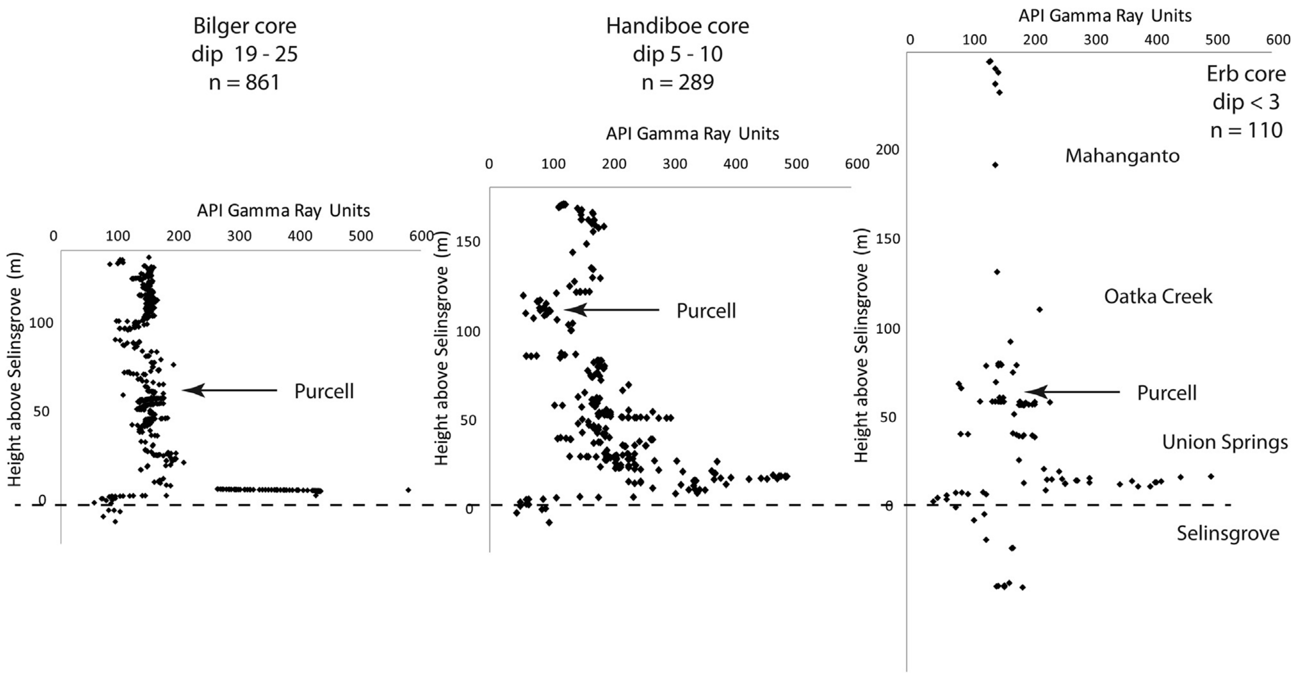

Fig. 10. API gamma ray units for rock matrix on which each slip surface sits. Note that one datum in the Bilger well approaches 600 API units. Number of slip surfaces in each well is indicated by *n*. Like Fig. 9, the height above the Selinsgrove is a vertical distance in a well bore. The horizontal datum is set at the Selinsgrove–Marcellus contact (dashed line).

abnormal pore pressure exist simultaneously along a detachment area of several thousand km^2? 2. What is the mechanism for maintaining high pore pressure over such an aerial extent? 3. Does Coulomb behavior govern slip over such an aerial extent? The answer to the first two questions emerges from the observation that bed-parallel slip in the form of both cleavage duplexes and slickensides are most commonly associated with black shale hosting the buildup of maturation-related pore pressure. While other mechanical properties of black shale may also concentrate detachment, it is hard to dismiss the role of reduced effective stress. The third question is answered by observing slickensides, particularly those with a mirror polish. The broad evidence for diffusion mass transfer along these slip surfaces speaks against a Coulomb material, sensu stricto. Drawing upon experience with central PA gas shale to explain the emplacement of the Pine Mountain detachment sheet without hinterland collapse, we reach an impasse. There is little doubt that maturation-related pore pressure is critical in preventing hinterland collapse. However, the jury is still out on whether an effective stress law coupled with classic Coulomb friction as presented by Hubbert–Rubey is that correct model for Pine Mountain and other large blocks that were pushed toward the foreland without hinterland collapse.

5.1. Pore pressure generation in Appalachian Basin

Abnormal pore pressure comes about in sedimentary basins by a number of mechanisms including mechanical loading (e.g., compaction disequilibrium), changes in volume of fluid when mass is conserved (e.g., thermal maturation of kerogen), fluid movement (e.g., hydrodynamics) or buoyancy when fluid movement is stopped by a trap (e.g., pressure at the top of a gas column) (Osborne and Swarbrick, 1997)). Of these mechanisms, both mechanical compaction and changes in volume of fluid can act over a region. The difference is that pressure from compaction disequilibrium is gone once it leaks whereas maturation-related pore pressure is continually renewed even when leaking. A hydrodynamic drive may be regional but does not focus exclusively at a detachment level. In the Appalachian Basin, evidence for a complex set of paleo-overpressure events is evident from fluid inclusion trapping pressures from veins cutting the Marcellus, thus indicating that the mechanism for pore pressure generation had to continuously recharge if there was leakage (Evans, 1994, 1995).

An early mechanism for abnormal pressure in the Appalachian Basin is compaction disequilibrium as recorded in the undercompaction of shale based on a chlorite fabric (Engelder and Oertel, 1985), anisotropy of magnetic susceptibility (Hirt et al., 1995), and compaction around concretions (Lash and Blood, 2007). Other indirect indicators of the presence of seal rocks with concomitant abnormal pore pressure include the distribution of volume-loss strain by pressure solution (Engelder, 1984) and the present stress profile in the Upper Devonian section indicative of poroelastic relaxation (Evans et al., 1989). Finally, natural hydraulic fractures are one of the most direct manifestations of high fluid pressures at some point in the burial history of the Marcellus (Engelder et al., 2009; Lacazette and Engelder, 1992; Lash and Engelder, 2007; McConaughy and Engelder, 1999). Natural hydraulic fracturing requires a mechanism capable of recharging which is not provided by compaction disequilibrium. All of this indicates an abnormal pore pressure history of 300 + My in the Appalachian Basin (Lash et al., 2004).

An influx of methane-saturated brines is trapped by fluid inclusions in the Middle and Upper Devonian clastic rock sequence, thus tying high pore pressure to the maturation of hydrocarbons, the mechanism most capable of recharging after leakage (Evans et al., 2012). The Marcellus is also presently overpressured in the northern half of the Appalachian Basin where operators report pressure above 90% of the vertical stress, thus indicating the preservation of high pore pressure for 200 + My (Zagorski et al., 2011). Of the mechanisms proposed by Osborne and Swarbrick (1997) pore pressure generation by thermal maturation in black shale with very low matrix permeability is the preferred explanation for high pore pressure, past and present, in the Appalachian Basin.

The concentration of both slickensides and cleavage duplexes in the lower, most organic rich portion of the Union Springs Member

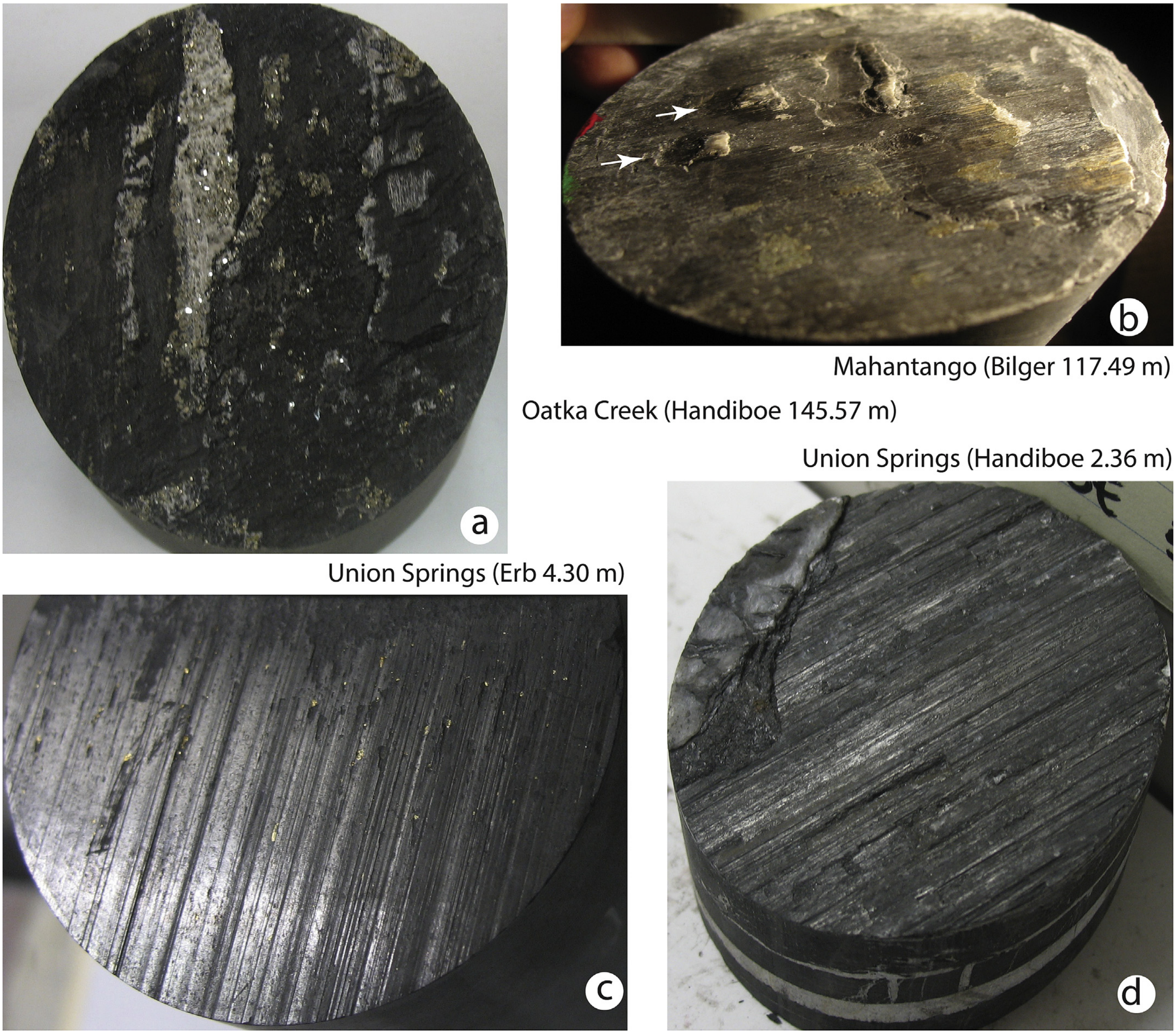

Fig. 11. The morphology of slip surfaces in the Mahantango-Marcellus section ranging from fibers (a and b) to ridge-in-groove striations (c and d).

near the maximum flooding surface is striking (Figs. 5 and 9). In general, the bottom portion of the Union Springs Member is the most organic rich, an indication of the potential for maturation-related pressure generation in this portion of the Marcellus relative to the overlying Oatka Creek (Fig. 10). While generation of pore pressure is not local in two-dimensions (i.e., X–Y) it is conceivable that the action of capillary pressure in a very low permeability rocks (i.e., <100 nD) is sufficient to hold pressure differences in the *Z*-direction on the scale of <30 m. In the Erb well, the development of both slickensides and cleavage duplexes is more common in the Marcellus black shale relative to the Mahantango gray shale, an observation consistent with detachment in the presence of maturation-related pore pressure within organic rich shale. Again this interpretation requires that capillary pressure maintains steep gradient in pore pressure ($\Delta P_p/\Delta z > 0.1$ MPa/m). The association between bed-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. Taking this observation at face value, one might conclude that detachment surfaces through black shale are indicative of a stress-sensitive Coulomb material.

5.2. Mirror-like slip surfaces

The correlation between bed-parallel slip and organic-rich shale is apparent and it is plausible that these slip surfaces are present because of low effective pore pressure during tectonic deformation. Despite the evidence for low effective stress across slip surfaces, pressure solution was an active mechanism during slip. XRD analyses show that chlorite, quartz, and illite are the most abundant minerals in both slickensides and the host matrix. However, the volume fraction of these minerals was altered by a mechanism that concentrated chlorite preferentially along slip surfaces. Concentration of clay and/or mica minerals is characteristic of pressure solution (Rutter, 1983). The idea is that a chlorite film forms as a thin but very planar layer by both deposition by diffusion mass

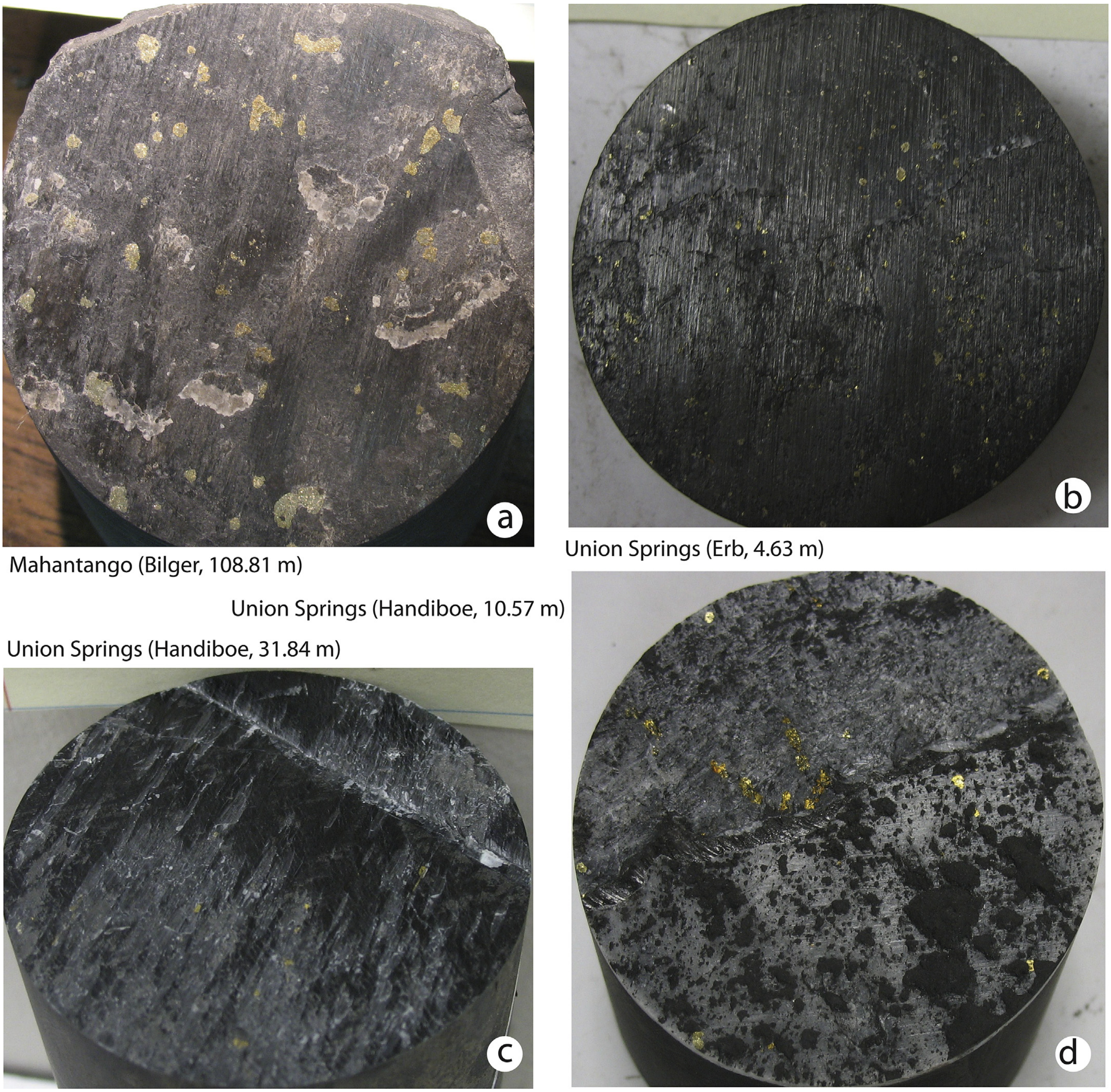

Fig. 12. Progressive mineral development on slip surfaces. (a) Pyrite and quartz entrained in fibers. (b) Pyrite entrained in a ridge-in-grove striations of chlorite. (c) Calcite and chlorite entrained in a mirror surface. (d) A matrix breccia entrained in calcite fibers.

transfer and 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) (Engelder and Marshak, 1985). Diffusion mass transfer is responsible for preferentially removing quartz to be deposited elsewhere as slickenside fibers (Durney, 1972, 1976; Rutter and Mainprice, 1979). The mirror is not so much a polish of concentrated chlorite as it is a residual of chlorite in a zone of slip localization so thin that mirror is the product (Arboleya and Engelder, 1995; Engelder et al., 1975). In many cases, the host rock may be seen right through the mirror finish (Fig. 6). It may be presumed that grains are aligned but these grains of chlorite cannot be resolved under high magnification SEM (Fig. 13).

Evidence of frictional wear, an indication of Coulomb behavior, is not seen at any scale. Chlorite is also deposited by diffusion mass transfer 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 (Fig. 6). In summary, all evidence points to mirror-like slip surfaces in Middle Devonian shale of the Appalachian Basin rising from a pressure solution mechanism causing chlorite and pyrite concentration at the expense of quartz dissolution and

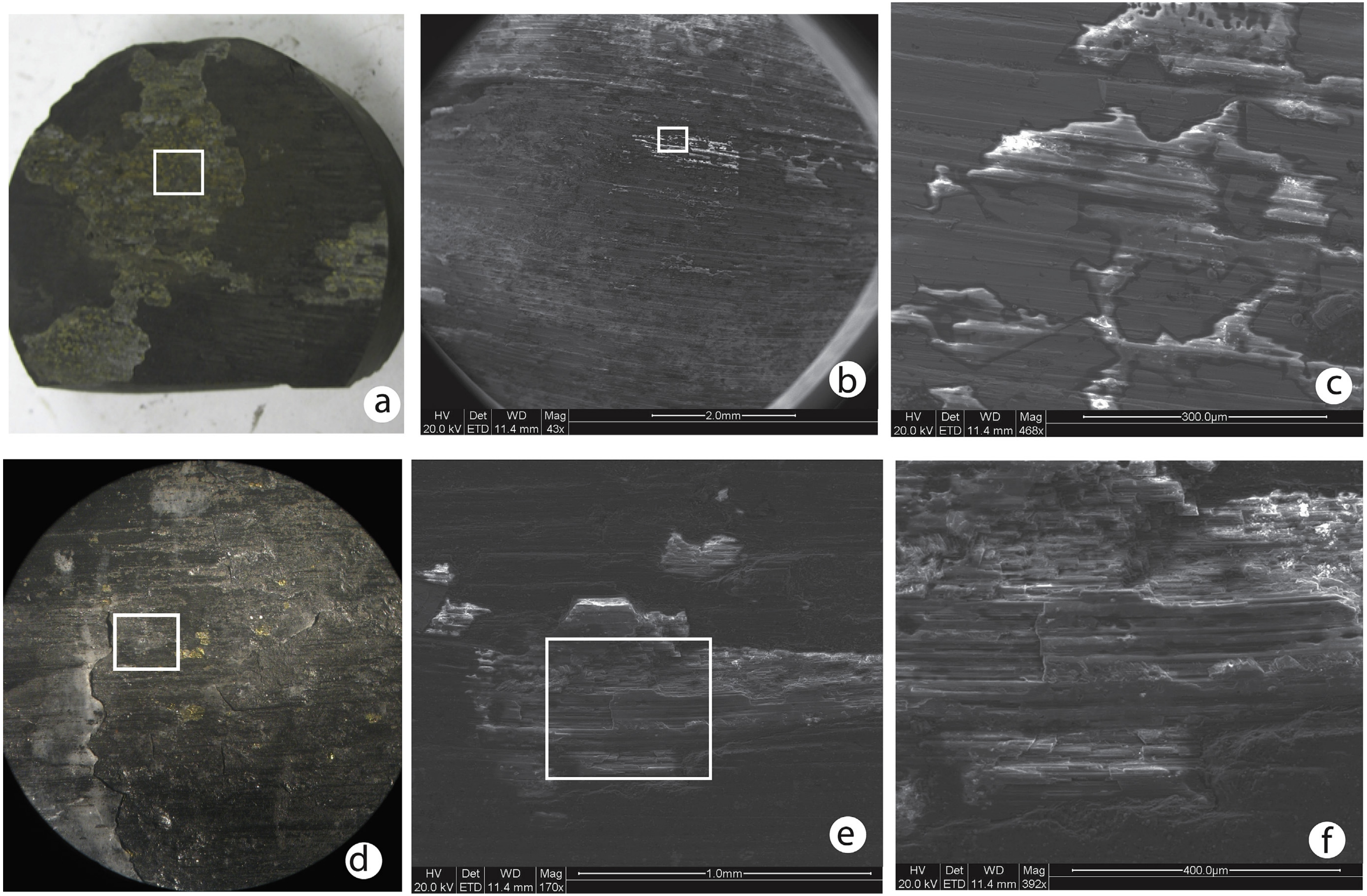

Fig. 13. Slip lineations at different scales. (a) Ridge-in-groove striation on Marcellus 7 m above the Selinsgrove Limestone in the Erb well. (b) Pyrite lineation in the form of ridge-in-groove striation. (c) Pyrite with a positive relief while still carrying ridge-in-groove striations. (d) Fibers of 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.

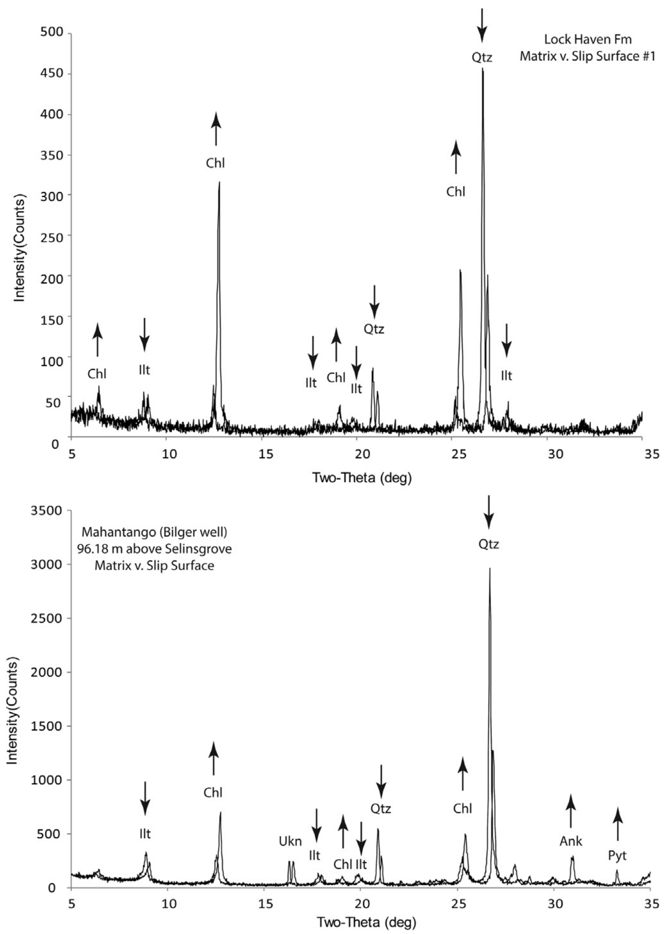

Fig. 14. XRD diffraction patterns from two slip surfaces in the Lock Haven Formation, Williamsport, PA and the Mahantango Formation, Bilger well. In each diagram the slip surface pattern is displaced to the right by 0.2° to allow for better comparison of the patterns. Arrows show which minerals increase and which decrease from the matrix to the slip surface. Qtz – quartz; Ilt – illite; Chl – chlorite Ank – Ankerite; Pyt – Pyrite; Unk – Unknown.

removal by diffusion mass transfer. Here, if an effective stress-like behavior of the type imagined for the Hubbert–Rubey model operates along detachment surfaces, it is associated with pressure solution rather than a classic brittle friction.

5.3. Ridge-in-groove striations

Ridge-in-groove striations are common at all scales down to the microscopic where grooves that are part of mirror-like slip surfaces on Marcellus bedding (Fig. 13). On the mesoscopic scale ridge and groove striations appear to imprint on both quartz (i.e., Lock Haven and Mahantango) and calcite (i.e., Marcellus) fibers. Such striations are seen on all minerals including chlorite (Fig. 6) and pyrite (Fig. 13). In fact, they may not be a separate structure but rather a feature of all slickenside surfaces on which there has been little to no brittle frictional wear (Means, 1987). Ridge-in-groove structures are also the manifestation of concentrated slip even when the slip surface is not planar as it does when it leaves the plane of bedding in cleavage duplexes. They also 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 always irregular at right angles to the slip direction but in the direction of slip it is a true lineation. Even on a mirror-like surface, ridge-in-groove grows as a consequence of pressure solution concentrating chlorite relative to quartz and illite. In summary, ridge-in-groove is scale independent and a manifestation of slip when the slip is not cataclastic and presumably the slip behavior is not dictated by a classic Coulomb friction (Fig. 13).

5.4. The Hubbert–Rubey model

There is more than one class of mechanisms for localized slip under large scale detachment. One class of mechanisms for strain localization involves a stress insensitive ductility such as grain boundary sliding in the form of superplastic flow accounts. This is seen at the base of the Glarus thrust in Switzerland where the slip surface is so weak that the detachment sheet may have moved as a rigid block (Schmid et al., 1977). The ductility of a very weak mineral such as halite under the Appalachian Plateau detachment sheet can have the same effect (Davis and Engelder, 1985). In either case, the role of the classical pore-pressure aided frictional slip is not apparent. A second class of mechanisms for slip localization involves a stress sensitive frictional contact where the deformation mechanism is cataclastic as is the case for the Muddy Mountain Thrust in Nevada (Brock and Engelder, 1977). These two classes merge when shale accommodates significant strain deformation by frictional sliding on clay packets (Kennedy and Logan, 1998). Ductility is further enhanced along frictional contacts with the onset of pressure solution by diffusion mass transfer (Wojtal and Mitra, 1986). Regardless of class of mechanism for localized slip (friction v. ductile or stress sensitive v. plastic), high fluid pressure is likely to have played a role in easing slip within a narrow detachment zone (Badertscher et al., 2002; Badertscher and Burkhard, 2000).

While the role of stress sensitive versus plastic slip in large-scale detachment is unclear, the role of reduced effective stress is apparent from the distribution of slip surfaces in the Marcellus. Slip surfaces, both cleavage duplexes and bed-parallel slickensides, are concentrated in the black shale interval in two places in both the Erb and Bilger cores: 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 (Fig. 9). 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 at the top of a buoyant column. The organic content of the Marcellus is different at these two locations. This distribution of slip surfaces supports the contention that low effective stress is important for promoting slip relative to a weakness of the shale, itself, particularly when Mahantango and Marcellus are arranged continuously from top to bottom of a section.

The Pine Mountain overthrust block which rides on the Chattanooga black shale at a thermal maturity sufficient for oil generation (Rimmer et al., 1993). The Upper Devonian Chattanooga extends well beyond the limits of the Pine Mountain detachment sheet, thus providing a regional source that might allow high pore pressure to exist simultaneously over the total length of the Pine Mountain thrust (Fig. 1). Thermal maturity is a process that continues over a temperature range between about 90 °C and 150 °C, thus providing a mechanism for maintaining high pore pressure over the entire length of emplacement time which was at least a few My. These observations point to a role for reduced effective stress but the debate will continue over whether the detachment in the Chattanooga shale slipped along a classic Coulomb material. We think not.

6. Conclusions

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

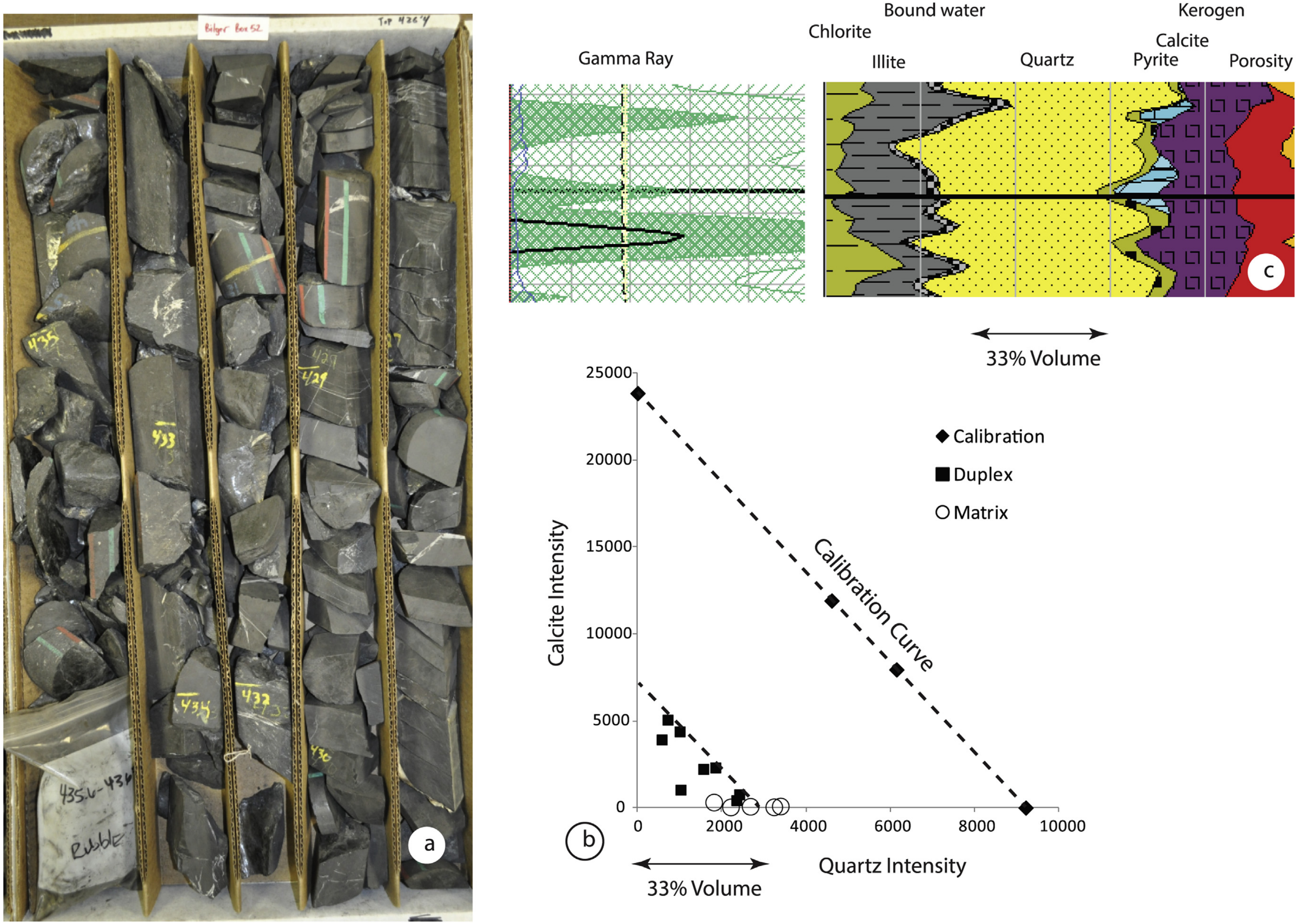

Fig. 15. (a) A box Marcellus core (1–4 m above the Selinsgrove) from the Bilger well showing part of a cleavage duplex (left three slots) and other slip surfaces (right two slots). (b) XRD analyses for eight slip surfaces through a cleavage duplex within the Marcellus between 2 m and 6 m above the Selinsgrove. 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.

witness the generation of high pore pressure in the Appalachian Basin. 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, particularly near the maximum flooding surface, witnesses the role that maturation-related pressure generation played in detachment at this scale. Slickensides are more abundant on the limbs of folds, an indication of flexural-slip folding aided by maturation-related pore pressure. On a larger scale, black shale is found at the base of the Pine Mountain block. Our interpretation is that the Hubbert–Rubey pore pressure model favors that development of these detachment zones rather than any inherent mechanical weakness of the shale, itself. However, the role of classic cataclastic friction versus a stress-insensitive ductility in the detachment of black shale subject to maturation-related pore pressure is less clear.

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Our colleague, Dave Wiltschko, wrote a number of fine papers on the structural geology of the Appalachian Mountains and, in a sense, this paper is an extension of Dave's interest in the Appalachians. This work benefitted from the support of the Penn State Appalachian Basin Black Shale Group and RPSEA contract 09122-32. As always, the text was improved through the reviews of Peter Cobbold, Gary Couples, and Rick Groshong.

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