Biaxial Horizontal Swelling Strain in West Virginia Coal Mine Roof Rocks in Response to Moisture Adsorption

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Abstract

Study of moisture-induced swelling strain in Pennsylvanian Period rocks of the Appalachian Plateau in West Virginia shows a 2:1 biaxial horizontal anisotropy which trends NW-SE. Oriented in-situ slabs of coal mine roof rock were collected across West Virginia, dry-sawed to size, air-dried to stability, and then monitored for moisture changes and deformations in the horizontal plane through one wetting cycle and drying cycle. Biaxial swelling strains were exhibited in nearly all rocks tested, with maximum horizontal deformations occurring normally-incident to the strike of regional geologic fold structures. This relationship persists as fold strike varies across the study area. A connection with Alleghanian fold development and/or post-Alleghanian fold relaxation is suggested. Deformations were largest in shales, but occurred in sandstones and siltstones as well. During testing, moisture-induced fractures (MIF) developed parallel to the regional fold structure and ranged in size from hairline cracks to sample-destroying cracks that were orthogonal to the observed biaxial swelling strain direction. Preferential wetting and swelling of clay minerals along NE-trending fractures, related to a fold-parallel fracture fabric of regional extent across West Virginia, is the most likely reason for the observed systematic NW-oriented biaxial swelling strains.

The testing methods used in this study are simple and inexpensive and produce robust results that offer insight into a regional, anisotropic mechanical weakness that imparts a dynamic, asymmetrical horizontal stress to moisture-sensitive coal mine roof rocks over time. Because a similar mechanical fabric has been reported in Devonian-age shales, these findings may have implications for shale gas developers in the Appalachian Basin challenged by rapid aperture closure rates along horizontally-drilled induced fracture networks in Devonian rocks like the Marcellus Shale. The paper concludes with an example of how the concept of a preferred swelling strain direction might be applied to improve the effectiveness of roof trusses.

Introduction

When clay minerals in rocks adsorb moisture they expand, creating swelling strain and stress that is separate and distinct from in-situ ground stress. This study tests oriented rock slabs pulled from the mine roof of approximately twenty (20) West Virginia coal mines operating in twelve (12) different coal beds to quantify the horizontal component of strains associated with the swelling stresses. The locations and stratigraphic positions of test samples appear in Figure 1, and span most of the Upper Carboniferous Period (Pennsylvanian Period), ranging from the Pocahontas No. 3 coal bed (Early Pennsylvanian) to the Sewickley coal bed (Late Pennsylvanian).

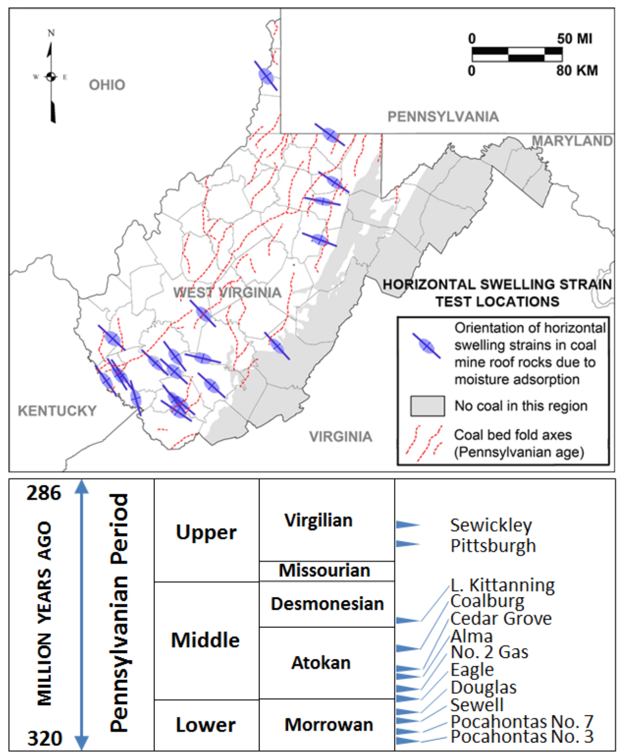


Figure 1. Approximately 69 oriented roof rock samples were pulled in-situ from underground coal mines across West Virginia, ranging upward in age from the Pocahontas No. 3 seam to the Sewickley seam

Pennsylvanian-age rocks of (286-320 million years) in the central Appalachian Basin are fluvial-deltaic successions of sandstone, shale, and minor limestone. The overall gentle northwestward regional dip is interrupted by a number of broad, open anticlines (Figure 1) with limbs dipping generally less than five (5) degrees and axes trending in a northeasterly direction. In West Virginia structural symmetry of these folds extends to deeper sedimentary rocks, including the well-studied gas-bearing Upper Devonian (360-408 million years) rocks that include the Marcellus Shale. Our test results show that during moisture adsorption, sedimentary Pennsylvanian rocks across West Virginia respond with biaxial deformations that are oriented NW-SE (Figure 1). This trend is orthogonal (approximately perpendicular) to a directional strength anisotropy which is aligned parallel to anticline fold axes, and imparts a NE-trending weakness anisotropy to moisture-sensitive shale roof rocks.

This study has two purposes. First, to investigate the possibility that horizontal, moisture-induced swelling strain in sedimentary rocks is related to the present-day horizontal in-situ stress field. Such a relationship has been previously reported for copper-bearing Precambrian (>600 million years) sedimentary rocks in the Michigan Basin (Parker, 1973; Fohey, 1976; Vermuelen, 2011).

The second purpose is to quantify, specifically, the horizontal component of swelling strains which accompany moisture changes in coal mine roof rocks. Shales, in particular, undergo relatively large volume expansions and contractions in response to changes in moisture content, leading to progressive unraveling and eventually roof failure. Prior studies have examined the problem volumetrically, and a few have examined the vertical component of swelling strain (e.g. Chugh, et.al.,1980; Hakan and Peng, 2006), but no previous work has examined the orientations and magnitudes of horizontal swelling strain across West Virginia using oriented samples. A distinct NW-SE oriented anisotropy has been found and an example of how knowledge of this anisotropy may be put into practice to improve the effectiveness of roof trusses will be presented.

Test Procedure

Experiments were performed using a 3-point rosette procedure (Parker, 1973, 2011-2012; Haas, 1982) for measuring the deformation of unconfined rock slabs, using a mechanical strain gauge. Approximately 69 oriented roof samples were collected from underground mines throughout West Virginia between October 2011 and June 2012. In-situ roof samples were collected, as close to the active section as practical. Sample selection targeted rocks that were free of visible cracks or joints, and had not experienced a seasonal humidity cycle. The minimum desired slab size was 16 x 16 x 2 inches, although often larger slabs were pulled, from which several samples could be cut. Most samples were shale although sandstone and sandy shale samples were also tested.

First, slabs were marked for true north using a Brunton compass and double plumb lines. They were then carefully scaled down, wrapped in ventilation curtain, and transported to the lab, where they were cut into octagon-shaped samples, with diameters of 11, 13, or 15 inches, using a dry masonry saw. Prepping the samples in this way minimized rock spalling during testing, provided a clear view of the bedding structure before and during testing, and minimized the potential of rock shape to bias the test results.

Samples were air-dried at 30-50% relative humidity, and their moisture losses recorded over the next 2-6 weeks (Figure 2) by tracking weight change using a digital scale with +/- 2-gram precision. Room humidity levels were monitored with a digital psychrometer and regulated with a dehumidifier.

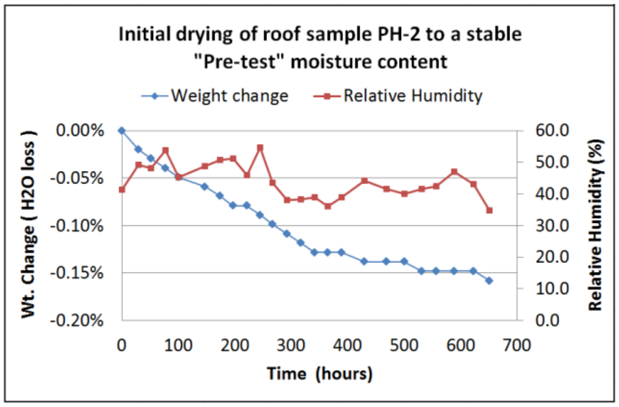


Figure 2. After sawing to size, test samples were air-dried at 30-50% ambient relative humidity. Relative changes in the rock's moisture content were determined by weight change.

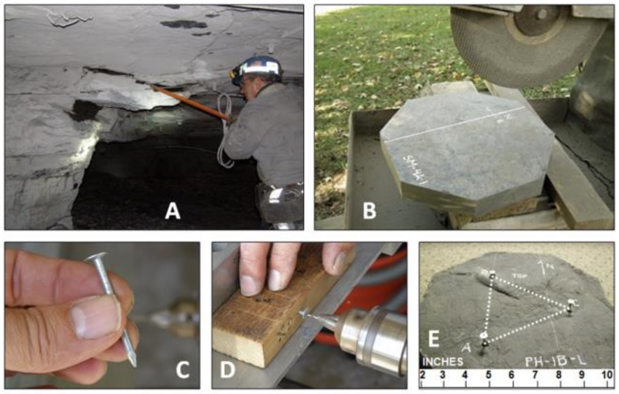


Figure 3. Rock slabs were first marked for true north, then (A) scaled from mine roof and (B) dry-sawed to standard geometry. Spad pins were fashioned (C, D) by drilling a 1/16-inch diameter hole into the top and shank of finished roofing nails, then (E) installed as an equilateral "3-pt. rosette" arrangement into each test sample.

After drying to a stable weight, monitoring points were installed in a 3-point strain rosette arrangement, at vertices A, B, C of a 6-inch equilateral triangle, with Leg AB always being aligned with true north (Figure 3). The slab side with the most level surface was usually chosen to serve as the side for monitoring points (spad pins), so samples tested upside down had an inverted spad pin arrangement.

Spad pins were fashioned by drilling a hole of 1/16-inch diameter through the head and into the shanks of 1.75-inch finished galvanized roofing nails using a drill press (Figures 3C, 3D). A masonry bit and impact drill were used to mount the spad pins. Holes were drilled normal to the bedding, usually to a depth of half the rock thickness, to ensure the spads terminated near a common bedding plane. Pins were trimmed for length and then installed using epoxy, turning and pumping the pins for thirty seconds each to work out air bubbles.

After epoxy cured 8 hours or more, baseline measurements were made between pins using a digital mechanical strain gauge (Figure 4D). When used properly, this simple instrument is accurate to 1/10,000 inch. The name "strain gauge" is a bit of a misnomer, because the measurements actually record a *deformation*, from which *strain* is calculated, and subsequent measurements are relative to the initial baseline readings. An invar steel bar was used to calibrate the strain gauge and compensate for temperature.

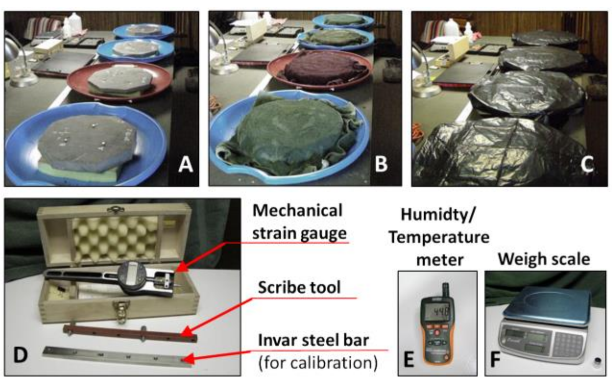


Figure 4. Oriented test samples are (A) placed in containers where (B) they are covered with a wetted towel then (C) covered by plastic sheets to restrict evaporation. Instrumentation includes (D) a mechanical strain gauge, (E) temperature and humidity meter, (F) digital scale.

The method of introducing moisture to the samples was a medium-weight cotton bath towel, wetted with approximately one-half gallon of water, and covered with a plastic sheet to limit evaporation (Figures 4B, 4C). This allowed the samples to take on moisture evenly and at their own rate without saturating them. Either aged water or discharge water from the dehumidifier was used. Two (2) tablespoons of vinegar per gallon were added to retard mildew. If the presence of carbonate minerals was suspected in specimens hydrogen peroxide was substituted for vinegar.

Horizontal, rock deformations were monitored at appropriate time intervals, and redundant measurements were made to verify accuracy. The strain gauge was checked before each session, and periodically during testing, using the invar steel calibration bar. Room temperature and humidity were tracked with a digital temperature/humidity meter (Figure 4E) and rock samples were weighed on a digital scale (+/- 5-grams) to track changes in moisture content (Figure 4F). Measurements were recorded on standard forms, together with the date, time, humidity, temperature, and visual observations. These data were then keyed into an Excel spreadsheet where temperature correction (ASTM, 1999) and charting operations were performed.

Samples were put through one wetting cycle, followed by one air-drying cycle. The wetting phase took 4-45 days (average 18 days) and was considered complete when an expansion plateau was achieved. Corresponding rock weight increases due to moisture uptake ranged 0.12 to 3.91 percent (average 1.06 percent) (Figure 8). When rocks reached this point they were removed from humidity, and the measurements continued for an additional 5-60 days (average 23 days) until the samples had air-dried back to their "pre-test" moisture. Approximately 69 rock samples were tested, of which 57 provided sufficient data to compute oriented strain ellipses for moisture-induced deformation in the horizontal plane (see Figure 8).

Summary of Test Results

Study and comparison of the compiled charts gives useful information about the horizontal swelling behavior. The measured deformations were generally proportional to the weight gain (moisture uptake), but comparisons between sample sets showed differences in the rate, magnitude, and elastic response. Sample sets for each mine ranged from 1 to 5 samples (average 3). An example is shown in Figure 5 which took 451 hours to reach its full expansion at a relative humidity range of 70-90%. During this time the triangle legs a, b, and c expanded by the amounts shown in Figure 5A, as the sample gained 0.35% of its original weight in moisture (Figure 5B). The sample was then allowed to air-dry at 30-50 %RH, until its pre-wet moisture was achieved, which occurred in this example after an additional 348 hours. As the moisture gain reverses, the swelling strain generally follows, but there were exceptions.

Insights into elastic response appear in Figure 5A**,** which shows that approximately 26% of the rock deformation did not recover after air-drying to the starting (pre-test) moisture. This is an example of a residual horizontal deformation that becomes the new starting point for the next humidity cycle.

When rock samples were temporarily removed from humidity for weighing, the surface evaporation tended to highlight and reveal subtle fractures on rock surfaces that were not obvious before wetting. As testing progressed it was noticed that these cracks developed on samples with a dominant northeast orientation (see Figures 11, 13 for examples). The significance of these fractures will be discussed later.

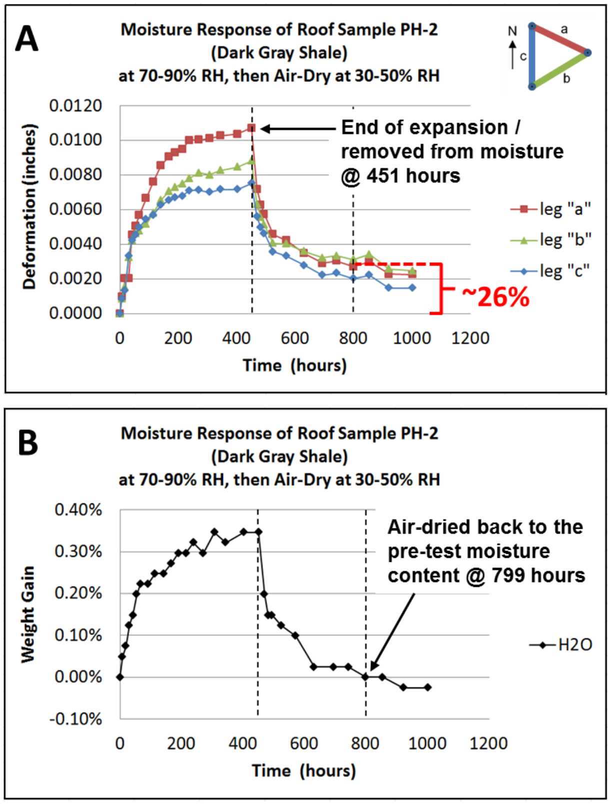
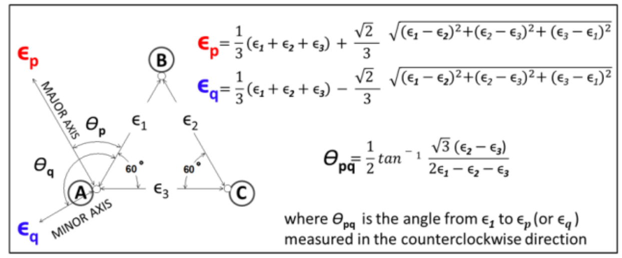


Figure 5. (A) Oriented rock samples were put through one wetting cycle and one drying cycle. Their 2D horizontal deformations were monitored at spad pins installed at the vertices of an equilateral triangle (legs are identified a,b,c). (B) Corresponding changes in moisture content were also monitored. Approximately 69 series of charts were compiled from over 16,000 measurements for this study.

The actual amount and types of clay minerals in the test samples were not measured, but samples were retained and may be tested at a later date. Sandstone response showed less correlation with moisture content than the shale samples. While sandstones initially showed a correlation between rock expansion and moisture increase, sometimes the expansions ceased, and sometimes reversed, even as moisture uptake continued. Sandstones have a greater porosity than shales, and their aberrant expansion response compared to shale is attributed to the permeability of sandstone samples we tested being dominated by pores rather than microcracks. Shales on the other hand appear to utilize the subtle NE-trending fractures and microcracks as conduits for transmitting water into the core of rock.

Deformation measurements were converted to strain ellipses using equations derived from U.S. Bureau of Mines research in the 1960's (Obert and Duvall, 1967) that is summarized in Figure 6. The solution is sometimes referred to as the "3-point strain rosette," and we used those parameters to compile and graph our strain statistics, in Excel.

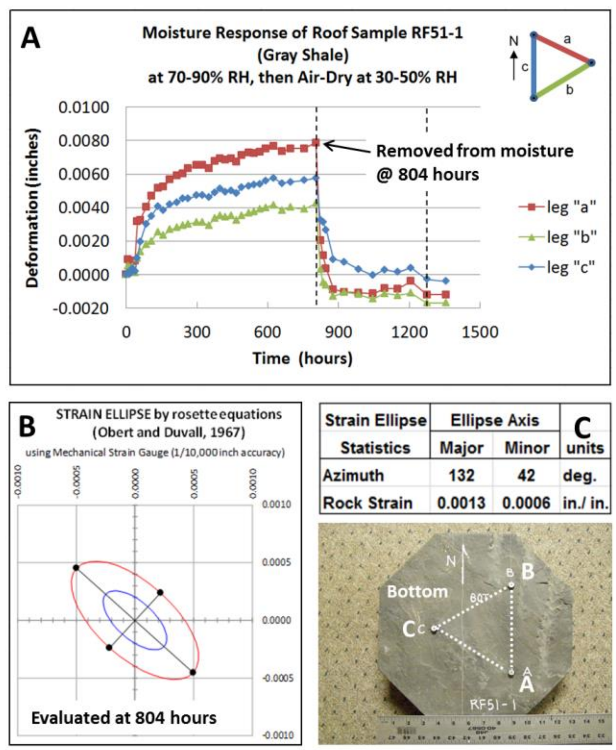


$$\epsilon_p = \frac{1}{3}(\epsilon_1 + \epsilon_2 + \epsilon_3) + \frac{\sqrt{2}}{3}\sqrt{(\epsilon_1-\epsilon_2)^2+(\epsilon_2-\epsilon_3)^2+(\epsilon_3-\epsilon_1)^2}$$

$$\epsilon_q = \frac{1}{3}(\epsilon_1 + \epsilon_2 + \epsilon_3) - \frac{\sqrt{2}}{3}\sqrt{(\epsilon_1-\epsilon_2)^2+(\epsilon_2-\epsilon_3)^2+(\epsilon_3-\epsilon_1)^2}$$

$$\theta_{pq} = \frac{1}{2}\tan^{-1}\frac{\sqrt{3}(\epsilon_2-\epsilon_3)}{2\epsilon_1-\epsilon_2-\epsilon_3}$$

Figure 6. Equations for resolving the strain ellipse for deformation between three monitoring pins at vertices *A, B, C* of an equilateral triangle *(adapted after Obert and Duvall, 1967; Haas, 1982)*.



Strain Ellipse Statistics	Ellipse Axis Major	Ellipse Axis Minor	units
Azimuth	132	42	deg.
Rock Strain	0.0013	0.0006	in./ in.

Figure 7. Example results of (A) measured deformations along legs a, b, and c that (B) can be resolved to a strain ellipse using the *3-pt. strain rosette* equations, and (C) from which the azimuth and strain along the major and minor axes are readily computed.

Strain ellipses can be constructed at any selected point during testing. Typically, the reference point used for strain comparison was at the end of moisture expansion. The measured deformation in the example shown in Figure 7A was evaluated at the end of moisture expansion (804 hours) and the calculated values for azimuth, deformation, and strain appear in Figure 7C. The resulting strain ellipse is shown Figure 7B. The strain values were checked using an independent geometrical solution developed for this project and found to be in close agreement.

Sample	A	HORIZONTAL SWELLING STRAIN from MOISTURE					
			Swelling Strain (in./in.)			ε_{max}	% H2O
Location	Rock Type	n	MAX	MIN	Ratio	Bearing	Gain
1	Med.-gr. SS; Micaceous, burrowed	2	0.0005	0.0004	1.4	N 44 W	1.17
2	SS with siderite cement	2	0.0006	0.0003	2.2	N 78 W	0.12
3	Med.-gr. SS; micaceous	3	0.0008	0.0005	1.6	N 51 W	0.57
4	Dark gray shale w/siderite bands	3	0.0010	0.0006	1.7	N 78 W	0.27
5	Fine gr. SS w/ siderite bands	3	0.0010	0.0006	1.8	N 48 W	0.63
6	Gray shale	3	0.0013	0.0006	2.0	N 49 W	0.31
7	Cannel bone	2	0.0016	0.0012	1.3	N 40 W	1.09
8	Dark gray shale	3	0.0016	0.0009	1.8	N 54 W	0.43
9	Gray silty shale / gray SS	3	0.0018	0.0010	1.9	N 36 W	---
10	Dark gray shale	2	0.0019	0.0010	1.9	N 39 W	0.45
11	Dark gray shale	4	0.0020	0.0011	1.8	N 69 W	0.38
12	Dark shale	2	0.0028	0.0019	1.5	N 37 W	1.54
13	Light gray shale	1	0.0029	0.0018	1.6	N 47 W	1.61
14	Gray shale	5	0.0030	0.0017	1.8	N 44 W	0.63
15	Gray shale	3	0.0034	0.0023	1.5	N 47 W	1.77
16	Dark gray shale	3	0.0043	0.0021	2.0	N 40 W	1.14
17	Dark gray shale	1	0.0047	0.0026	1.8	N 16 W	1.08
18	Dark gray shale	4	0.0054	0.0025	2.2	N 45 W	1.26
19	Soft gray shale	2	0.0076	0.0040	1.9	N 53 W	1.42
20	Gray shale; soft, soapy	3	0.0117	0.0048	2.4	N 34 W	3.91
21	Dark gray shale w/ FeCO3 nodules	3	0.0121	0.0041	3.0	N 39 W	1.33
		57		AVERAGE	1.9		1.06

B	IN-SITU EXCESS HORIZONTAL STRAIN Tectonic horizontal strain in Central Appal. (1)				(1) Also called "excess horizontal strain," calculated from the measured horizontal stresses by removing the expected effects of gravity (assumes 0.25 value for Poissons Ratio). Ref.: Dolinar, (2003)
n	HI- MAX	HI-MIN	LO-MAX	LO-MIN	
12	0.000760	0.000410	0.000370	0.000170	
	0.0008	0.0004	0.0004	0.0002	
	(rounded to 4 significant digits)				

Figure 8. Test results summarizing (A) horizontal strains from moisture-induced rock expansion, compared to (B) the *in-situ* tectonic component of horizontal strain (excess horizontal strain) in the "high-strain" zone of the Central Appalachian basin *(Dolinar, 2003)*.

Test results (Figure 8A) show that the swelling strains are biaxial, with the ratios of the ellipse axes ranging from 1.3 to 3.0 (average 1.9). Interestingly, all test locations demonstrated northwest-oriented biaxial strains. Sandstones exhibited the smallest horizontal swelling strains, with major axes between 500 and 1,000 micro-strains (0.0005 to 0.0010 inch/inch). Shales exhibited the highest horizontal swelling strains, typically 2,000 to 8,000 micro-strains, with one shale sample set having a swelling of 12,100 micro-strains. For comparison, 4,000 micro-strains over a 20-ft.-wide mine opening would produce nearly 1 inch of horizontal rock expansion.

Compared to strains associated with horizontal in-situ rock stress reported for the Appalachian Basin (Dolinar, 2003), our swelling strains are non-trivial. Figure 8B details previously published values of "excess horizontal strain" in the Central Appalachian Region (Dolinar, 2003), calculated from measured horizontal stresses by removing the expected effects of vertical load. These in-situ rock stresses are some of the highest values in the Appalachian Basin, yet their strains were less than the horizontal swelling strains we measured due to moisture changes. This does not imply that the swelling *stress* is greater, however, because wetted rocks lose strength, so the elastic moduli are different (Chugh and Missavage, 1981).

Cause of the Biaxial Swelling Strains

Relationship to In-situ stress

Contrary to initial expectations, the direction of moisture-induced horizontal swelling strain does not appear to be correlated to the horizontal stress field that exists in West Virginia today (Figure 9). Instead, it appears to be related to an earlier stress field that existed during the early Alleghanian Orogeny when NW compression initiated development of the regional NE-trending anticline fold structures in West Virginia (Figures 1, 12).

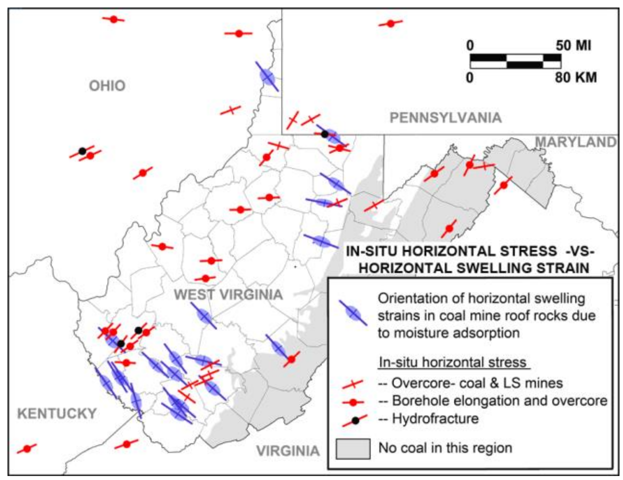


Figure 9. There is no apparent correlation between horizontal swelling strains in Pennsylvanian Period rocks and the present in-situ horizontal stress field in West Virginia.

Previous conclusions by Michigan researchers (Parker, 1973; Vermuelen, 2011) of a parallelism between horizontal swelling strain direction and contemporary stress direction in northern Michigan Basin Precambrian sediments may be explained by the comparatively quiet subsequent tectonic history for the northern Michigan Basin from then to present-day. The stress field remains aligned in the same NW-SE compression direction since its inception (Vermuelen, 2011, Parker, 1973). In contrast, Pennsylvanian rocks in West Virginia have been subjected to multiple subsequent episodes of tectonic deformation, including a general counter-clockwise rotation in the stress field orientation after initial fold development (Evans, 1994). Consequently, the stress field responsible for the NW-trending biaxial swelling strain development has been over-printed, explaining the lack of a general correlation to present-day in-situ stress in West Virginia.

Relationship to Coal Cleat

Coal cleat orientation is indirectly related to swelling strain direction, but with exceptions. As shown in Figures 10A and 10B the trends of coal extension fractures (face cleats) are divided into seven (7) domains in West Virginia (Kulander and Dean, 1993). Each domain has a major cleat trend and, sometimes, a minor cleat trend. The dominant, major cleat trends are likely the first-formed (Kulander and Dean, 1993), and their strike is in the direction of maximum horizontal stress at the time formed.

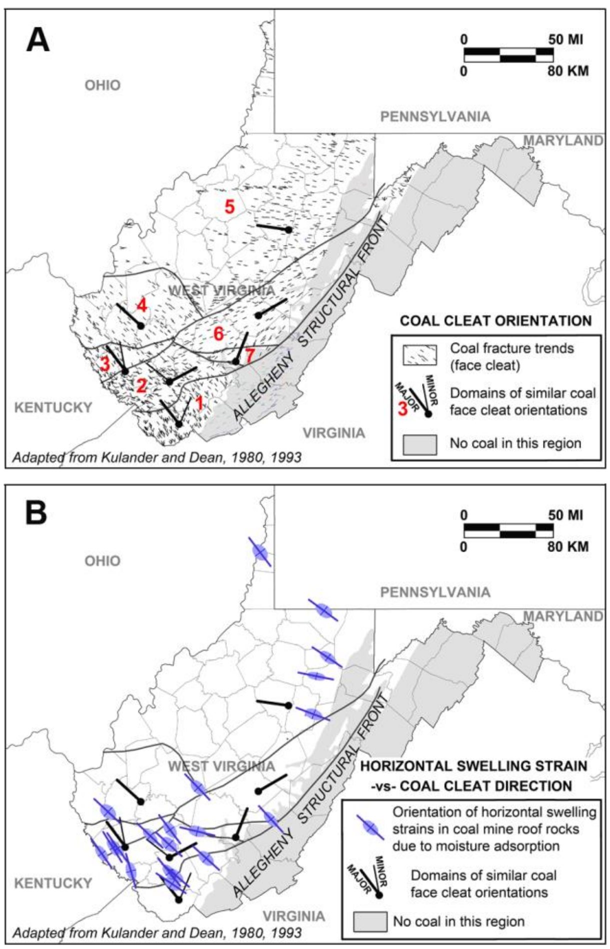


Figure 10. (A) Coal cleat trends are divided into seven (7) domains of similar orientations *(Kulander, and Dean, 1981, 1993)*. (B) When generally compared to the trends of horizontal swelling strains in coal mine roof rocks they are similar, except for Domains 6, 7, and part of 2.

Major coal cleat trends across West Virginia are predominantly oriented NW-SE, normal to regional fold axes and parallel to horizontal swelling strain. There is an exception that includes a single contiguous area along the Allegheny Structural Front in Domains 6, 7, and the eastern part of 2, where coal cleats strike predominately ENE, and are seemingly correlated with today's horizontal stress field (Figure 9), but this may be coincidental (Engelder and Whitaker, 2006). The ENE coal cleats of Morrowan-age coal beds (see Figure 1) situated along the Allegheny Structural Front are believed to pre-date Alleghanian fold development (Engelder and Whitaker, 2006). West Virginia's NE-trending regional folds developed next, and their anticline fold axes (Figure 12) appear as the common denominator between the orientation of remaining major coal cleats and orientation of the maximum horizontal swelling strain west of the Allegheny Front.

Relationship to Regional Anticline Fold Axes

The trends of maximum horizontal swelling strain in our dataset appear to be normally-incident to anticline fold axes, and this relationship persists as fold strike varies across the study area (Figure 12). Regional fold axes developed during the early part of the Alleghanian Orogeny when the horizontal stress field was oriented NW. A relationship to this earlier stress field is suggested, either as 1) an artifact of residual Alleghanian stress, or 2) post-Alleghanian stress unloading and relaxation.

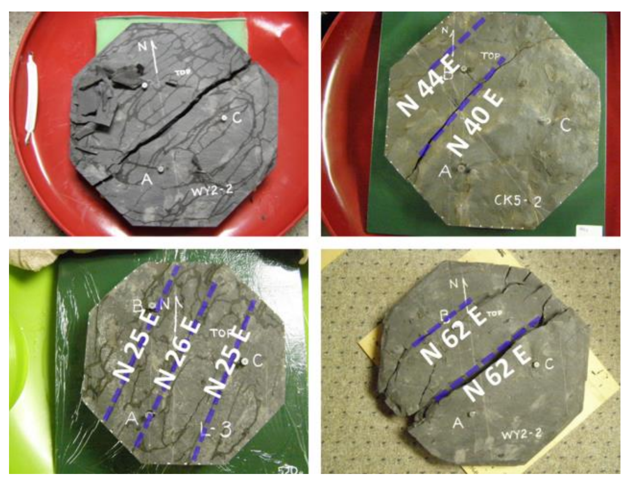


Figure 11. Examples of NE-trending cracks observed during moisture adsorption.

This relationship extends to the NE-trending fabric of tensile weakness that was mentioned earlier (see Figure 11). The moisture-induced fractures that developed in about 25% of our test samples in West Virginia (predominantly shale rocks) always trended northeast. Some samples failed along these cracks, spoiling the results for strain measurement. These fractures were not discernible in the rocks until they began to take on moisture during testing.

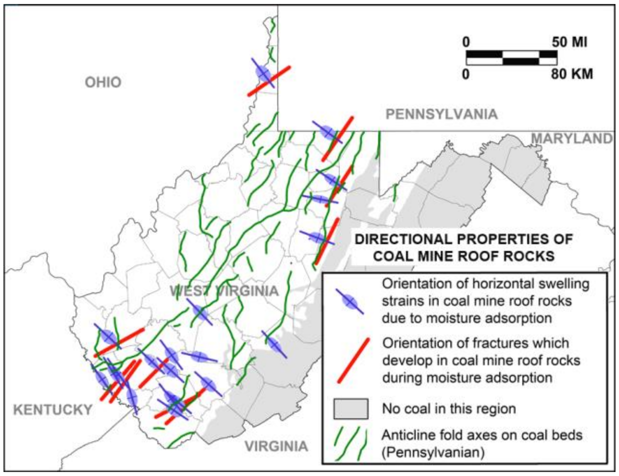


Figure 12. NE-trending fractures (red) that develop in coal mine roof rocks during moisture adsorption open along directions that are sub-parallel to anticline fold axes (green). Our tests show biaxial horizontal swelling strains develop perpendicular to these fracture trends.

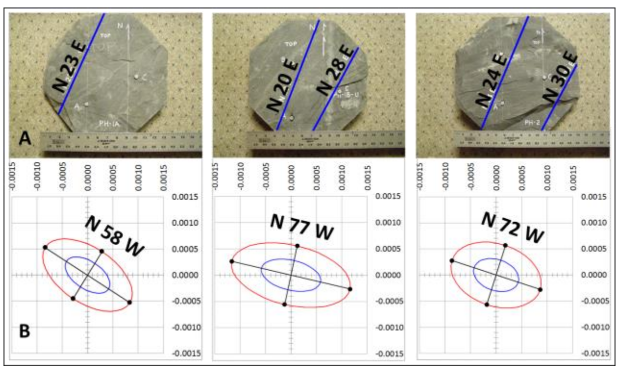


Figure 13. (A) Moisture-induced, NE-trending fractures which developed in test samples are (B) orthogonal to the major axis of swelling strain. The samples depicted came from the same mine.

The orientation of moisture-induced fractures (MIF) from the various locations we tested varied between N 25 E and N 62 E (average N 45 E). MIF trends are aligned orthogonally to the major axis of swelling strain, which varies, by test location, between N 16 W and N 78 W, (average N 47 W). An example of this orthogonal relationship is shown in Figure 13. MIF directions follow the primary NE-trending fold axes across West Virginia and are believed to be related to the "SJV" joints in Devonian cores described by Evans (Evans, 1994) and to a direction of inferred tensile weakness in Devonian rocks (Figure 14). These are attributed to post-Alleghanian release fractures that impart a preferred direction of weakness in (Devonian) shales, facilitating the opening of joints during stress relaxation or reorientation (Evans, et. al., 1989; Evans, 1994). Parallelism between this weakness trend and fold axes persists, even as fold strike varies across West Virginia. This rock strength anisotropy affects the direction and manner in which the immediate shale mine roof unravels and transmits moisture across bedding planes and into the internal rock mass.

Other insight into the mechanical fabric in Pennsylvanian Period rocks comes from the research of Devonian rocks sponsored by the U.S. Department of Energy in the 1970's and 1980's, as part of the Eastern Gas Shale Project (EGSP). An adaptation of some of that information is incorporated into Figure 15.

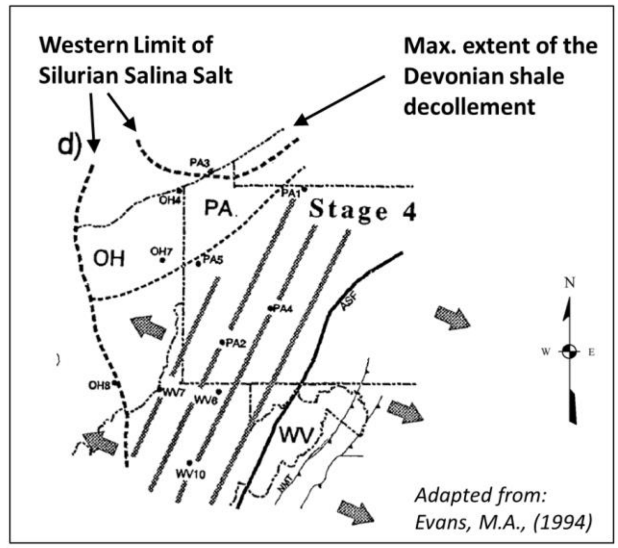


Figure 14. The NE-oriented moisture fracture fabric that developed in our test samples is related to a preferred direction of weakness that facilitated opening of release joints *(Stage 4)* during Post-Alleghanian stress relaxation and reorientation. *Adapted from Evans, M.A., (1994).*

The NE-oriented dotted lines across West Virginia shown in Figure 15 delineate a preferred direction of weakness in Devonian rocks (based on core analyses) which manifests itself as 1) a fracture direction in point load testing, 2) as a minimum tensile strength plane in directional tensile strength testing, and 3) as an ultrasonic velocity minimum in wave velocity testing (Cliff Minerals, Inc., 1982). This "mechanical fabric" is attributable to a microstructure that appears to be an oriented array of micro-cracks on grain boundaries (Cliff Minerals, Inc., 1982).

The Devonian strength anisotropy follows the Devonian anticline fold axes (Cliff Minerals, Inc., 1982). The NE-trending weakness we find in Pennsylvanian Period coal mine roof rocks trends parallel to fold axes in those rocks. Since Devonian and Pennsylvanian fold axes are symmetrical, it appears the NE-trending MIF observed in Pennsylvanian rocks (trends indicated in red, Figure 15) are related to a common Pennsylvanian/Devonian "mechanical fabric."

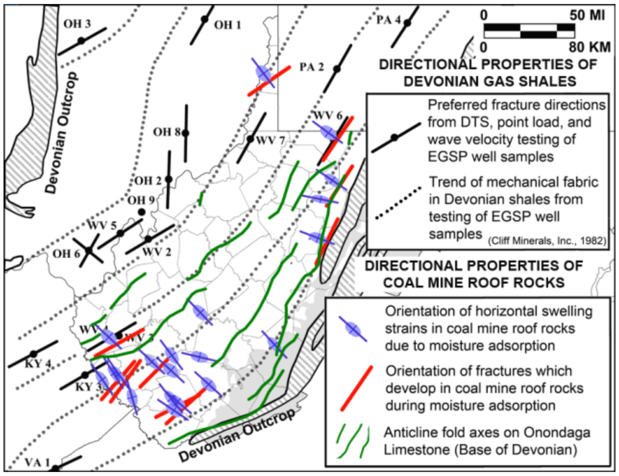


Figure 15. Directional properties observed in Devonian rock cores from the Eastern Gas Shale Project (EGSP) display a mechanical fabric which follows moisture-induced fractures (MIF) observed in coal mine roof rocks.

Consequently, these results suggest the interesting conclusion that there is a subtle, but pervasive, NE-trending mechanical weakness in coal mine roof rocks across West Virginia which is associated with, and perhaps the mechanism for, a NW-oriented swelling strain anisotropy that is also state-wide. Pennsylvanian rocks experienced the same folding event as Devonian rocks. Also, Pennsylvanian coals exhibit a well-developed cleat and a well-developed optical anisotropy. It follows that fine-grained rocks (shales and mudstones) in Pennsylvanian rocks would display a similar fabric (Evans, M.A., 2012). Therefore, Devonian shale rocks may very well possess a NW-SE biaxial swelling response to moisture adsorption as do Pennsylvanian rocks. This may have implications for shale gas developers in the Appalachian Basin challenged by rapid aperture closure rates along horizontally-drilled induced fracture networks in Devonian rocks like the Marcellus.

Implications for Mining

Instability in shale roof strata takes many forms, but, fundamentally, it occurs when separation develops 1) between horizontal weaknesses along bedding planes and, 2) along vertical and angled fractures where friction reduction along impinging surfaces initiates an unraveling process that once started can culminate in massive roof failure (Figure 16).

Weak shale roof rock, when it is first exposed and supported with standard patterns of roof bolts, may initially give the appearance of being adequately supported. However, clay-rich roof shales are susceptible to moisture damage over time (Figure 17). The moisture may be introduced either from recurring seasonal humidity changes brought into the mine via the ventilation system (Unrug and Nandy, 1988; Stateham and Radcliffe, 1978) or by roof bolt penetration into overlying wet strata that introduces dripping water into the annulus where it then distributes moisture throughout the rock mass. The result is a loss of rock strength that appears as 1) lost cohesion and fracture surface friction, and 2) a reduction in the elastic modulus (softening) of the rock. Eventually massive roof failures can develop, in intersections and elsewhere, where pressures from swelling strain, combined with the reduction in rockmass strength, culminate in an unraveling and "dead weight" roof that no longer has sufficient internal strength to remain supported by vertical roof bolts.

Figure 16. An example of coal mine shale roof unraveling between roof bolts in response to internal strains and reduction in rock strength caused by moisture adsorption.

Successfully supporting moisture-sensitive weak shale roof in critical entries over the long term remains one of the unsolved challenges in coal mining. While it is unlikely that a magic bullet exists that can fix the problem, supplementing our understanding of the geo-mechanical behavior of weak shale roof rock facilitates management of the problem. In this regard, the recognition that, when roof rocks cycle through humidity changes, they develop preferential NW-trending swelling strain and preferential NE-trending mechanical weakness gives insight that might inspire refinements that can enhance the effectiveness of new and existing roof control strategies.

An example of this might include unconventional installations of trusses, whereby lateral compression is directed where it does the most good (Figure 18).

Roof trusses are sometimes installed in intersections to control weak shale ground movement. When trusses are installed after moisture damage has already occurred, they function basically as a "sling." However, if trusses are installed early, before damage occurs, they are more effective, and their effectiveness may be further enhanced by installing them normal to the NE-trending "mechanical fabric." Further, trusses that are so oriented are automatically in alignment with maximum horizontal swelling strain, thereby increasing rock compression by increasing truss tension. The idea is that the lateral compression of the truss helps keep vertical joints and fractures locked together.

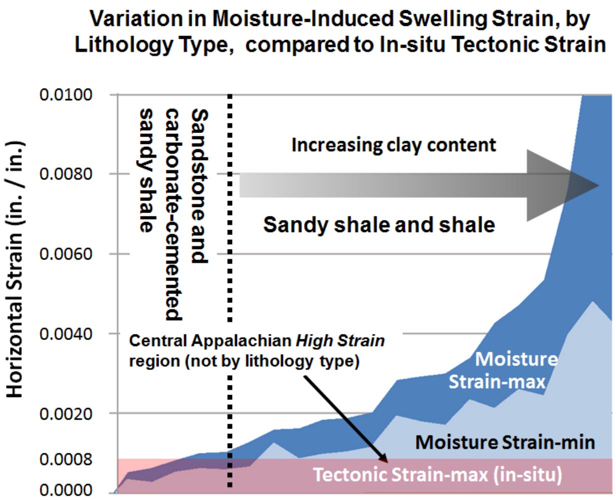


Figure 17. Swelling strains increase with apparent clay content. Shale rocks exhibit moisture-induced strains exceeding calculated *in-situ tectonic horizontal strain* for the Central Appalachian *High-Stress* Region (refer to Figure 8).

In theory, trusses installed (A) perpendicular to the mechanical weakness direction (MIF) would tend to maximize their effectiveness in reducing roof unraveling during humidity uptake. Conversely, trusses installed (B) parallel to the NE-trending fabric (MIF) would provide less benefit.

In 4-way intersections where entries have been driven in a NE-SW direction, conventional truss installation (across the entries and with carriers installed in cross-cuts) would be appropriate. However, for intersections in which entries are developed NW-SE, a non-conventional installation, one in which trusses are aligned in the direction of the entries, might be more effective. Headings driven N-S or E-W would be installing trusses oblique to the fabric so would see comparatively little difference.

Solid bar trusses that are 1-inch in diameter or greater are typically more desirable in this application than cable trusses because they are more rigid. During fall and winter months when humidity subsides and swelling strain reverses, it would be useful if the trusses could be re-torqued, as needed, in preparation for the next spring/summer humidity cycle.

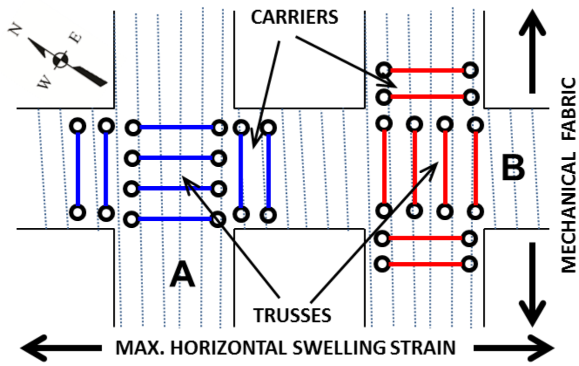


Figure 18. Roof trusses installed in 4-way intersections to arrest unraveling of moisture-sensitive weak shale roof might be more effective (A) installed *perpendicular* to the NE-trending strength anisotropy (mechanical fabric) versus (B) in parallel with it.

While this is a hypothetical example, and has not been tested to our knowledge, it illustrates one way that design enhancements incorporating knowledge of directional rock anisotropy in mine roof might be put into practice.

Conclusions

Tests of oriented roof rocks in underground West Virginia coal mines show the following:

1) Evidence of a regional NE-trending fracture fabric in roof rocks that is coupled with a dynamic, asymmetrical horizontal stress caused by NW-SE swelling strain in response to a moisture uptake. The swelling strain anisotropy appears to be related to preferential hydration and swelling of clay minerals along NE-trending fractures, but more study will be needed to confirm this conclusion.

2) The NE-trending fracture fabric appears in both Pennsylvanian and Devonian rocks and is likely related to post-Alleghanian stress relaxation facilitating tensile crack development oriented sub-parallel to anticline fold axes. Moisture adsorption exploits these unhealed fractures, weakening roof rocks preferentially in a NE direction as it induces a 2:1 biaxial expansion in a NW-SE direction.

3) Because their mechanical fabrics are similar, the NW-trending horizontal swelling strains may exist in Devonian rocks as well. This has implications for shale gas developers in the Appalachian Basin who are challenged by the rapid aperture closure rates along horizontally-drilled induced fracture networks in Devonian rocks like the Marcellus.

4) The concept of a NW-oriented swelling strain anisotropy perpendicular to a regional mechanical weakness trend may be a useful new addition to the geo-mechanical toolkit.

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