URTeC: 2670437

Insights from the Marcellus Shale Energy and Environment Laboratory (MSEEL)

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This paper was prepared for presentation at the Unconventional Resources Technology Conference held in Austin, Texas, USA, 24-26 July 2017.

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Summary

The Marcellus Shale Energy and Environment Laboratory (MSEEL) involves a multidisciplinary and multi-institutional team undertaking integrated geoscience, engineering and environmental research in cooperation with the operator, Northeast Natural Energy LLC., numerous industrial partners and the National Energy Technology Laboratory of the US Department of Energy. The objective of MSEEL is to provide a long-term collaborative field site to develop and validate new knowledge and technology that can improve recovery efficiency while minimizing environmental implications of unconventional resource development

MSEEL consists of two legacy horizontal production wells completed in 2011, two new logged and instrumented horizontal production wells completed in 2015, a cored vertical pilot bore-hole, a microseismic observation well, and surface geophysical and environmental monitoring stations (Figure 1). Production from the new horizontal wells began in December 2015 and monitoring continues. Production logging to determine production efficiency was undertaken in early 2017 and is under evaluation. MSEEL has generated a large and diverse (multiple terabyte) dataset that provides significant insight into drilling operations, Marcellus Shale geology and fracture stimulation operations.

During drilling detailed geomechanical and image logs of the lateral and geochemical analysis of the whole core and sidewall cores were obtained. As part of the core analysis, kerogen was extracted from the different zones and analyzed to understand hydrocarbon generative potential, and interaction of the organic and inorganic matrix components with the fracture stimulation fluids (Agrawal et al., 2016; Agrawal et al., 2017; Agrawal and Sharma, 2017; Sharma et al., in press). Core and log data were coupled with microseismic and slow-slip seismic monitoring, and distributed temperature sensing (DTS) and distributed acoustic sensing (DAS) fiber-optic monitoring during completion. Subsequent production logging and continued DTS monitoring show the influence and interaction in the Marcellus Shale of both the present stress regime oriented northeast-southwest and the numerous preexisting healed and calcite cemented fractures oriented approximately east-west. The analysis of the comprehensive cluster-by-cluster completion data derived from surface and subsurface from the MSEEL project has contributed to an improved understanding of the effect of stage spacing and cluster density practices that could be used to significantly improve stimulation effectiveness and optimize recovery efficiency in the Marcellus and other unconventional reservoirs. The results provide an unprecedented picture of subsurface rock properties, stimulated reservoir volumes, faults and fracture systems. Understanding the distribution and strong influence of preexisting

fractures is demonstrated to lead to improved completions in an individual well, and strategies to improve completions across the southern portions of the Marcellus Shale play. Overall MSEEL is working to develop and validate new knowledge and technology and identify best practices for field implementation that can optimize hydraulic fracture stimulation and minimize environmental impacts of unconventional resource development.

Introduction

The Marcellus Shale Energy and Environment Laboratory (MSEEL) consists of a multidisciplinary and multi-institutional team undertaking integrated geoscience and engineering in cooperation with the operator Northeast Natural Energy, LLC., numerous industrial partners, and the Department of Energy. MSEEL consists of two legacy horizontal production wells (MIP 4H and MIP 6H) drilled in 2011, two new logged and instrumented horizontal wells (MIP-3H and MIP-5H) drilled and completed in 2015, a cored and logged vertical pilot bore-hole (MIP-3H), and a microseismic observation well (MIP-SW) (Figure 1). Production from the new horizontal wells began in December 2015 and is available online (http://www.mseel.org). Production is limited by pipeline distribution and consumption in the City of Morgantown, but the MIP wells are capable of producing multiple millions of cubic feet per day. MSEEL has integrated geophysical observations (microseismic and surface), fiber-optic monitoring for distributed acoustic sensing (DAS) and distributed temperature sensing (DTS) in the MIP-3H, advanced well logs, core data and production monitoring, to better characterize subsurface rock properties, and propagation pattern of induced fractures in the stimulated reservoir volume. We will concentrate on the evaluation of the completion efficiency of the MIP-3H undertaken in late 2015.

Data and Methods

Multistage hydraulic fracture stimulation is a required for viable production from unconventional shale-gas and tight-oil reservoirs. In the case of the MIP-3H stimulation over 28 stages involved injection, at high pressure, averaging 8500 psi (58.6 MPa), to break the formation and establish a complex network of permeable fracture pathways, of 1,900 pounds of proppant (20.2 cubic feet) and 1,760 gallons of fluid (235.3 cubic feet) along every foot of the 6,058 feet (1846m) of completed lateral (~255 cubic feet per foot of lateral, 23.7 cubic meters/meter). Generally, reservoir stimulation is thought to be associated with reactivation of pre-existing faults and fractures, with minor contribution from creation of new hydraulic fractures (Moos et al., 2011; Das & Zoback, 2013). Pre-existing natural fractures appear to affect the stimulation process. Gale et al., (2008) analyzed natural fractures of Barnett Shale core from Pecos County, Texas. The tensile testing on the cores showed failure along fractures even though fractures were sealed. They proposed that the Barnett Shale in the Fort Worth Basin has sealed natural fractures that affect hydraulic fracture propagation. This could be a result of reactivation of natural fractures and hence hydraulic fracture propagation at natural fracture tips. The distribution of microseismic events is most commonly used as a proxy for deformation along pre-existing faults and fracture, and opening of new fractures during hydraulic fracture treatment to outline the shape of stimulated reservoir volume (SRV). Evidence exists both in support of and opposed to microseismic as a method to image the SRV (e.g., Wilson et al., 2016a; Sicking et al., 2013).

The MIP 3H was drilled initially as a pilot, and cored and logged. A total of 111 feet (34m) of core was recovered from the top of the Marcellus Shale to the top of the underlying Onondaga Limestone. Core and related sidewall cores are undergoing analysis for geomechanical properties, geochemistry, porosity and permeability. Computerized tomography (CT) of the vertical core from the MIP-3H pilot hole displays the horizontal laminated nature of the shale and several vertical natural fractures in Marcellus Shale that are calcite cement filled (Figure 2).

The orientation of S_{Hmax} estimated from induced fractures in the Marcellus Shale observed in the vertical pilot hole is N57°E. A comprehensive suite of logs were collected in the vertical pilot hole and used to develop geomechanical properties and log derived parameters (Wilson et al., 2016b and Wilson et al., submitted). The logs being used to calculate geomechanical parameters (Poisson, Young's, Brittleness) are integrated with microseismic parameters (event count, b-value, and moment magnitude (Zorn et al., in press).

The MIP-3H lateral was targeted to and maintained within a 10 foot (3m) zone just above the Cherry Valley Limestone Member of the Marcellus Shale. A wealth of data concerning geomechanical properties, fracture orientation and intensity were acquired (Figure 3). The P32 fracture intensity was calculated using the wireline image logs. Medical computed tomography (CT) scanning of the vertical core from the MIP-3H pilot hole shows several natural fractures in Marcellus Shale that are mineral filled (Figure 2). More than 1600 resistive (healed) fractures are documented from the wireline image logs in the MIP-3H. Based on image log data obtained in the vertical pilot well, natural fractures are dominated by two sets: a N57ºE set consisting largely of open fractures and a N87ºE set consisting entirely of healed fractures (Figure 4). Healed calcite-cemented fractures observed in the image log along the length of the lateral number more than 1,600 and have an average trend of N79ºE (Figure 3). The first two groups of stages (1-13) were geometric with change in proppant size. The next three groups (14-28) used geomechanical data and fracture intensity acquired by well logging, along the lateral to modify the stage length, cluster spacing and treatment parameters. In addition to a limited entry approach, stages were strategically placed in segments with similar gamma ray, minimum horizontal stress, and natural fracture intensity (Anifowoshe et al., 2016).

MIP-3H completion

The MIP-3H well was completed in five sections from the toe to the heel: A, B, C, D, and E. Sections A and B are completed using a geometrical approach in which geomechanical parameters such as fracture closure stress, fracture intensity are not accounted for. Two types of proppants were used for hydraulic fracturing of MIP-3H: 100 mesh sand and 40/70 white sand. Section A has around 35% 100 Mesh proppants and 65% 40/70 white sand, while Section B has 75% 100 mesh and 25% 40/70 white sand. The completion extends to Section C, named as an engineered completion; Section C is designed by appraising geomechanical parameters from the well logs: each stages is set in a zone with similar fracture closure stress, fracture intensity, and gamma ray (Anifowoshe et al., 2016). The proportion of proppants varies between stages in Section C: Stages 13, 14, 15, 17, and 19 have 35% 100 mesh while Stage 16 has 67% mesh 100 and Stage 18 around 43% mesh 100. In addition, limited entry approach was undertaken by decreasing the number of shots per clusters to enhance stimulation efficiency (Anifowoshe et al., 2016). A new guar-free viscoelastic fracturing fluid known as Sapphire VF140, a trademark of Schlumberger, was used in Stages 20 and 21(Section D). The Section E, involving stages 22 to 28, were completed using a combination of engineered approaches using variations in pumping schedule

Hydraulic fracture stimulation of both the MIP-3H and MIP-5H were monitored with a vertical microseismic array in the MIP-SW well located between the two laterals, and a set of five surface seismometers (figures 1 and 5). Clusters of microseismic events produced during stimulation of the MIP-3H well are oriented on average N59ºE as expected from the regional patterns and from the induced fractures observed in the vertical pilot hole. Wilson et al, (2016b) calculated an average distance of 190 feet (58m) above the MIP-3H wellbore to the center of the radiated microseismic energy (Figure 6). The microseismic energy is distributed through the entire Hamilton Group and not localized in the vicinity of the lateral. Fiber optic cable, installed on the outside of the MIP-3H casing, provided distributed temperature (DTS) and acoustic (DAS) data. Acoustic energy and temperature were monitored with the fiber optic cable during fracture stimulation of individual stages, and production continues to be monitored via temperature.

There is a significant difference between the radiated microseismic energy produced during MIP-3H stimulation and injection energy obtained from pumping data available for each stage during well treatment. This analysis reveals that radiated microseismic represents less than 0.01% of the total injected energy (Kavousi et al., submitted). Similar observations of the disparity between energy of microseismic events and moment release expected from hydraulic fracture treatment have been made in other wells (Warpinski et al., 2012; and Das and Zoback, 2013). Much of this energy could be expressed as long period, long duration LPLD events (Das and Zoback, 2011). Numerous similar LPLD events were observed during hydraulic fracture stimulation of the Marcellus Shale at six wells in Pennsylvania and at the MSEEL pad (Kumar et al. 2016, Kumar et al. in press). Two probable mechanisms have been suggested for the occurrence of LPLD events including; higher clay content (>30%) at a local scale, and slip along pre-existing fractures that are unfavorably oriented in the ambient stress field (by Das and Zoback, 2011 and Zoback et al., 2012).

The extracted phase of DAS data (hDVS) measures the local vibrations around the fiber, and fracture stimulation in the Lower Marcellus Shale. Completion energy as expressed by hDVS is linearly correlated with the injection energy and has a strong negative correlation with natural fracture intensity (P32), but microseismic energy is not correlated with either injection energy or hDVS energy (Kavousi et al. submitted). DTS measures temperature changes and was monitored in all stages in the MIP-3H including the stimulated (S+0) stage and the adjoining two previous stages (S-1, S-2) and subsequent stages (S+1, S+2) (Figure 7) (Amini et al. in press). Cooling of the treatment stage and the two following stages toward the heel of the well is expected due to injection of surface water used for fracture stimulation. However, as in Stage 6 (Figure 7), the previously treated stages toward the toe of the well often show an increase in temperature that approaches the temperature of the formation (~165^{o}F). This increase in temperature in previous fracture stimulated stages is especially prevalent in areas with multiple fractures and faults as determined by log data (e.g., Stage 6, Figure 3c).

Discussion

A conceptual model is proposed as an attempt to explain the effect of the numerous preexisting N87^{o}E healed fractures and faults observed in logs, open fractures and borehole breakouts observed in the vertical pilot hole oriented N57^{o}E with observations during fracture stimulation in the MIP-3H (Figure 8). These observations during fracture stimulation include; the extreme disparity between energy of microseismic events and moment release expected from hydraulic fracture treatment, clusters of microseismic events centered well above the lateral and orientated N59^{o}E, observed LPLD events during stimulation, correlation of hDVS with P32 and not with microseismic, and significant warming observed as measured by DTS in previous stages associated with fractures in the lateral. The rapid injection during fracture stimulation of an average of 255 cubic feet of proppant and fluid for every foot of the 6,058 feet (1846m) completed lateral would rapidly change both pore pressure, and vertical and lateral stresses. With the N36^{o}W orientation of the MIP-3H lateral (Figure 1), fracturing and injection could occur along non-critically oriented N79^{o}E preexisting fractures in the lower Marcellus Shale and predominately expessed in the aseismic "slow slip" with low frequency seismic events that are not picked up by standard microseismic monitoring. The oblique orientation of the lateral to prexisting fractures could explain the warming as detected by DTS of previous stages to near formation temperatures by movement of fluids previously injected and warmed by the formation through stimulated fractures communicating from one stage to the previous stage(s). This change in temperature in the previous stage(s) appears to be more prevalent between stages with numerous observed faults and fractures (e.g., Stage 6, figures 3c and 7). Microseismic events are centered significantly above the stimulated interval and follow optimal oriented fractures to the present day stress regime. The observed microseismic events may not be a direct expression of stimulated fractures and propopant placement in the targeted lower Marcellus shale, but indirect expression in the overlying stratigraphic units imposed by the injection of more than 250 cubic feet of sand and fluid per foot of lateral.

Conclusions

The following observations in the MIP-3H well indicate that the Marcellus Shale is a complex unconventional reservoir that does not respond in a straightforward manner during large scale hydraulic fracture stimulation. Completion efficiency along the lateral appears to be affected by preexisting fractures oriented at an angle to existing principal stresses and strongly influence hydraulic fracture propagation. The following conclusions support this interpretation:

- Open fractures and induced fractures in the vertical pilot well are oriented N57^{o}E on average.
- Core from the vertical pilot hole displayed the horizontal laminations and several calcite cemented fractures in the Marcellus Shale.
- Logging of the MIP-3H lateral revealed more than 1600 healed (calcite cemented vertical fractures) with average orientation of predominately N79^{o}E±18^o.
- Microseismic clusters have average orientation of N59^{o}E with radiated energy centered, on average, 190 feet (49m) above the MIP-3H lateral.
- The disparity between radiated microseismic energy and energy associated with fluid and proppant volumes and injection pressures during hydraulic fracture treatment is very significant.
- Completion energy (hDVS) generated from DAS is correlated with the injection energy and natural fracture intensity (P32), but microseismic energy is not correlated with either injection energy or hDVS energy
- Numerous LPLD events measured were observed during active fracture stimulation of individual stages.
- Warming of previous stages to near formation temperature was detected by DTS.

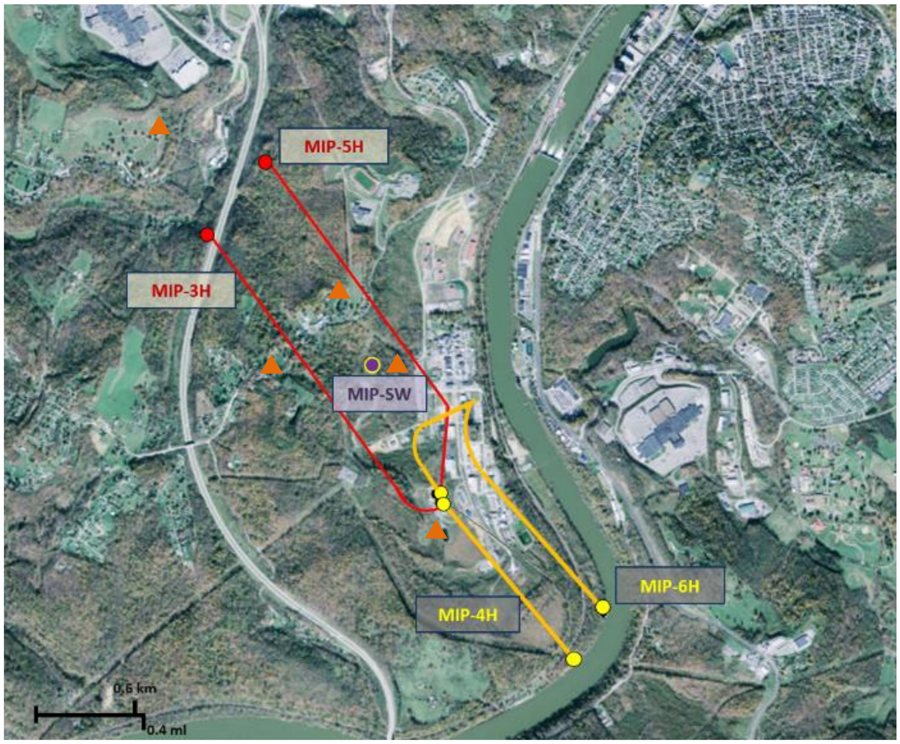


Figure 1: Marcellus Shale Energy and Environment Laboratory (MSEEL) just outside Morgantown, West Virginia, USA. The MSEEL site consists of four horizontal production wells operated by Northeast Natural Energy LLC. (MIP-3H, MIP-4H, MIP-5H, MIP-6H), two pilot holes (MIP-3 and MIP-4), a micro-sesimic and sampled observation well (MIP-SW) and a grid of five surface seisometer (triangles). The Northeast Natural Energy MIP-3H (47-061-01707) surface location is longitude W79.976624º and latitude N39.602203º.

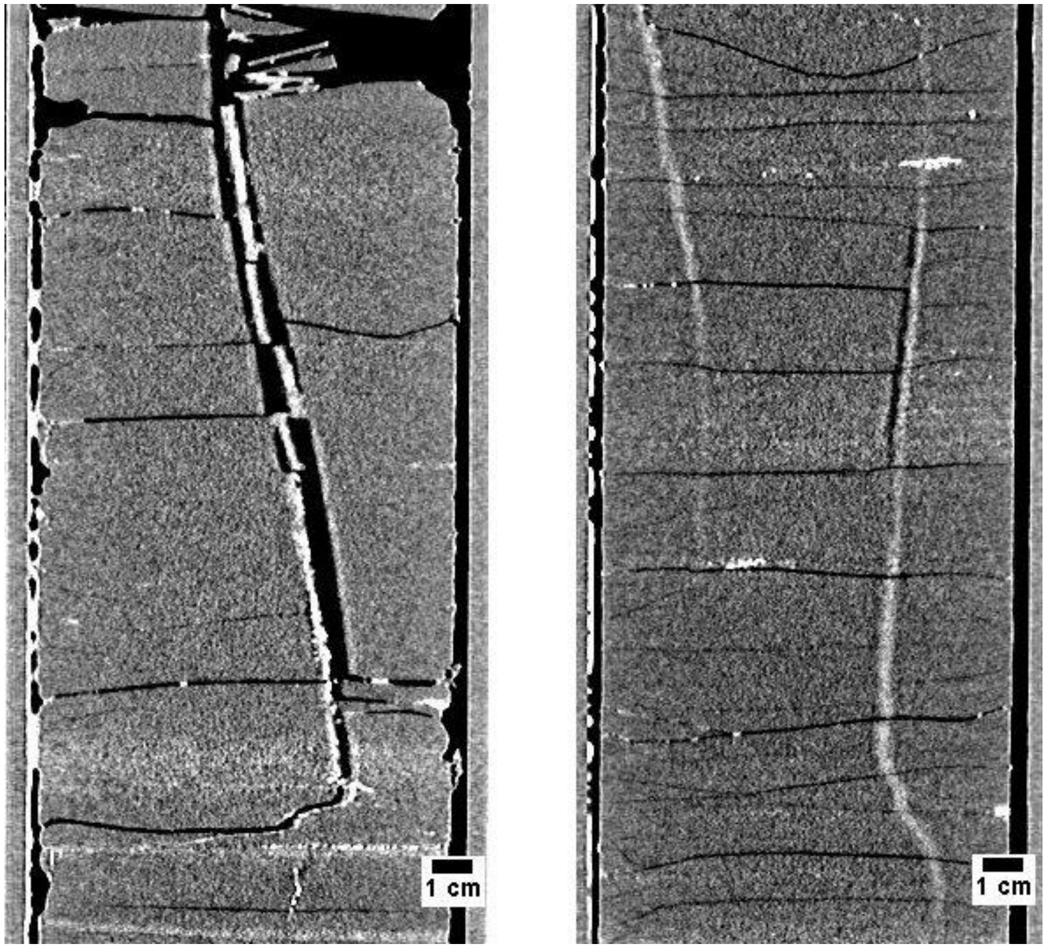
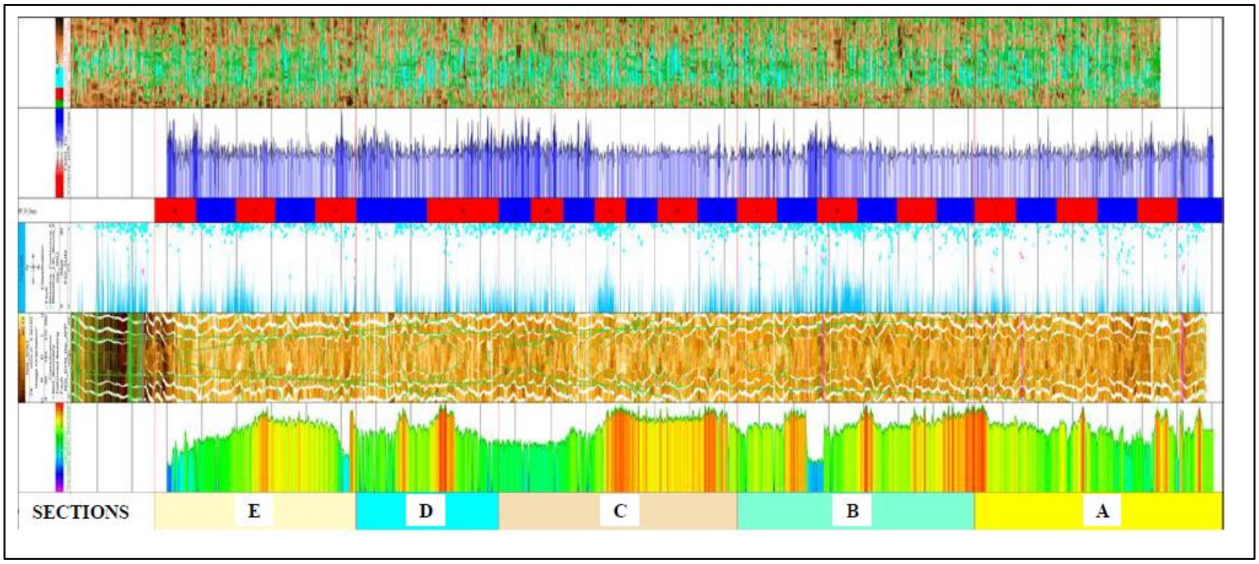
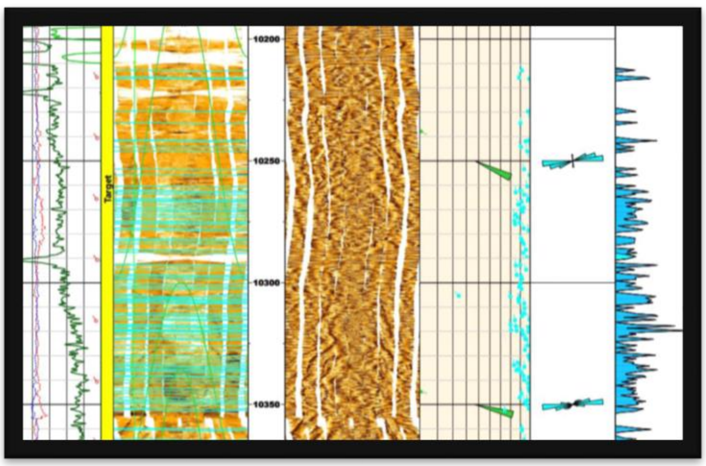


Figure 2: Vertical medical CT scan of a small portion of the core from NNE MIP-3 vertical pilot (left 7, 496 feet, right 7,508 feet) showing rare vertical fractures that were cemented with calcite. Horizontal white areas are heavy minerals.

A. C



B.



C.

Stage / Fault/Fracture	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
No of Faults	3				2	1				2	1																	
No of Fractures	41	25	48	29	15	69	47	51	97	160	86	65	72	17	14	90	25	56	68	71	37	46	21	41	42	89	66	28

Figure 3: **A.** Logs acquired along the lateral of the MIP-3H. Curves from bottom to top are gamma-ray, QuantaGeo borehole image, natural fracture density (P32) with fracture/fault tadpoles, TIV closure stress and cement bond image. Over 1600 fractures were identified along the lateral. Leterred sections show five differnt completion strategies that were applied to the 28 stages of the MIP-3H lateral. **B.** Detail of portion of MIP 3H lateral showing QuantaGeo boreimage with sinusoids and fracture intensity and orientation. Fracture orientation is N87ºE. **C.** Number of identified fractures and faults for each of the 28 stages of the MIP 3H.

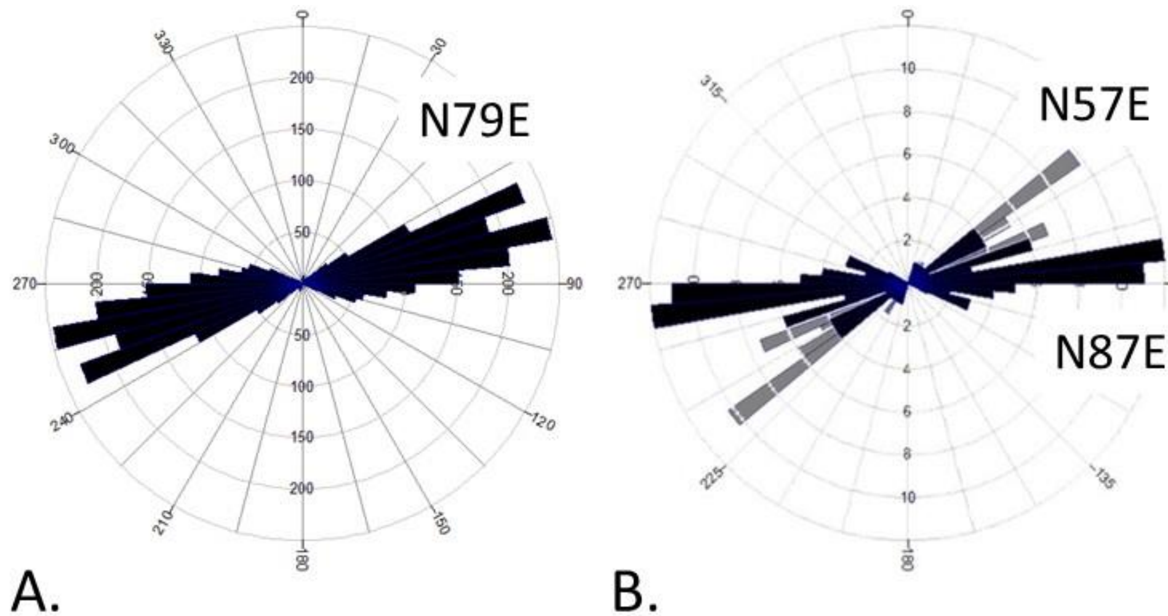


Figure 4: Rose diagrams of natural fractures a) observed along the length of the MIP-3H lateral (N=1640) and B) in the vertical pilot well (N=91). Fractures observed in the vertical well consist of 21 open fractures (light grey color) in the N57ºE cluster and 70 healed fractures mainly concentrated in the N87ºE cluster with a smaller fraction falling in the N57ºE cluster.

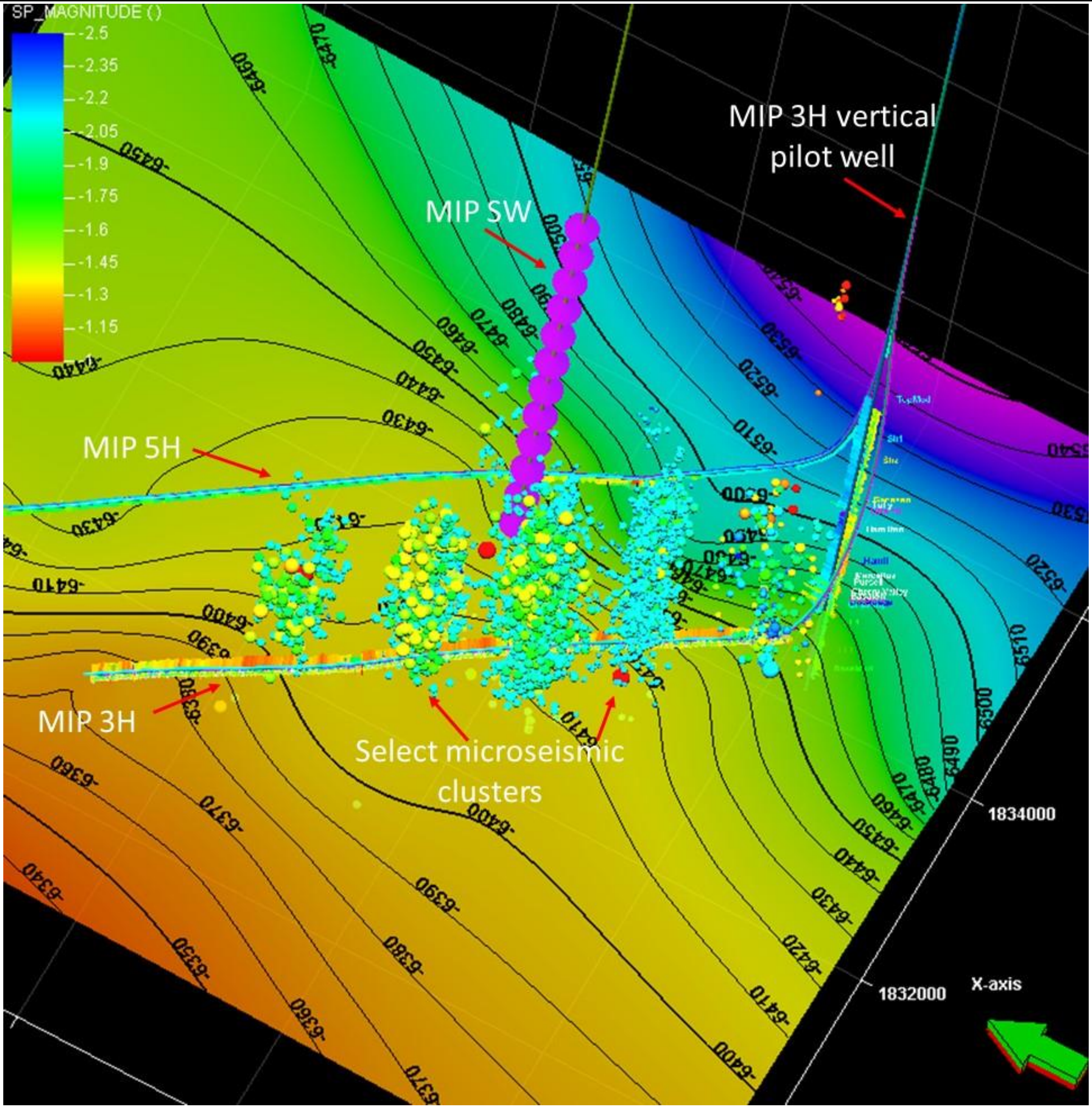


Figure 5: Structural view showing the MIP-3H and MIP-5H wells along with MIP-SW vertical monitoring well. Microseismic data from selected stages show the trend parallel to S_{Hmax}. Structural relief is on the top of the Onondaga Limestone.

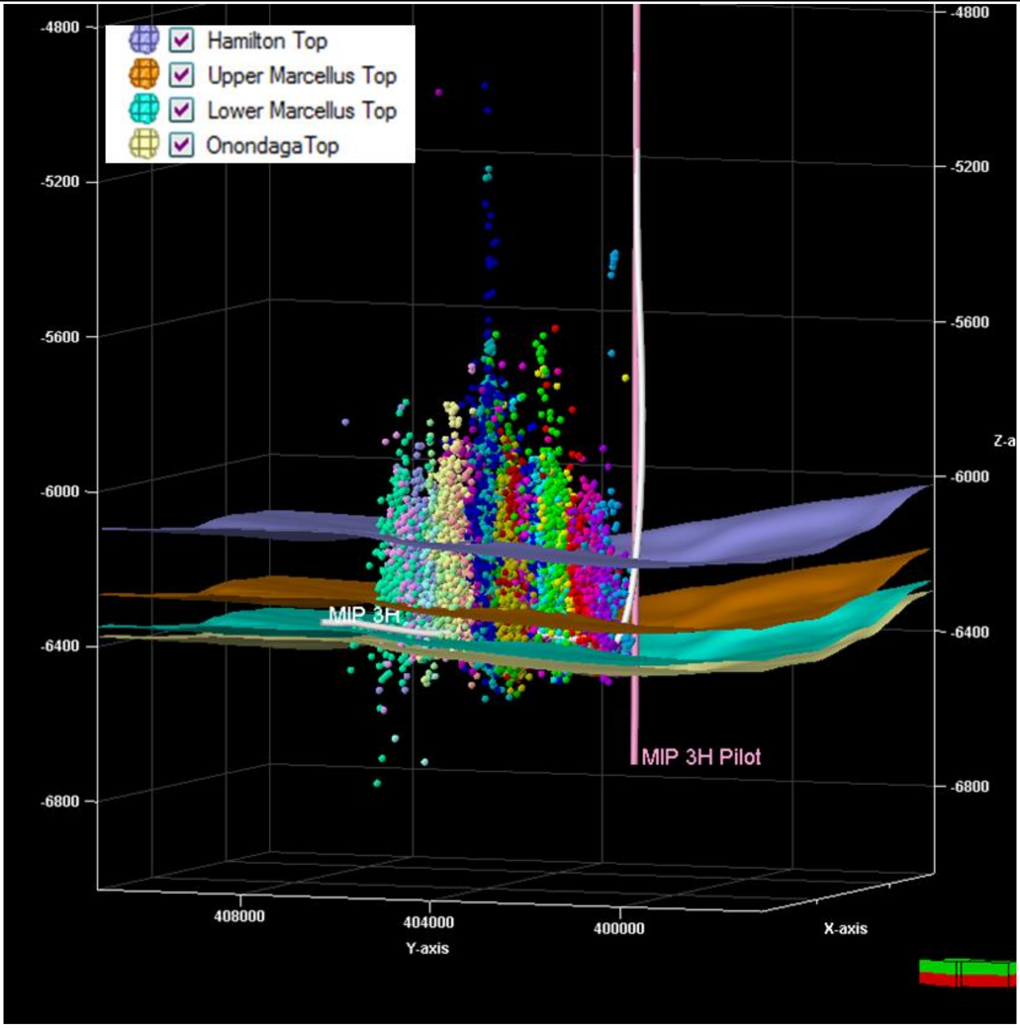


Figure 6: Microseismic data for Stages 7 to 28 recorded for well MIP-3H. The center of radiated microseismic energy is located 160 feet (49m) above the location of the lateral in the Lower Marcellus Shale as defined by the Cherry Valley Limestone and extends to well above the top of the Hamilton Group. (Kavousi and others, submitted; Wilson and others, submitted).

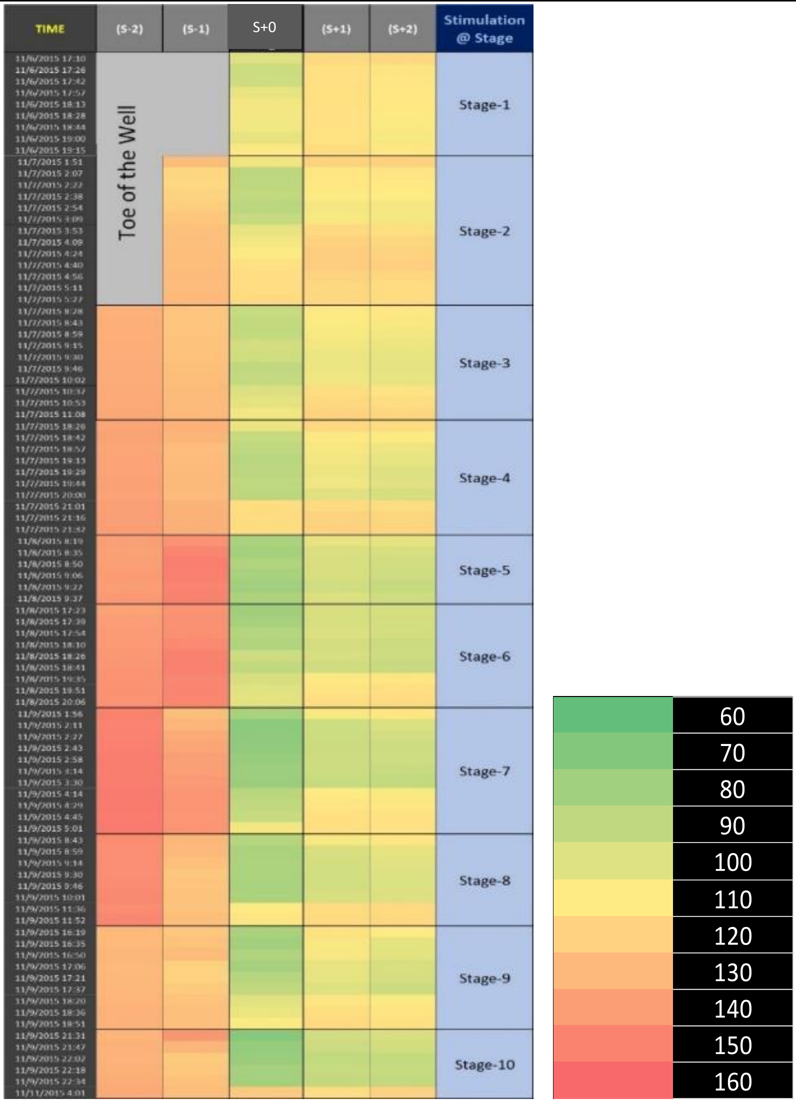


Figure 7: Data from continuous DTS monitoring of the stages 1-10 in the MIP-3H as they are being stimulated (S+0) and the adjoining two underlying (S-1, S-2) and overlying (S+1, S+2) stages. The cooling in the stage be stimulated and the two stages above is expected due to injection of surface water used for fracture stimulation. However, as in Stage 6, the previous stages below the stage being stimulated show temperatures warming and approaching the temperature of the formation (~165ºF). This is especially prevalent in stages with multiple fractures and faults as determined by log data (Figure 3c). Modified from Amini et al., (in press)

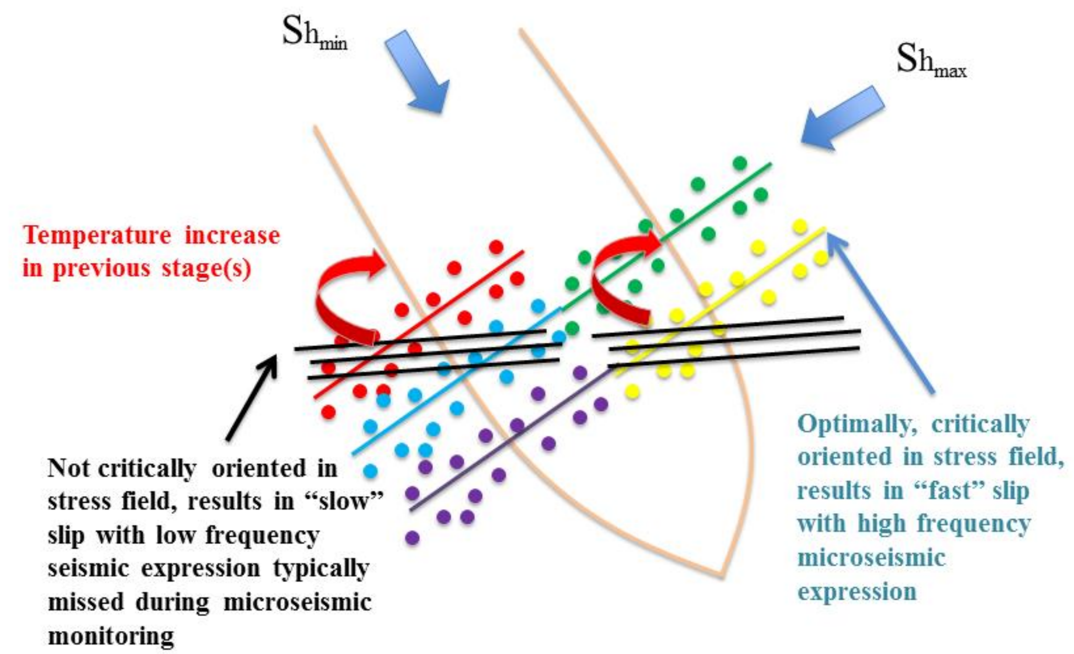


Figure 8: Conceptual model of observed pattern of the numerous preexisting N87ºE fractures and faults observed in logs, microseismic orientated N59ºE, LPLD events and warming observed in DTS in previous stages during fracture stimulation in the MIP-3H. Basic figure was modified from Das and Zoback, 2012. Movement and injection along non-critically oriented preexisting fractures in the lower Marcellus Shale resulted in the "slow" slip with low frequency seismic expession that was not picked up by microseismic monitoring and movement of fluids warmed by the formation to previous stimulated stages. Microseismic events follow optimal oriented fractures to the present day stress regime and are centered significantly above the stimulated interval. The observed microseismic events may be the expression of the stress on overlying layers imposed by the injection of more than 250 cubic feet of sand and fluid per foot of lateral.

References

Agrawal, V., Sharma, S., 2017, Use of organic-geochemical proxies to assess organic matter sources, thermal maturity, and paleoredox conditions during deposition of Marcellus shale: Journal of Petroleum Science and Engineering (in review)

Agrawal, V., Warrier, A., Sharma, S., 2017, Decoding molecular geochemistry of kerogen from Marcellus shale: American Association of Petroleum Geologists, Annual Convention and Exhibition, Houston, Texas.

Agrawal, V., Sharma, S., Warrier, A., 2016, Understanding kerogen composition and structure in pristine shale cores collected from Marcellus Shale Energy and Environment Laboratory: Eastern Section AAPG 45th Annual Meeting in Lexington, KY.

Amini, Shohreh, Payam Kavousi, and Tim Carr, in press, Application of Fiber-optic Temperature Data Analysis in Hydraulic Fracturing Evaluation: A Case Study in Marcellus Shale, Unconventional Resources Technology Conference, Unconventional Resources Technology Conference, Austin, Texas, July 24-26, DOI 10.15530-urtec-2017-2686732.

Anifowoshe, O., Yates, M., Xu, L., Dickenson, P., Akin, J., Carney, B.J., Hewitt, J., Costello, I. and Arnold, Z., 2016, Improving Wellbore Stimulation Coverage in the Marcellus: Integrating Lateral Measurements with Enhanced Engineered Completion Design and Fiber Optic Evaluation: In SPE Eastern Regional Meeting. Society of Petroleum Engineers, SPE, paper no. 184051-MS, https://doi.org/10.2118/184051.

Das, Indrajit, and M. D. Zoback, 2011, Long period long duration seismic events during hydraulic fracture stimulation of a shale gas reservoir: The Leading Edge, 30, 778–786, http://dx.doi.org/10.1190/1.3609093.

Das, Indrajit and Mark D. Zoback, 2012, Microearthquakes Associated with Long Period, Long Duration Seismic Events During Stimulation of a Shale Gas Reservoir. SEG Technical Program Expanded Abstracts 2012: pp. 1-5, http://dx.doi.org/10.1190/segam2012-1484.1.

Das, Indrajit, and M. D. Zoback, 2013, Long-period, long-duration seismic events during hydraulic stimulation of shale and tight-gas reservoirs—Part 1: Waveform characteristics: Geophysics, **78**, no. 6, KS107–KS118, http://dx.doi.org/10.1190/GEO2013-0164.1.

Gale, J.F., Reed, R.M., Becker, S.P. and Ali, W., 2008, Natural Fractures in the Barnett Shale in the Delaware Basin, Pecos Co. West Texas: Comparison with the Barnett Shale in the Fort Worth Basin, AAPG Search and Discovery, http://www.searchanddiscovery.com/pdfz/documents/2010/10226gale/ndx_gale.pdf.html'

Kavousi, Payam. Timothy Carr, Thomas Wilson, and Shohreh Amini, Collin Wilson, Mandy Thomas, Keith MacPhail, Dustin Crandall, BJ Carney, Ian Costello, and Jay Hewitt, submitted, Correlating distributed acoustic sensing (DAS) to natural fracture intensity for the Marcellus Shale, SEG Technical Program Expanded Abstracts 2017.

Kumar, Abhash, Richard Hammack, Erich Zorn, and William Harbert, 2016, Long period, long duration (LPLD) seismicity observed during hydraulic fracturing of the Marcellus Shale in Greene County, Pennsylvania. SEG Technical Program Expanded Abstracts 2016: pp. 2684-2688, http://dx.doi.org/10.1190/segam2016-13876878.1.

Kumar Abhash, Erich, Zorn, Richard, Hammack, William Harbert, in press, Surface Seismic Monitoring of Hydraulic Fracturing Activity in Pennsylvania and West Virginia, Unconventional Resources Technology Conference, Expanded Abstracts 2017.

Moos, D., G. Vassilellis, R. Cade, J. Franquet, A. Lacazette, E. Bourtembourg, and R. Cade, 2011, Predicting shale reservoir response to stimulation in the upper Devonian of West Virginia: Annual Technical Conference, SPE, paper no. 145849, https://doi.org/10.2118/145849-MS.

Sharma, Sharma, Timothy Carr, Paula J. Mouser, Kelly Wrighton, David Cole, Michael Wilkins, Thomas Darrah, and Alexander Hakala, in press, Biogeochemical Characterization of Core, Fluids and Gas at MSEEL Site, Unconventional Resources Technology Conference, Unconventional Resources Technology Conference, Austin, Texas, July 24-26, DOI 10.15530-urtec-2017-2669965.

Sicking, C., J. Vermiliye, P. Geiser, A. Lacazette, and L. Thompson, 2013, Permeability field imaging from microseismic: Geophysical Society of Houston Journal, **3**, 11–14, http://dx.doi.org/10.1190/segam2012-1383.1.

Warpinski, N. R., J. Du, and U. Zimmer, 2012, Measurements of hydraulicfracture-induced seismicity in gas shales: Hydraulic Fracturing Technology Conference, SPE, paper no. 151597, http://dx.doi.org/10.2118/151597-PA.

Wilson, Thomas, A. Hart, and P. Sullivan, 2016a, Interrelationships of Marcellus Shale gas production to frac-induced microseismicity, interpreted minor faults and fractures zones, and stimulated reservoir volume, Greene County, Pennsylvania: Interpretation, **4**, T15–T30, http://dx.doi.org/10.1190/INT-2015-0045.1.

Wilson, Thomas, Timothy Carr, B. J. Carney, Jay Hewitt, Ian Costello, Emily Jordon, Keith MacPhail, Natalie Uschner, Miranda Thomas, Si Akin, Oluwaseun Magbagbeola, Adrian Morales, Asbjoern Johansen, Leah Hogarth, and Kashif Naseem, 2016b, Microseismic and model stimulation of natural fracture networks in the Marcellus Shale, West Virginia. SEG Technical Program Expanded Abstracts 2016: pp. 3088-3092. http://dx.doi.org/10.1190/segam2016-13866107.1.

Wilson, Thomas, Malcolm Yates, Keith MacPhail, Ian Costello, Tim Carr, B. J. Carney, Jay Hewitt, , Emily Jordon, Natalie Uschner, Mandy Thomas, Si Akin, Oluwaseun, Magbagbeola, Adrian Morales, Asbjoern Johansen, Leah Hogarth, Olatunbosun Anifowoshe, Kashif Naseem, submitted, Marcellus Shale model stimulation tests and microseismic response yield insights into mechanical properties and the reservoir DFN, SEG/AAPG Journal Interpretation.

Wilson Thomas, Payam Kavousi, Tim Carr, B. J. Carney, Natalie Uschner, Oluwaseun Magbagbeola and Lili Xu, submitted, Relationships of $\gamma\rho$, $\mu\rho$, brittleness index, Young's modulus, Poisson's ratio and high TOC for the Marcellus Shale, Morgantown, West Virginia SEG Technical Program Expanded Abstracts 2017.

Zorn Erich, William Harbert, Richard Hammack, and Abhash Kumar, in press, Geomechanics of the Microseismic Response in Devonian Organic Shales at the Marcellus Shale Energy and Environment Laboratory (MSEEL) Site, West Virginia, Unconventional Resources Technology Conference, Expanded Abstracts 2017.