



Stress rotations in the Delaware Basin—How to plan the direction of your well in a complex local stress field – Examples from Loving, Ward, and Reeves Counties, TX (Grisham fault)

N. Umholtz, Y. Aimene, A. Ouenes
FracGeo, The Woodlands, TX

Introduction

Production of unconventional wells is dictated by both the geological (resource) and geomechanical (recoverability) properties of the reservoir. The geomechanics of a reservoir can be broken down into the rock mechanical properties, which near the wellbore primarily control fracture initiation potential, and the current stress state, which away from the wellbore controls the propagation of successfully induced hydraulic fractures and their interaction with natural fractures and layer interfaces. The consequential properties of the stress state can be further refined to be represented as the differential stresses and the maximum horizontal stress orientation. To maximize an unconventional well's stimulated reservoir volume (SRV) it is critical that a well is drilled nearly perpendicular to the maximum horizontal stress direction to induce transverse hydraulic fractures. Additionally, maximum horizontal stress orientation is a major control on fault stability and a primary concern when quantifying the induced seismicity potential in a given area. Stress rotations have been documented at regional, basin, field, and pad scales (Umholtz & Ouenes, 2015, Umholtz & Ouenes, 2016, Ouenes et al., 2016). What cannot be ignored, is the reciprocal relationship between fault networks and stress fields. While fault quantification is readily available at field scales (when seismic data exists), operators rarely disclose these interpretations to be used in comprehensive regional studies. This study will focus on quantifying stress rotations at basin and county scales using publicly available data.

This study will focus on a Delaware basin dataset and will use publicly available fault data to drive the geomechanical simulation that will lead to maps showing the orientation of the maximum stress direction in the Delaware basin. These maps are derived by using basic principles of continuum mechanics augmented with the presence of the discontinuities introduced by the regional faults. To solve the continuum mechanics equations, we used in this study, GMXPredictor™ one of the eleven modules available in FracPredictor™. GMXPredictor™ uses the material point method (MPM) which is a particle-based method that combines both Lagrangian and Eulerian descriptions to solve the continuum mechanics equations. The entire Delaware basin is covered with a grid of 1000ft x 1000ft and the regional tectonic stress is applied to the entire basin and its fabric disrupted by the presence of multiple regional faults. The resulting maximum horizontal stress direction (S_{Hmax}) is used extensively in this study to provide to E&P operators the necessary information required to position their horizontal wells in the optimal direction that takes into account the complex resulting stress field.

Using average rock mechanical properties and publicly available fault data, the model results presented in this paper are validated with few well-known stress directions from limited data. After validation, the models are used to highlight the value of robust geomechanical simulation to estimate the maximum stress direction at any point of the Delaware basin or any other basin.

Stress rotation around a single fracture

Using a simple one fracture example from Dr. Patrice Rey structural geology course notes,

<http://sydney.edu.au/science/geosciences/users/prey/Teaching/Geos-2123/Stress/Slid20.html>

the stress field rotations around the single fault (Fig. 1) is computed. Using as input in GMXPredictor™ the single fault used in Dr. Patrice Rey structural geology course and shown in Fig. 1A, a geomechanical model using MPM (Aimene & Ouenes,

2015) is simulated (Fig. 1B) and compared to the course notes. The colors in Fig. 1B show the maximum stress horizontal direction introduced by the presence of the fracture. The green colors represent the regional N-S direction of the maximum stress direction while the red and blue colors represent the directions shown on the colored wheel at the bottom right of Fig. 1B. Each color in that colored wheel represents a direction. The same information could also be seen with the black lines in Fig. 1B that show the local maximum stress horizontal stress direction. Rotations up to 45 degrees from the input N-S stress field can be observed in this simple system. These same features are observable in outcrops (Fig. 1C). In the next section we will investigate the rotations in a fault system of approximately 60 faults interpreted in the Woodford Shale.

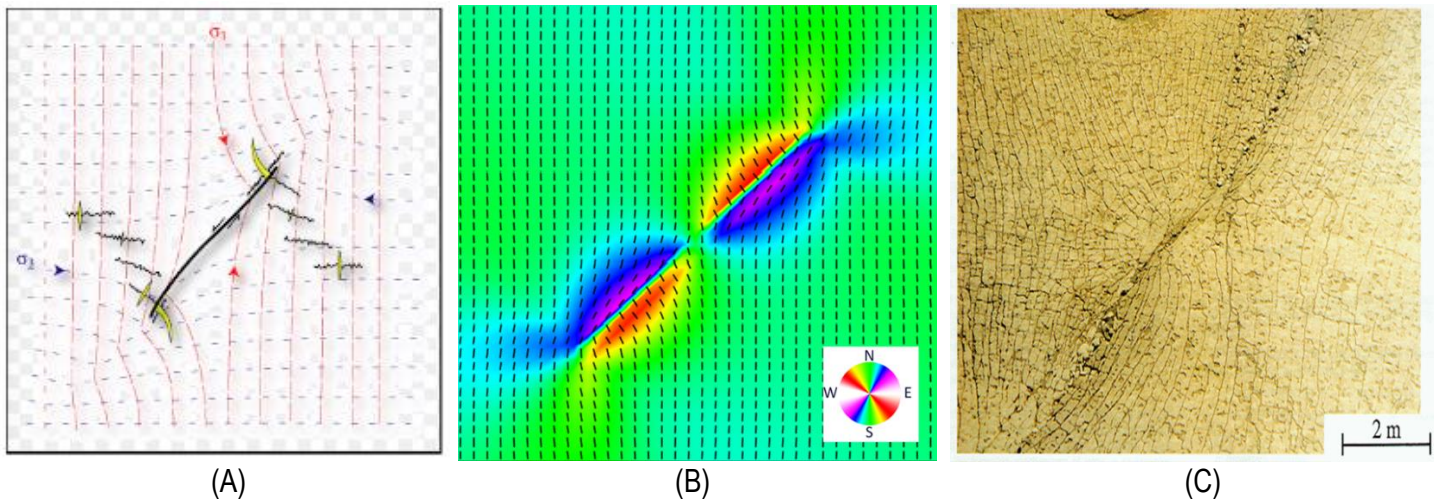


Figure 1. Comparison between (A) anecdotal structural geology observations used in Dr. Rey structural geology course notes showing the maximum horizontal stress direction orientation in red lines around a single fracture and (B) MPM results of a similar fracture where the tick marks represent S_{Hmax} orientation. Red and yellow areas indicate NW-SE deflection of the input N-S maximum stress while purple and blue areas indicate NE-SW deflection of the input stress field. (C) outcrop observations of fracture rotations around faults modified from Dr. J.P. Petit, Université Montpellier II.

Stress rotations in the Delaware Basin

Fault information can come from seismic studies in a field, or even large public data sets. A very large (basin) scale fault system is used here to demonstrate the method on real, publicly available data (Fig. 2.). When the Woodford faults are subjected to a dominant E-W tectonic stress, rotations in the maximum horizontal stress direction arise as shown in Fig. 3. It is important to note that faults which are oriented parallel or perpendicular to the stress field, such as the N-S trending fault in SW Lea County, cause little perturbation and critically stressed faults (roughly 30° to 60° from local maximum stress direction) cause large perturbations. While much of the basin is still subject to a S_{Hmax} within 10 degrees of the input orientation, several areas evidence large deflections from this input orientation. We will now validate these results with multiple well data and illustrate the stress rotations that occur around some key areas that are currently under heavy development.

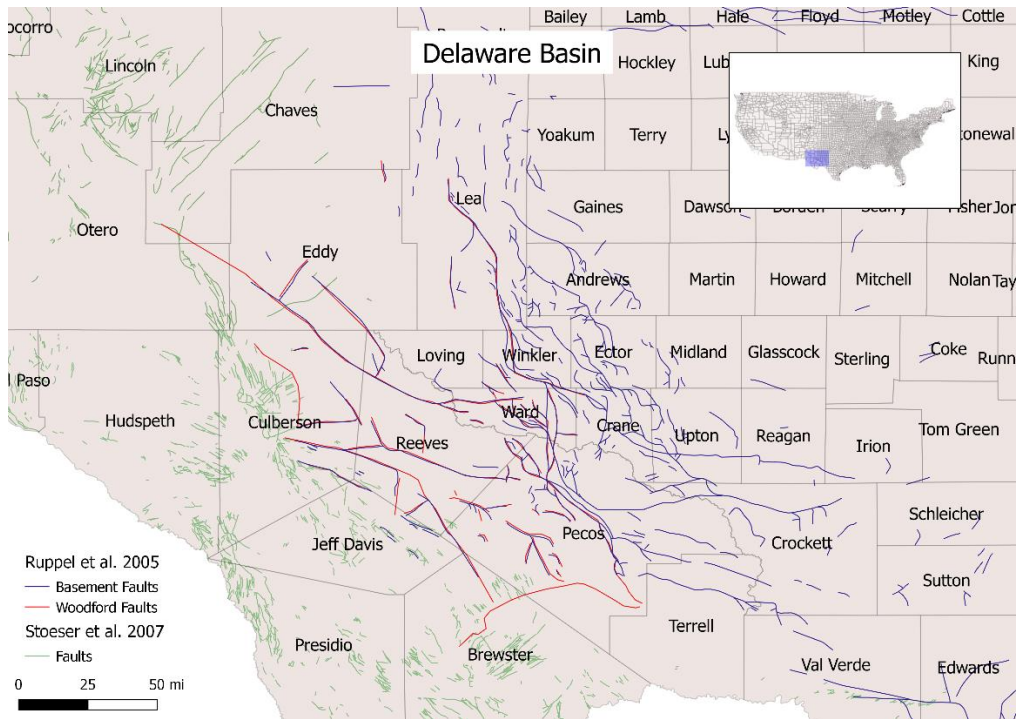


Figure 2. Faults from (Ruppel *et. al* 2005 and Stoesser *et al.* 2007) of which a subset (Woodford) will be imposed on the material model to capture stress rotations in the Delaware basin.

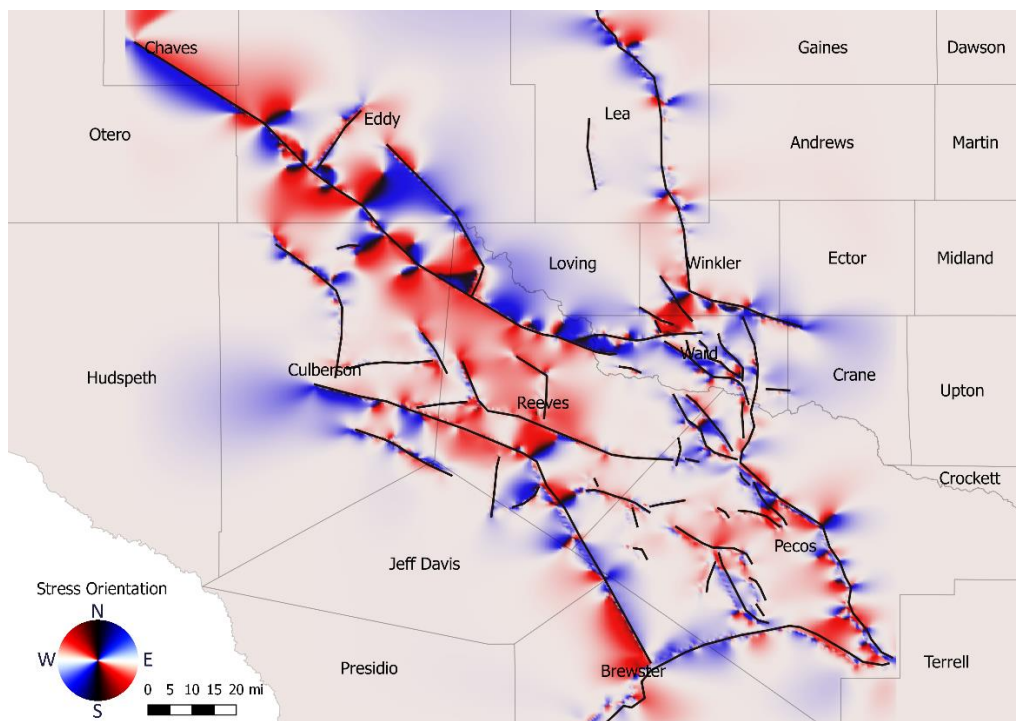


Figure 3. Results of the MPM simulation of the complex fault networks in the Delaware basin, showing the maximum horizontal stress orientation varying as a result of the interaction between natural fracture systems and tectonic stresses. Red colors indicate NW-SE deflection of the input E-W stress field, and blue areas indicate NE-SW deflection of the input stress field.

Limitations of well data

Forand et al. (2017) used 35 wells with image logs (three of them in horizontal wells) to study the natural fractures and Drilling Induced Tensile Fractures to estimate the S_{Hmax} (Fig. 4). They also noticed that the stress orientation does not vary with depth. From these limited well interpretations, it is clear that at the regional scale, the maximum stress direction is rotating from the NE-SW direction in the Northern part of the basin, E-W in the central part of the basin and NW-SE in the southern part. Unfortunately, the Delaware basin is 8,465 square miles and when planning their wells, an operator needs more information than the map shown in Fig. 4. The need for deriving a much finer map showing the maximum stress orientation at a scale of a section or below can be illustrated with the two areas highlighted in green and yellow in Fig. 4. In these areas, it is apparent that the maximum stress direction is affected by a major fault causing important stress rotations within a very short distance. One of these areas is the Grisham fault.

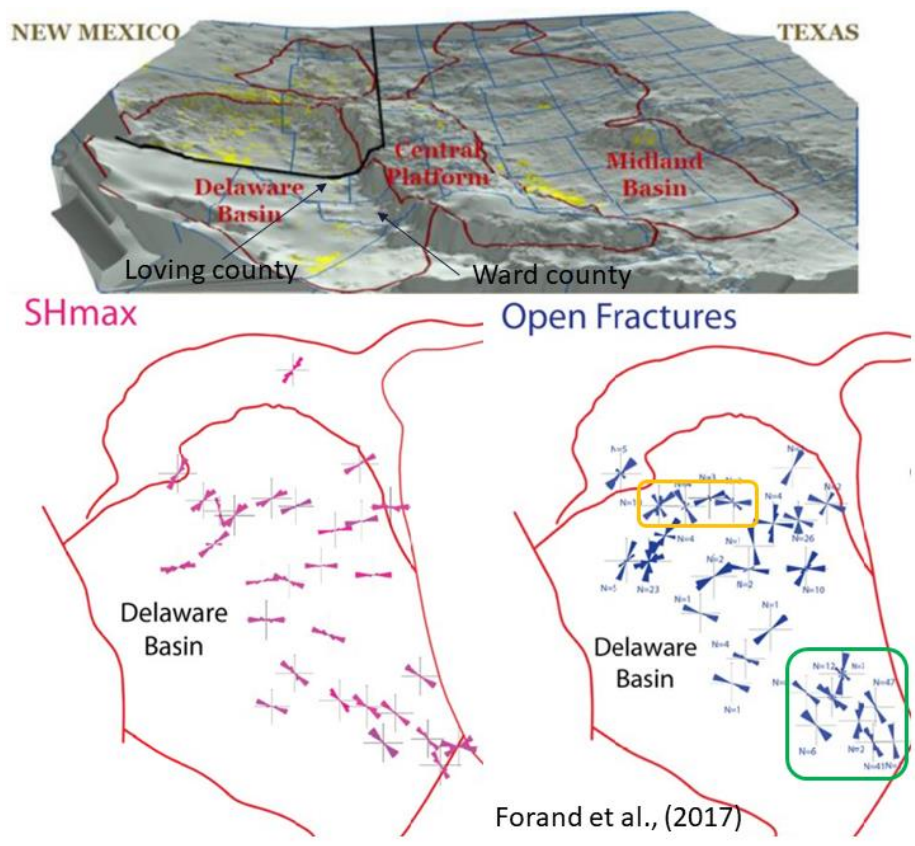


Figure 4. Estimated S_{Hmax} from drilling induced tensile fractures and natural fracture orientation from image logs as interpreted by Forand et al. (2017) from well data.

Complex stress fields around the Grisham Fault

The maximum stress direction around the Grisham fault (Fig. 5) shows lot of variability. This major fault crosses the western part of Ward county where there is an important drilling activity as shown in Fig. 6. The operators in Ward county who want to optimize their well orientation will need more details than the map shown in Fig. 4 where only three regional directions are

provided. The map shown in Fig. 5 and derived at a scale of 1000 ft x 1000ft provides the maximum stress direction needed for any well drilled around the Grisham fault.

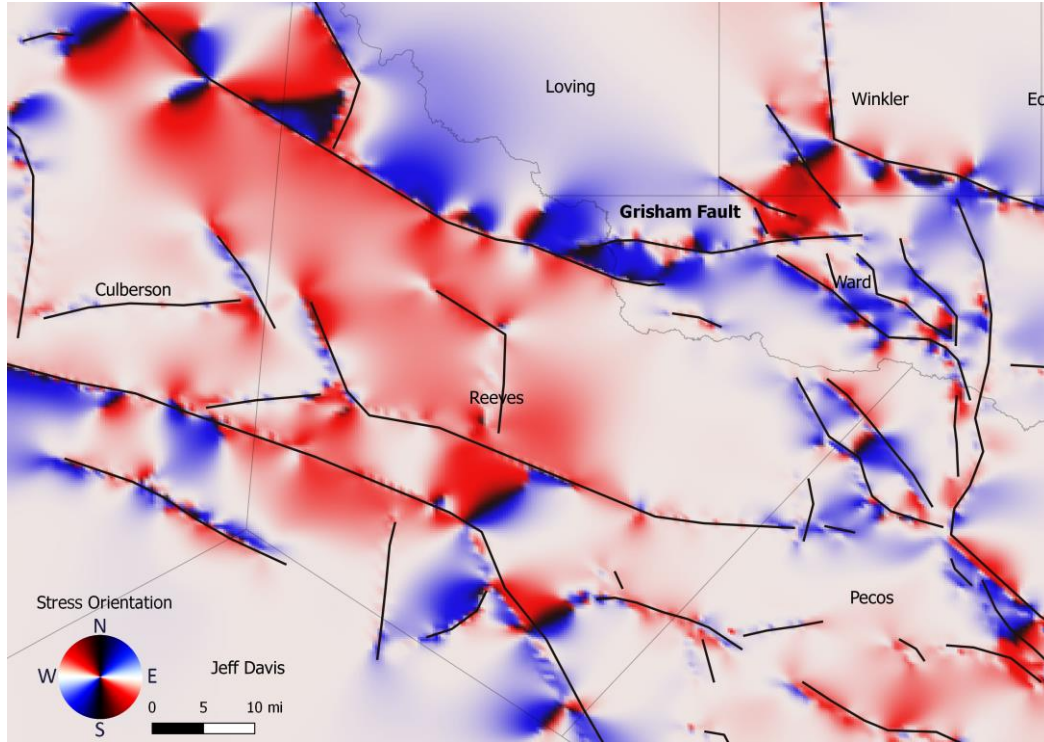


Figure 5. Loving, Reeves and Ward county results around the Grisham fault showing distinct behaviors of the stress field orientation North and South of the fault, and also along strike of the fault.

Top Producing Operators in Ward County, TX

Based on March 2018 Production

Operator	Oil Prod (BBLs)	Gas Prod (MCF)	Active Leases	Active Wells
Abraxas Petroleum Corporation	104,005	458,743	86	162
Anadarko E&P Onshore LLC	2,159,971	9,673,554	433	554
Blackbeard Operating, LLC	83,595	210,286	94	200
Callon Petroleum Operating Co	915,313	1,895,521	158	370
Chevron U. S. A. Inc.	1,928,650	9,609,128	1,402	3,374
Cimarex Energy Co.	291,241	11,989,040	432	485
Cimarex Energy Co. Of Colorado	49,058	400,994	205	306
COG Operating LLC	3,656,108	11,597,373	709	2,868
Diamondback E&P LLC	1,442,527	2,507,643	317	954
Energen Resources Corporation	1,861,202	6,409,255	507	3,337
Felix Energy Holdings II, LLC	155,725	311,708	40	41
Four Corners Petroleum II, LLC	263,831	131,609	57	971
Jagged Peak Energy LLC	703,466	1,229,215	67	91
Jetta Operating Company, Inc.	76,402	351,119	131	292
Luxe Operating LLC	948	258,601	19	16
Oasis Petroleum Permian LLC	99,597	169,970	26	35
Occidental Permian LTD.	3,358,213	5,347,472	354	6,783
Oxy USA Inc.	1,415,307	3,824,255	659	1,958
Shell Western E&P	1,937,621	4,278,076	157	297
Sundown Energy LP	53,778	272,803	55	164

Figure 6. Top producing operators and their active leases in Ward county as of March 2018.

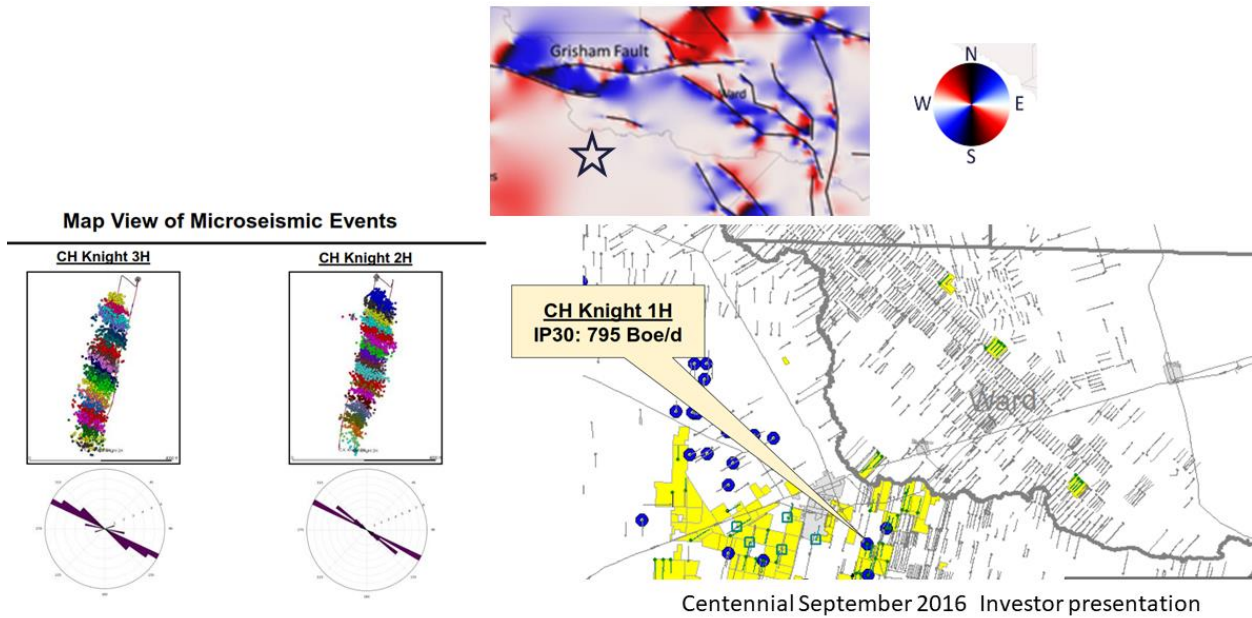


Figure 7. Validation of the maximum stress direction map with a well south of the Grisham fault. The black star on the maximum stress direction map shows the approximate location of the considered well. The interpreted microseismic data published in the investor presentation indicate a maximum stress direction similar to the one predicted by the map.

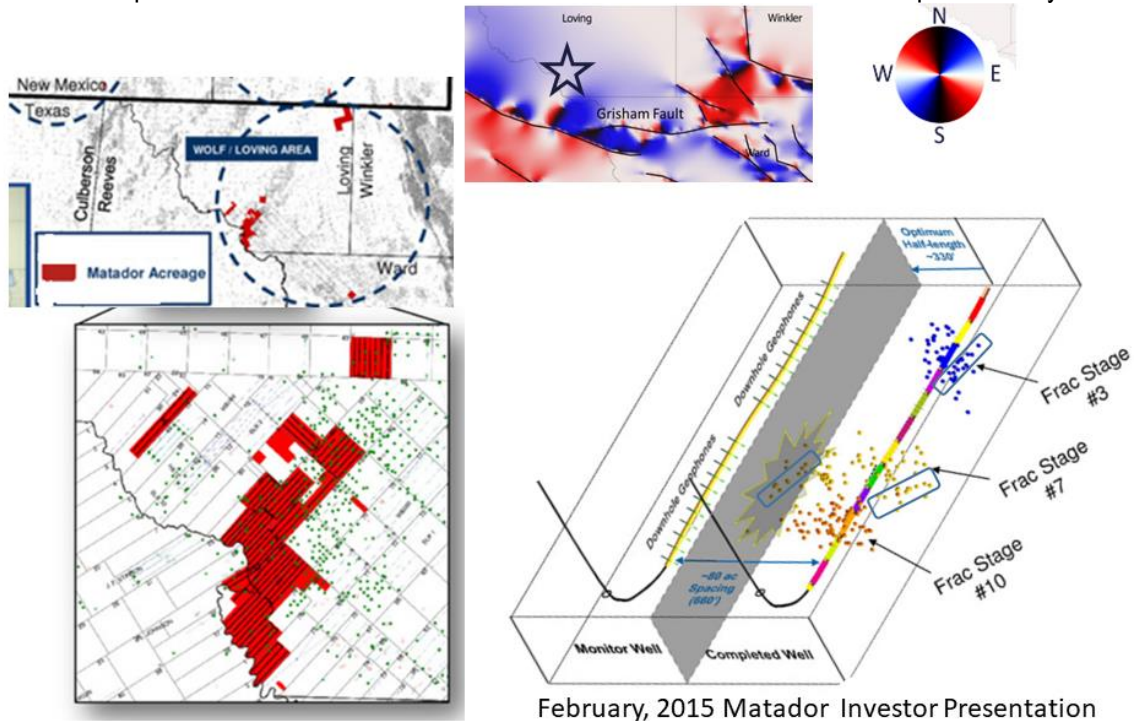
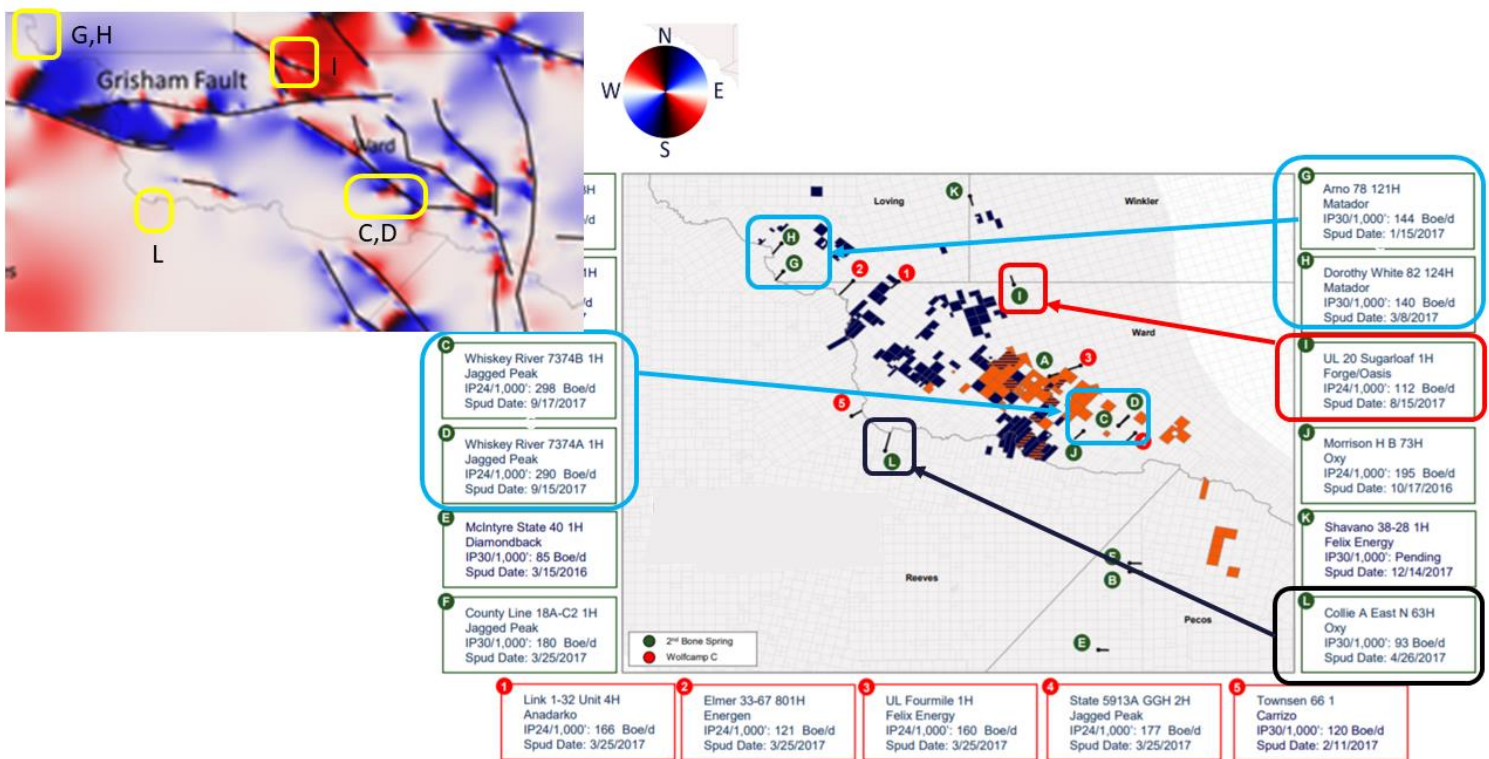


Figure 8. Validation of the maximum stress direction map with a well North of the Grisham fault. The black star on the maximum stress direction map shows the approximate location of the considered well. The interpreted microseismic data published in the investor presentation (blue boxes) indicate a maximum stress direction similar to the predicted one.

Fig. 7 shows a well in Reeves county where the microseismic was published in a 2016 investor presentation. In this figure we can see that most of the Wolfcamp wells drilled in Ward county were oriented NE-SW which is not the optimal direction when considering that most of the colors in Fig.5 is mostly blue and white which indicates a maximum stress direction mainly in the NE-SW and E-W direction thus requiring wells drilled NW-SE. In few areas shown in red in Fig. 5, the orientation of the maximum stress direction is NW-SE thus requiring wells drilled in the NE-SW direction as commonly seen in Fig. 7. Notice in Fig. 7, the seven wells on the east side of Ward county drilled in the NW-SE direction bucking the trend of all other wells drilled in the NE-SW direction. It looks like somebody knew about the stress rotation and had the necessary acreage to orient their wells accordingly.

The problem of acreage position is well illustrated with Fig. 7 and the well with the published microseismicity used to validate the maximum stress direction map. Companies are most of the time limited by their acreage and drill their wells along the lease lines.

In Fig. 8 another well with a published microseismicity shows the ability of the computed maximum stress direction map to predict correctly the orientation as interpreted by the microseismic and highlighted by the blue boxes around the interpreted microseismic events. As we cross the Grisham fault, the maximum stress direction is rotating and takes different orientations. When the acreage position allows, using the maximum stress direction shown in Fig. 5, operators could now optimize their well orientations. For example, the operator shown in Fig. 8, has enough contiguous acreage that could allow him to drill his wells in a direction almost N-S or slightly NW-SE to fully take advantage of the stress rotation caused by the Grisham fault.



June 18, 2018 Callon Investor Presentation

Figure 9. Variable wellbore orientations around the Grisham fault and its potential impact on well performance. Three groups of well orientation show important variability in the maximum horizontal stress orientation (yellow boxes) which could explain some of the low performance of certain wells drilled in the 2nd Bone Spring.

Drilling in the direction imposed by lease lines comes at a price that is better illustrated in Fig. 9 where a recent investor presentation is showing multiple wellbore orientations for 2nd Bone Spring wells and their corresponding well performances. The same operator discussed in Fig. 8, has two wells labeled G and H in Fig. 9 with an IP30/1000ft around 140 Boed. In the area of wells G and H, the S_{Hmax} orientation shown in the map is rather NE which could explain the low performance of these 2 wells. Same observation for well labeled I oriented in the NW direction. The stress orientation map shows a strong NW direction for the well labeled I which also could explain its low IP. On the other hand, the wells labeled C and D are drilled in the NE direction and appear to benefit from a major stress rotation around that area where the maximum stress direction may have turned NW in a very localized area where these two wells are drilled. The performance of these two wells is far superior to those discussed earlier.

Many other factors could affect the well performance and maximum stress orientation is only one of them albeit an important one. Thus, if the well is drilled in the optimal orientation and yet the performance is lower than its neighboring wells, then it is most likely that other geologic or completion factors have affected the final performance. A good example of such a well is the one labeled L in Fig. 9 where it appears that the NE orientation of the well (most likely imposed by the lease lines) is adequate for the slightly NW maximum stress orientation, yet the well performance is low.

Predicting maximum stress orientation at the Hydraulic Fracture Test Site 2 – Delaware Basin

As the industry embarks in more field tests to better understand hydraulic fracturing, it is important to add in the list of priorities experimental and field data needed to estimate the maximum horizontal stress direction to validate the computed one that could be derived across the entire basin through geomechanical simulation as shown in Fig. 3. The predicted maximum stress direction extracted from Fig. 3 at the upcoming Hydraulic Fracturing Test Site II – Delaware Basin is shown in Fig.10. Industry partnerships with key players such as University Lands that has many faults in their acreage (Fig.10) are important to build a complete database near the Grisham Fault. Who thought that the Permanent University Fund and all the great benefits it provides to the Texas educational system would depend on faults and the stress rotation they cause!!!

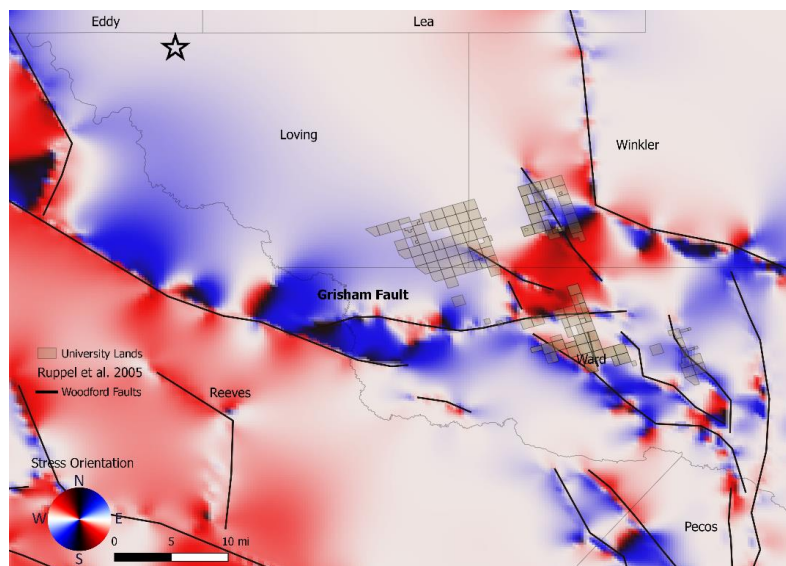


Figure 10. Predicted maximum stress direction map at the Hydraulic Fracture Test Site 2 -Delaware basin. The black star shows the approximate location of the considered test wells. Acreage of the University Lands shows their unique situation where many faults cause major stress rotation in and around their acreage.

Conclusions

Variable in situ stresses are a reality of unconventional reservoir development. Quantifying the rotation of stress through basins and fields can inform field development strategies and help constrain completion strategies and frac design. In this case study, publicly available fault data for the Delaware basin is used to simulate a detailed map of maximum stress direction at a scale of 1000ft x 1000ft throughout the Delaware basin. The resulting maps highlight the complexity of stress fields in the Delaware basin and the importance of accounting for entire fault systems interactions with regional stresses, underpinning the dire need of the industry to better quantify structural features in and around unconventional reservoirs. For the engineers wondering why we need to acquire 3D seismic, this case study shows how the maximum stress direction that controls the performance of hydraulic fractures depends heavily on those faults that can be imaged with 3D seismic and input in advanced validated geomechanical technology such as those found in GMXPredictor.

Acknowledgments

The authors extend their appreciation to their colleagues Sonia Sanchez Hoff and Djamel Sia for their contribution to this study. The authors thank Dave Gray (Nexen) for providing the Fig. 1C outcrop picture. Comments and feedback from Riley Bates (Sable Permian Resources), Owen Hurd (EOG Resources) and Pedram Zarian (Shell) enhanced the paper and are greatly appreciated.

References

- Aimene, Y. and Ouenes, A. (2015). Geomechanical modeling of hydraulic fractures interacting with natural fractures — Validation with microseismic data and tracer data from the Marcellus and Eagle Ford. *Interpretation*, **3** (3), 1-18. doi.org/10.1190/INT-2014-0274.1
- Forand, D., Heesackers, V., & Schwartz, K. (2017). Constraints on Natural Fracture and In-situ Stress Trends of Unconventional Reservoirs in the Permian Basin, USA. Unconventional Resources Technology Conference. doi:10.15530/URTEC-2017-2669208
- Ouenes, A., Umholtz, N., Aimene, Y. (2016). Using geomechanical modeling to quantify the impact of natural fractures on well performance and microseismicity: Application to the Wolfcamp, Permian Basin, Reagan County, Texas, *Interpretation*, Vol. 4, No 2, May. doi: 10.1190/INT-2015-0134.1
- Ruppel, S. C., Jones, R. H., Breton, C.L., and Kane, J.A., (2005), Preparation of maps depicting geothermal gradient and Precambrian structure in the Permian Basin: The University of Texas at Austin, Bureau of Economic Geology, Contract report to the U.S. Geological Survey, order no. 04CRSA0834 and requisition no. 04CRPR01474
- Stoeser, D.B., Green, G. N., Morath, L.C., Heran, W.D., Wilson, A.B., Moore, D.W., Van Gosen, S.V., (2007). Preliminary integrated geologic map databases for the United States Central States: Montana, Wyoming, Colorado, New Mexico, North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Texas, Iowa, Missouri, Arkansas, and Louisiana Version 1.2, U.S. Geologic Survey, Open-File Report 2005-1352
- Umholtz, N., Ouenes, A. (2015). Optimal Fracing Near Faults - Quantifying the Interaction Between Natural and Hydraulic Fractures Using Geomechanical Modeling. Society of Petroleum Engineers. doi:10.2118/176932-MS
- Umholtz, N., Ouenes, A. (2016). Geomechanical Modeling of Fault Systems Using the Material Point Method – Application to the Estimation of Induced Seismicity Potential to Bolster Hydraulic Fracturing Social License, *Journal of Sustainable Energy Engineering*, Volume 4, Numbers 3-4, December 2016, pp. 262-277(16). Doi: 10.7569/JSEE.2016.629515