SPE-184850-MS

Lithology Variations and Cross-Cutting Faults Affect Hydraulic Fracturing of Woodford Shale: A Case Study

Xiaodong Ma and Mark D. Zoback, Stanford University, Department of Geophysics

Copyright 2017, Society of Petroleum Engineers

This paper was prepared for presentation at the SPE Hydraulic Fracturing Technology Conference and Exhibition held in The Woodlands, Texas, USA, 24-26 January 2017.

This paper was selected for presentation by an SPE program committee following review of information contained in an abstract submitted by the author(s). Contents of the paper have not been reviewed by the Society of Petroleum Engineers and are subject to correction by the author(s). The material does not necessarily reflect any position of the Society of Petroleum Engineers, its officers, or members. Electronic reproduction, distribution, or storage of any part of this paper without the written consent of the Society of Petroleum Engineers is prohibited. Permission to reproduce in print is restricted to an abstract of not more than 300 words; illustrations may not be copied. The abstract must contain conspicuous acknowledgment of SPE copyright.

Abstract

We conducted an integrated geomechanics case study of the Woodford shale to understand the effectiveness of multi-stage hydraulic fracturing. The study involves two parallel horizontal wells, each about 5,000 feet long with ~15 frac stages. Analysis of Instantaneous Shut-In Pressure (ISIP) of each frac stage indicates significant variations of the minimum horizontal principal stress (S_{hmin}) magnitude along the well length. We observed that S_{hmin} by stage rises with the content of clay and organic matter. The number of micro-earthquakes and the amount of proppant embedment, seems to be affected by the S_{hmin} variation. By combining the analysis of the compositional log and the well steering data, we found that the wellbore traveled in and out of the target zone and penetrated different facies of the Woodford shale along its path, resulting variations of lithology and consequently patchy stimulation performance. The distribution of microseismic events away from the well both vertically and laterally is also influenced by the lithology variation, as well as the presence of pad-sized faults.

Introduction

With the advent of horizontal drilling and multi-stage hydraulic fracturing (HF), the Woodford Shale (WDFD), which underlies the prolific Mississippi Limestone (MSSP), becomes economically viable. We conducted an integrated geomechanics case study of a WDFD pad to investigate the effectiveness of multi-stage HF. The studied pad is approximately one square mile and hosts four sub-parallel horizontal wells (A, B, C, and D). Two wells were drilled in the MSSP (wells A and C) and two in the WDFD (wells B and D), each about 5,000 feet long and with up to 15 frac stages. In addition, three vertical wells (I, II, and III) were drilled for micro-seismic monitoring. Figure 1 illustrates the spatial configuration of these wells. WDFD wells B and D are placed close to the top of the WDFD. The focus of our analysis is on the two parallel WDFD wells.

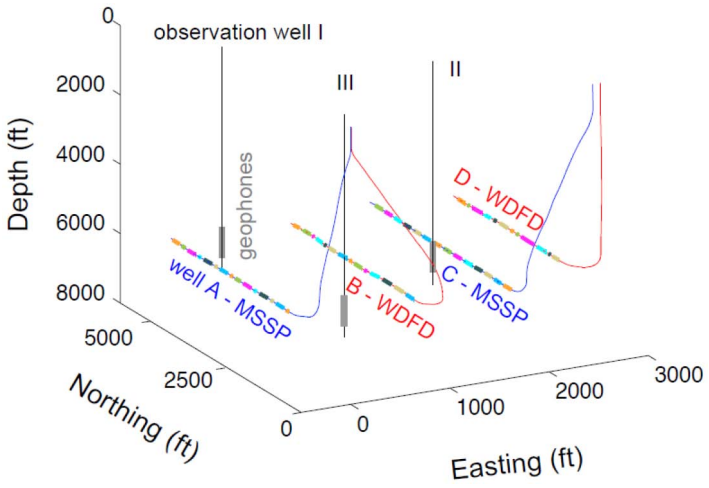

Figure 1—The configuration of four horizontal wells (A, B, C, D) and three vertical observation wells (I, II, III) in the study area. The positions of the hydraulic fracturing stages in Well A, B, C, D and geophone arrays in Well I, II, III are colored accordingly.

Geophysical logs, HF treatment records, and micro-seismic monitoring data are available for the study area. In this paper, a geomechanical model is first developed. We then integrated geological, geophysical and micro-seismic data to examine the relationship between *in situ* stress conditions and lithology variations along horizontal wells, and the role of lithology and fault presence on stimulation effectiveness.

Geomechanical Model

We began developing a geomechanical model by constraining the *in situ* state of stress in the study area. The overburden stress (S_V) is determined by integrating the density log of the central vertical well (Well II). The S_V profile with depth is shown in Figure 2. S_{Hmax} and S_{hmin} can only be partially constrained given the available data. The direction of the maximum horizontal stress (S_{Hmax}) across the study area is approximately $N85°E$, suggested by fast-shear velocity direction obtained using dipole sonic logs from multiple vertical wells. This is reasonably consistent with the azimuth of dirlling-induced tensile fractures in the same wells (*Ma and Zoback*, 2016) and the regional S_{Hmax} direction compiled by *Alt and Zoback* (2016).

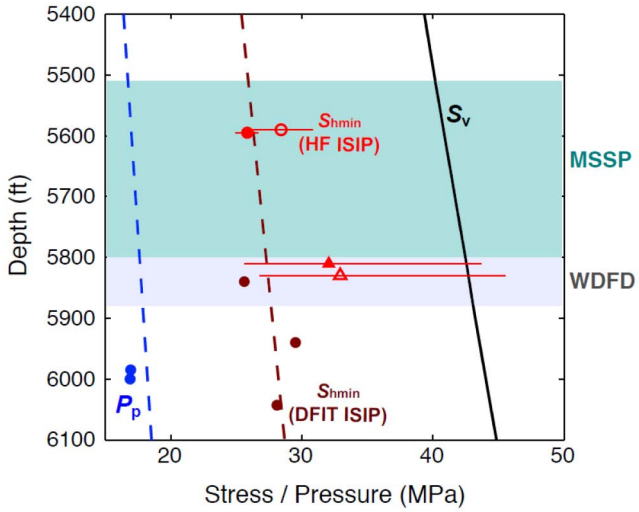

Figure 2—Geomechanical model of the study area. Hydrostatic pressure gradient (blue) and Shmin gradient (maroon) based on DFIT's (Diagnostic fracture injection tests) measurements are shown in dashed lines. Red error bars represent the ranges of instantaneous shut-in pressures (ISIP's) of frac'ing stages within each horizontal well.

Information on the magnitude of S_{hmin} at a given depth is available from several sources. S_{hmin} is best measured by the instantaneous shut-in pressure (ISIP) recorded during diagnostic fracture injection tests (DFIT's) or from the pumping records of each HF treating stage. A limited number of DFIT's were conducted in the central vertical well (II), giving only rough estimation of the S_{hmin} magnitude within both formations and below. The S_{hmin} gradient shown in Figure 2 was fitted based on DFIT's data. The ISIP's of MSSP Well A and C stimulation stages generally indicate S_{hmin} values of 25.5 MPa and 27.5 MPa at perforation depth of 5595 ft and 5590 ft, respectively. ISIP's within Well A are self-consistent, whereas in Well C they fluctuate within a 5 MPa window. Nonetheless, S_{hmin} magnitudes inferred from both MSSP wells are consistent with the S_{hmin} gradient based on the DFIT's.

S_{hmin} values for WDFD (estimated from staged ISIP's) are much less consistent than those for MSSP. In particular, the ISIP's within Well B and D are significantly scattered (Figure 2). The ISIP's generally range between the lower bound dictated by *NF* frictional equilibrium and the S_v level, and in certain stages even above S_v. The stress regime within WDFD therefore remains inconclusive.

ISIP variations along WDFD horizontal wells

Analysis of instantaneous shut-in pressures (ISIP's) measured during each HF stage reveals significant variations in the estimated minimum horizontal principal stress (S_{hmin}) magnitude along the length of both WDFD wells. Although the ISIP measured during HF treatments is affected by the complexity of the created fracture network and near-borehole stress conditions, it qualitatively reflects the magnitude of S_{hmin} within the stimulated rock masses. The dramatic variations in ISIP are not clearly correlated with the sequence of HF treatment stages (Well B and D were treated in order of stage number) (Figures 4 and 5). This suggests the sequence of treatments and associated poroelastic effects ('stress shadow') (*Vermylen and Zoback*, 2011) poses no major influence on ISIP.

To better understand the causes of significant ISIP variations within the WDFD formation, we attempted to correlate the variations along the length of both wells with available formation properties and HF treatment data. The WDFD formation exhibits significantly higher and much wider fluctuation of natural gamma-ray (GR) than the MSSP formation. Since high GR is a reasonable indicator of the presence of clay-rich shales, varying GR qualitatively reflects mechanical heterogeneities due to clay content within the rock. As shown in Figures 3 and 4, variations in GR appear to weakly correlate with ISIP in Well B, but are apparently unrelated to ISIP in Well D.

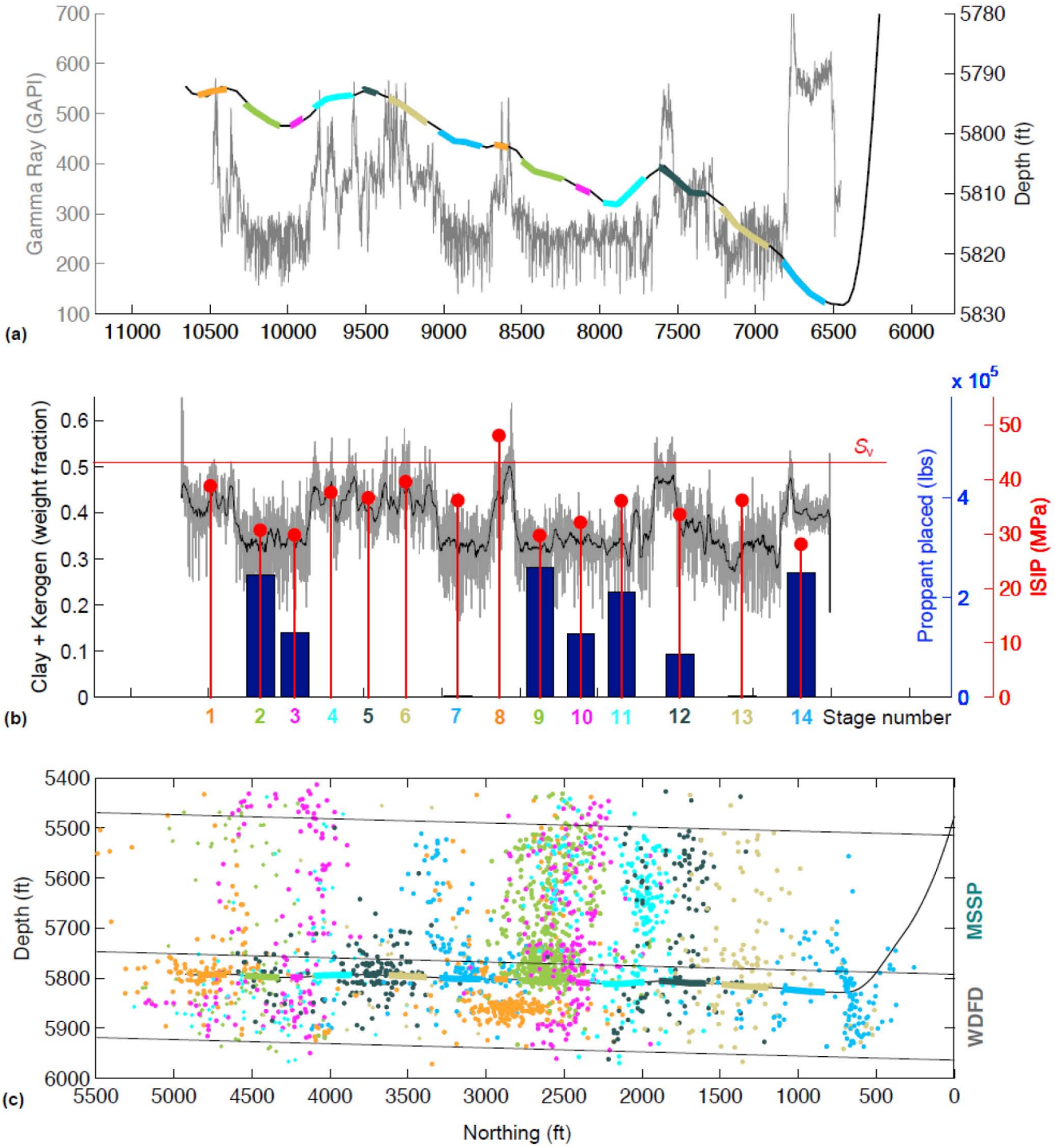

Figure 3—Correlated well information, treatment data and associated microseismic events of Horizontal Well B. (a) Variation of natural Gamma Ray along the horizontal section of the well and the exaggerated well trajectory in the vertical direction. (b) Variation of the content of clay plus kerogen (based on Elemental Capture Spectroscopy (ECS) log) along the well and its correlation with the instantaneous shut-in pressure (ISIP) and the amount of proppant placed of each frac'ing stage. Both ISIP and placed proppant amount are marked at the middle of the perforation location. The horizontal reference line indicates the overburden stress magnitude. (c) East-view of all microseismic events locations associated with the treatment of Well B (perforation sections of each stage are colored accordingly). The estimated depths of MSSP and WDFD formations are delineated.

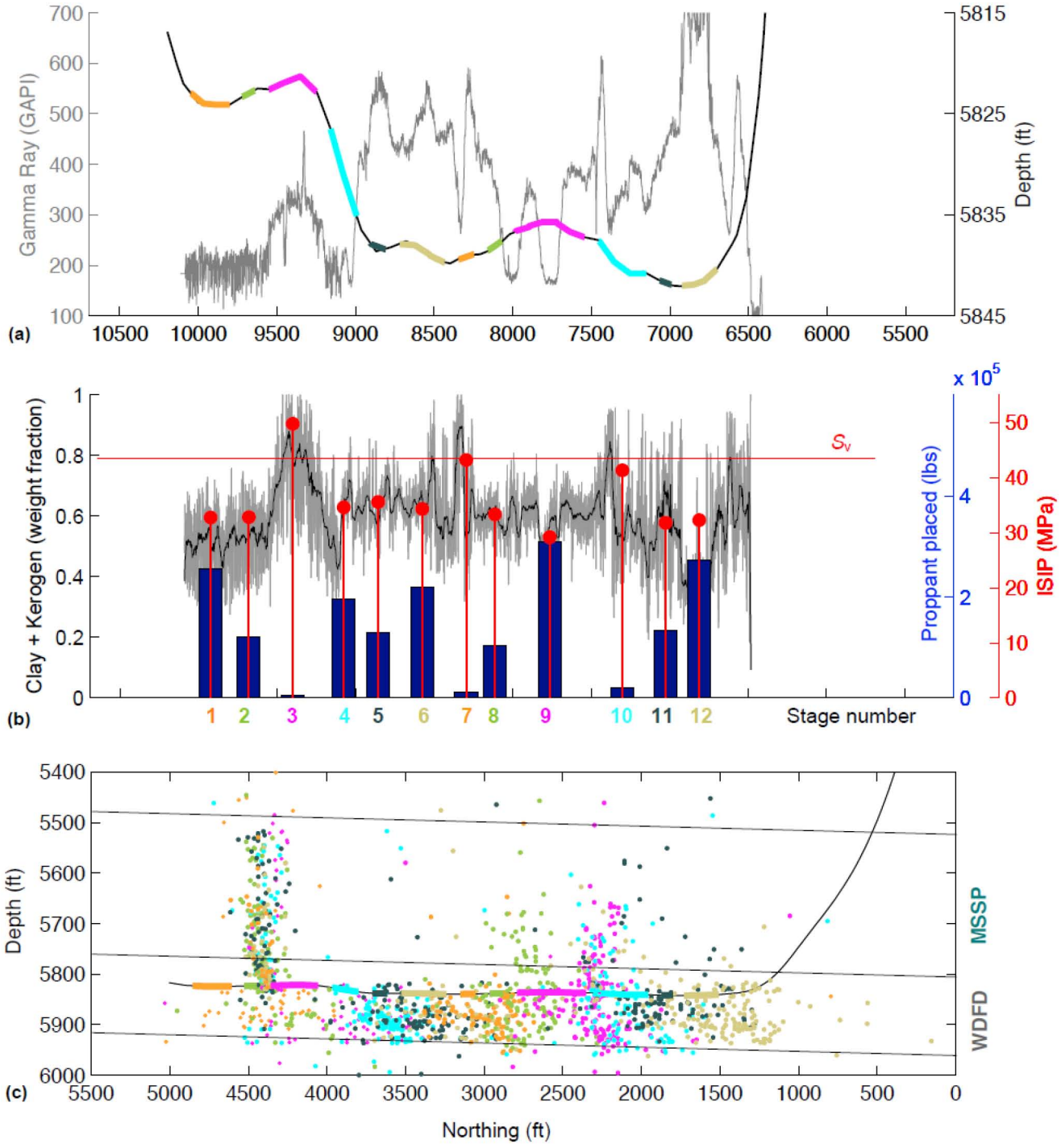

Figure 4—Correlated well information, treatment data and associated microseismic events of Horizontal Well D. (a) Variation of natural Gamma Ray along the horizontal section of the well and the exaggerated well trajectory in the vertical direction. (b) Variation of the content of clay plus kerogen (based on Elemental Capture Spectroscopy (ECS) log) along the well and its correlation with the instantaneous shut-in pressure (ISIP) and the amount of proppant placed of each frac'ing stage. Both ISIP and placed proppant amount are marked at the middle of the perforation location. The horizontal reference line indicates the overburden stress magnitude. (c) East-view of all microseismic events locations associated with the treatment of Well D (perforation sections of each stage are colored accordingly). The estimated depths of MSSP and WDFD formations are delineated.

We then utilized Elemental Capture Spectroscopy (ECS) logs to determine the concentrations of silicates, carbonate minerals, and clay and organic matter constituents over the entire lengths of Wells B and D. As demonstrated by *Sone and Zoback* (2013), compliant components (clay and organic matter) separate themselves from clastic components (silicate and carbonate minerals) in their control on many aspects of

rock mechanical properties. Here we adhere to *Sone and Zoback*'s (2013) classification for the convenience of our analysis. Figures 3b and 4b show that ISIP is generally correlated with the abundance of compliant components (clay and organic matter) in both Wells B and D. Variations in stress can be plausibly explained by modification of the stress state by visco-plastic effects. According to *Sone and Zoback* (2014a), the presence of compliant components (mainly clay and organic matter) induces visco-plastic (time-dependent) deformation. The more abundant the compliant components are, the more viscous the rock is, which in turn limits the differential stress accumulation for the same tectonic strain loading. *Sone and Zoback* (2014a,b) proposed that the contrast in compliant component content causes the contrast in the extent of differential stress accumulation. This is largely consistent with our observation: ISIP rises with clay and organic matter content (Figures 3b and 4b) as the maximum differential stress (S_v - S_{hmin}) decreases under constant overburden stress S_v.

The significant variations of ISIP within the WDFD formation would pose difficulties to the successful stimulation of certain treatment stages. We found the amount of proppant placement is interestingly associated with the ISIP in the frac stages of Wells B and D. As shown in Figures 3b and 4b, for those stages exhibiting ISIP's significantly greater than the normal S_{hmin} expected, little proppant was successfully placed. In contrast, in stages where ISIP was close to the expected value, considerable volumes of proppant were sucessfully injected. Despite that, the amount of proppant placement does not seem to be dependent on the magnitude of ISIP.

Although there is no direct correlation between the number of micro-seismic events and the magnitude of ISIP for a given stage, lower ISIP values generally correlate to a wider spatial distribution of microseismic events (Figures 3c and 4c).

Lithology variations along well trajectory

Drastic variations of lithology along both WDFD wells are associated with significant changes in rock mechanical properties and, subsequently, stress magnitudes. For generally laminated sedimentary sequences, we normally expect a uniform lithology within a given horizon. One possible reason that the horizontal WDFD wells in this study encounter such drastically varying lithology is that the well path does not conformably follow a single layer. To see if this was the case, we examined the well steering data and relevant lithological sequences. Within the WDFD formation, the ECS log of central vertical Well II shows sharp changes in clay and organic matter content near the perforation depths (Figure 5). As a result, it is highly possible that the perforations along the horizontal were performed within distinct lithologies. According to the abundance of clay and organic matter content, the WDFD formation can be further divided into several distinct facies. Correlation of several nearby vertical well logs suggests these facies are laterally conformable and sequentially consistent. Combining the lithological variations in the horizontal wells and the verticals and the horizontal well steering data, we confirmed the horizontals penetrated different facies of the WDFD formation along the well length (Figures 3a and 4a). Although the depth deviation in the horizontals is typically less than 20 feet, so is the thickness of the facies in question. Given this fact, it is not surprising that the well may deviate from the optimum facies even with careful steering. Even if the majority of each horizontal well is drilled through optimum facies featuring low clay and organic matter contents (and therefore normal ISIP), a short detour into the facies immediately below and above the target zone could result in substantial increases in ISIP (Figures 3b and 4b).

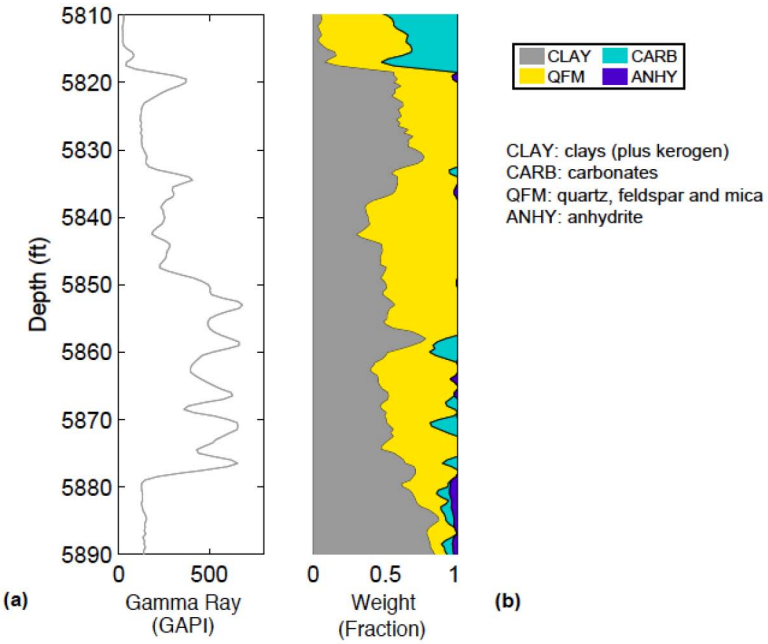

Figure 5—Geophysical logs of the vertical Obeservation Well II: (a) Natural Gamma Ray log; (b) Compositional log representing the composition of major constintuent minerals by weight fraction.

Micro-seismicity indicating patchy stimulation and faults Presence

Microseismic events during hydraulic fracturing were monitored using three-component (3C) geophone arrays vertically placed along Wells I, II and III. Each of the three monitoring arrays includes 15 levels of geophones, spanning a depth range of approximately 850 ft. A total of 8865 microseismic events were detected and located during stimulation of the four horizontal wells. We examined the distribution of events in relation to the perforation locations. Figure 6 shows a map-view of all the events. Generally, a patchy distribution of events across the study area is observed, and the desired bi-lateral, well-perpendicular distribution pattern is lacking. Notably there are more events clustered in the vicinity of the three observation wells.

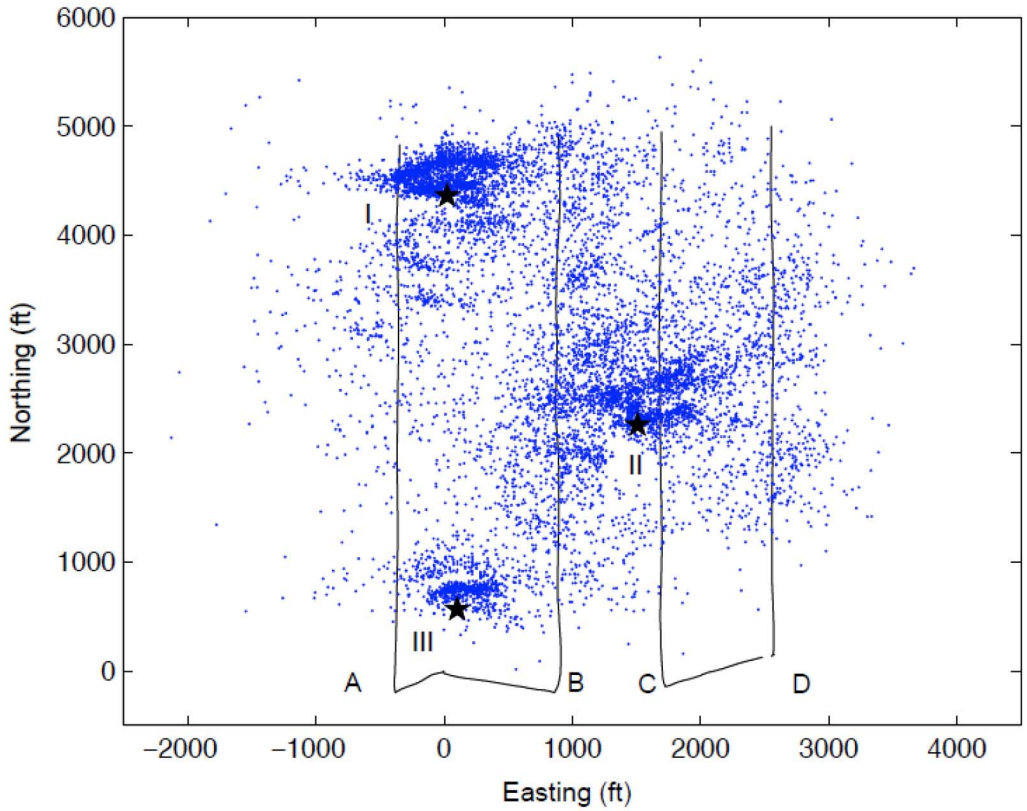

Figure 6—Mapview of the study area and configuration of four horizontal wells (A, B, C, D) and three observation wells (I, II, and III, indicated by black stars) and microseismic events locations. All events recorded by any of the three arrays (blue dots).

Figures 3c and 4c display the east-view of events (marked by stage) in Wells B and D. For Well B, significant upward propagations are observed in some, but not all, stages. In Well D, upward propagations are strictly limited to a few stages. Those stages in Wells B and D associated with abnormally high ISIP and difficult proppant placement (Figures 3b and 4b) feature the majority of events contained in the WDFD formation with limited upward propagation. In addition, those stages demonstrating significant vertical growth into MSSP are mainly associated with normal ISIP magnitudes; however, this correlation is not conclusive.

In addition to the vertical connection between the two formations, we also noticed a few interesting trends in the events shown on the map-view (Figure 7). The first is a cluster of events which occurred near the toe of Well A and observation Well I when the distant Wells C and D were stimulated. These events apparently reflect the vertical linkage between WDFD and MSSP. Second, there are clusters of events across the middle of Well B and C (and near observation Well II), delineating a trend slightly oblique to the prevailing S_{Hmax} direction. These events are pervasive across MSSP and WDFD and even occurred within surrounding formations. Third, seemingly isolated events occurred between the heels of Wells A and B (and near observation Well III) when Wells B and C were stimulated. These events also vertically connected MSSP and WDFD.

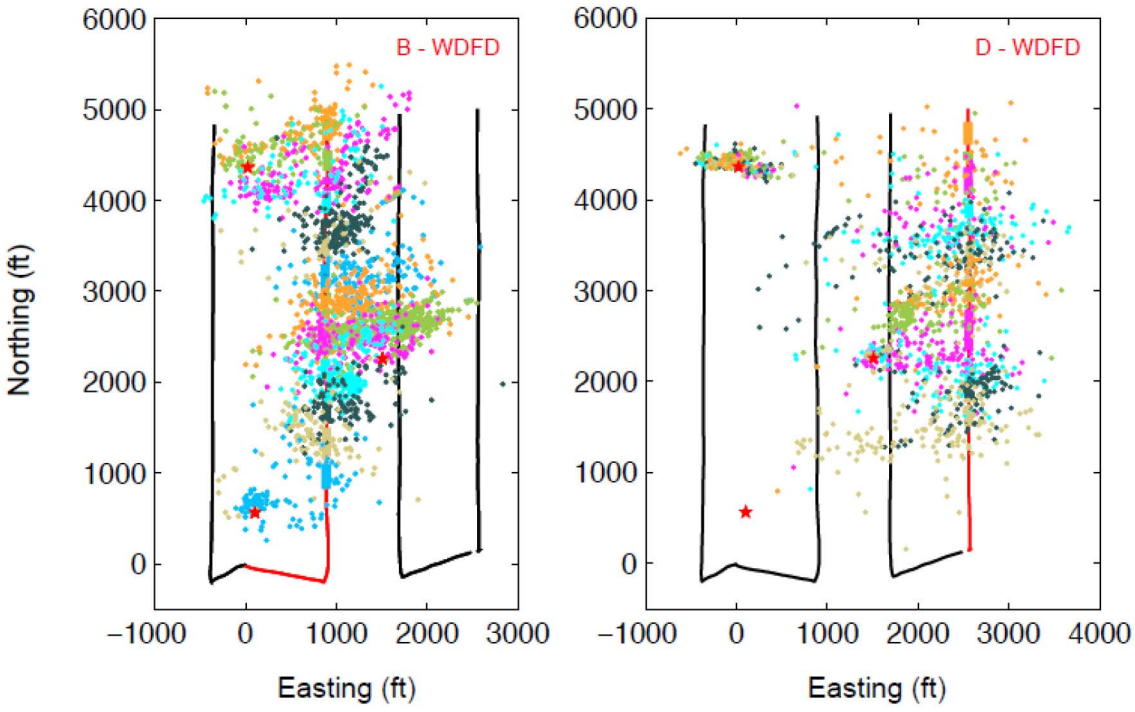

Figure 7—Mapview of microseismic events locations for each well by stage.

The unusual spatial and temporal patterns of the events described above suggest the presence of hydraulically-conductive paths not characteristic of stimulated hydraulic fractures. We suspect these are well-oriented faults because the event trends are close to the slip directions preferred under the prevailing in situ stress conditions. In a normal-faulting stress regime, faults dipping about 60° to S_{hmin} and striking along S_{Hmax} direction can be easily re-activated by moderate pore pressure perturbations; in a strike-slip stress regime, nearly-vertical faults trending 30° away from the S_{Hmax} direction are expected to slip. These expected fault orientations are somewhat consistent with the observed events trends.

Concluding Remarks

In this study, we integrated geomechanics concepts with formation properties and microseismic monitoring data to understand the effectiveness of multi-stage hydraulic fracturing stimulation in an area of the WDFD shale oil play. We identified positive correlations between compliant component (clay and organic matter) content and the magnitude of instantaneous shut-in pressure (ISIP) along two horizontal wells in the WDFD formation. The abnormally high ISIP's observed in some stages appear to inhibit the propagation of hydraulic fractures and the placement of proppants. Variations in ISIP with lithology can be plausibly explained by the viscous stress relaxation, which postulates that the difference between S_v and S_{hmin} diminishes as the compliant component content increases. In the future we plan to quantitatively model the stress variations with lithology using the stress relaxation model.

Microseismic monitoring data indicates patchy stimulation across the stimulated wells, particularly in certain stages of the WDFD wells. Stages lacking stimulation generally coincide with those showing high ISIP's. We also observed abnormal lineations of events trending in preferred orientations along which fault-slip may occur in the prevailing in situ stress condition. We plan to resolve discontinuous features based on 3D seismic reflection data and will conduct a detailed fault-slip analysis based on realistic in situ conditions and additional information to confirm the presence of these faults.

To conclude, the inherent non-uniformity inside shale reservoir induces lithological variations, which in turn cause variations in stress states and mechanical properties. It is imperative to integrate the lithological and mechanical information for effective hydraulic fracturing stimulation.

Acknowledgement

This work was supported by the Devon Energy and the Stanford Rock Physics and Borehole Geophysics Project (SRB).

References

Alt, R and M.D., Zoback, 2016, In-situ stress and active faulting in Oklahoma, *Bulletin of the Seismological Society of America*.

Ma, X., and M.D., Zoback, 2016. Geomechanical Study of Hydraulic Fracturing in Woodford Shale, Oklahoma. AAPG Annual Convention & Exhibition, Calgary, Alberta, Canada, 19-22 June 2016.

Sone, H. and M.D., Zoback, 2013. Mechanical properties of shale-gas reservoir rocks - Part 1: Static and dynamic elastic properties and anisotropy, *Geophysics*, v. **78**, no. 5, D381-D392.

Sone, H. and M.D., Zoback, 2014a. Time-dependent deformation of shale gas reservoir rocks and its long-term effect on the in situ state of stress. *International Journal of Rock Mechanics & Mining Sciences* **69**: 120–132.

Sone, H., and M. D. Zoback, 2014b. Viscous relaxation model for predicting least principal stress magnitudes in sedimentary rocks. *Journal of Petroleum Science and Engineering* **124**: 416–431.

Vermylen, J.P., and M.D., Zoback, 2011. Hydraulic fracturing, microseismic magnitudes, and stress evolution in the Barnett Shale, Texas, USA. SPE Hydraulic Fracturing Technology Conference and Exhibition, Woodlands, Texas, USA, 24-26 January 2011.