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Simultaneous Hydraulic Fracturing of Adjacent Horizontal Wells in the Woodford Shale

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Abstract

Hydraulic fracturing of horizontal wells in shale gas reservoirs is now an established, commercially successful technique. The evolution of the completion technique has reached the point that numerous stimulation stages through multiple perforation clusters in wellbores with some form of annular isolation is now an accepted practice. The objective is to place multiple closely spaced hydraulic fractures. This has proven to be a viable development strategy for many shale reservoirs in North America.

To further enhance the recovery factor in these ultra low permeability reservoirs simultaneously hydraulically fracturing of adjacent wellbore is increasingly being tested. Most of the time this is performed in horizontal wellbores paralleling each other. The goal is to create hydraulic fractures more closely spaced than can be achieved from a single wellbore. When real time microseismic monitoring of the stimulation treatments is incorporated changes can be made “On-the-Fly” to improve the effective stimulated reservoir volume.

Continental Resources has employed simultaneous hydraulic fracturing as a development strategy for their Woodford Shale acreage in the Arkoma Basin of Eastern Oklahoma. To monitor the effectiveness of the stimulations geophones have been deployed into horizontal wellbores to record microseismic events when offsetting vertical wellbores are unavailable. Cased hole sonic logs have also been run to quantify cement bond quality, estimate stress variation along the lateral, and to pick optimum perforating points.

This paper reviews the methodology employed in the completion design and process. The impact of the simultaneous stimulations and geologic structure on the fracture geometry are shown as well as the impact on well productivity.

Woodford Geology

The Devonian Woodford shale is a prolific gas producer in the western Arkoma Basin in Atoka, Coal, Hughes, and Pittsburg Counties, Oklahoma where there are over 527 Woodford completions since January, 2004. The majority of these wells are horizontal with multistage fracture stimulation treatments performed on them. In these four counties, the Woodford formation ranges in depth from approximately 4,000 ft to over 14,000 ft and varies in thickness from 35 ft to over 280 ft. In the area

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thick. The Woodford lies upon the post-Hunton unconformity and is underlain by Hunton Limestone with the calcareous Mayes formation overlying the Woodford.

The Woodford Shale is an organic-rich, siliceous shale with 48 - 74% quartz, with an additional 3 - 10% feldspar, 7 - 25% illite clay, 0 - 10% pyrite, 0 - 5% carbonate, and 7 - 16% kerogen based on log and core analyses. The Woodford in this study area has been sub-divided into 4 units, Upper Woodford, Woodford A, Woodford B, and Woodford C. The Upper Woodford frequently has the highest clay content, while the Woodford A and C intervals have the highest silica content along with the highest effective porosity. The Woodford B has lower apparent porosity than the Woodford A and C (Figure 1).

In this area, seismic data indicates there is an E-W trending fault/fracture network with an ENE-WSW secondary fault/fracture network (Figure 2). The horizontal wells in this area target the Woodford A interval and are drilled N-S to maximize the drainage of the section. This orientation also approaches the azimuth of the minimum horizontal stress (σ_h) which results in hydraulic fractures that are perpendicular to the wellbore. This stress orientation has been identified by induced fractures on image logs (Figure 3) and confirmed by microseismic imaging of hydraulic fractures.

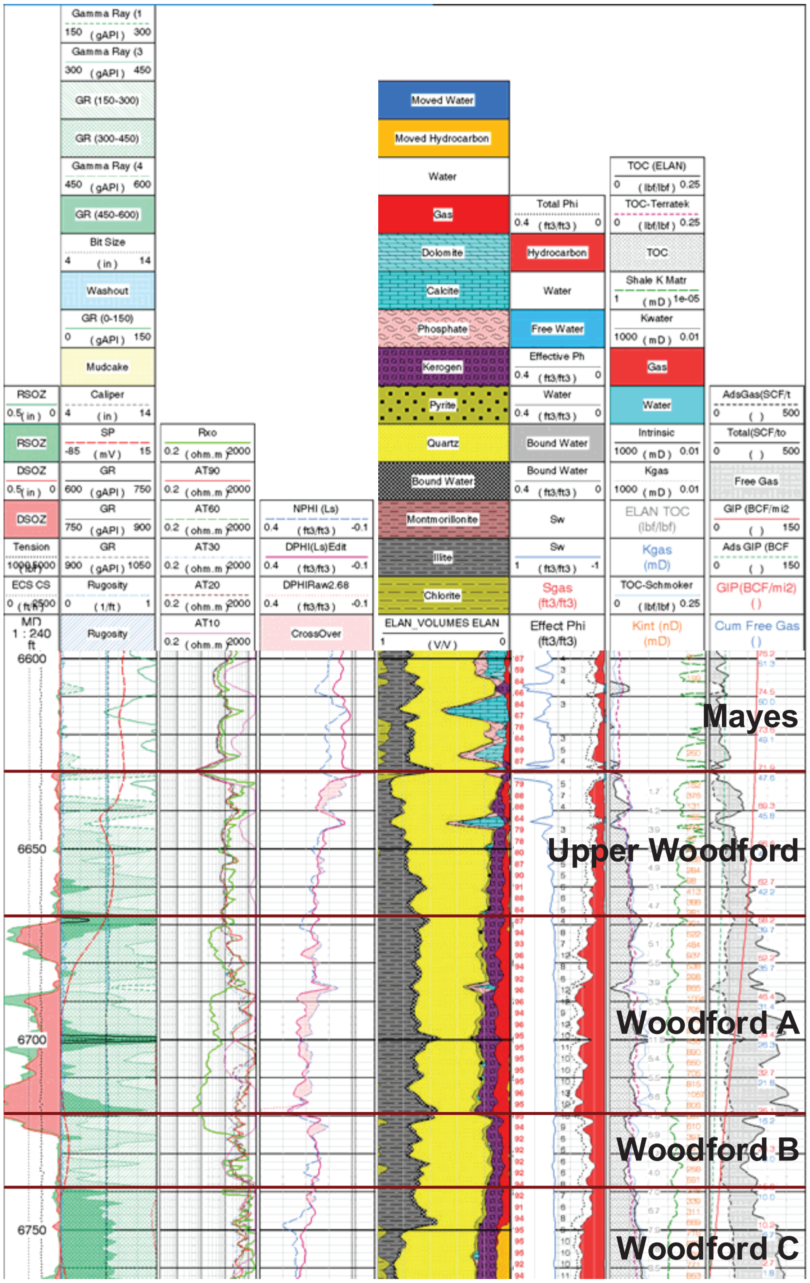

Figure 1 – Woodford Shale Type Log with sub-divisions noted. Log does not penetrate all of Woodford

Hydraulic Fracturing of Shales

Hydraulic fracturing of ultra low permeability reservoirs is required to establish commercial productivity. Commercial shale reservoir permeabilities are in the range of 200 nd, or 0.0002 md. With formation permeabilities of this magnitude the pressure drop in the system occurs primarily in the reservoir near the fracture face. Analytical techniques support this conclusion even assuming no fracture face damage[1]. Figure 4 shows the source of pressure losses versus time in a low permeability shale reservoir assuming no fracture face skin.

Reservoir simulations have also shown that this is the case for many years after production commences (Figure 5)[2,3]. As Figure 5 indicates, large sections of

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pressure after 10 years of production, when hydraulic fractures are spaced 1,000 ft apart in a 400 nd shale gas reservoir. Even after 60 years of production the reservoir pressure still approaches 50% of its initial value for this fracture spacing. The recovery factor is increased dramatically when the hydraulic fractures are spaced closer together. As indicated by Figure 6 a 250 ft hydraulic fracture spacing drains as much of the reservoir in 10 years as the 1,000 ft spacing does in 60 years. With this spacing the reservoir is largely depleted between the fractures after 60 years of production.

Recovery can be accelerated further by even closer spacing of hydraulic fractures, or in reservoirs where dense natural fractures that remain open during production are present. Ultimately the optimum spacing of hydraulic fractures is driven by two parameters:

- The incremental cost associated with creating an ever denser fracture system versus the productivity improvement from the denser fracture network.
- The ability to physically, continually propagate hydraulic fractures in close proximity to one another.

An investigation of theoretical hydraulic fracture spacing provides a lower bound for their proximity. As a first pass one can use Hooke's Law to determine realistic minimum hydraulic fracture spacing. For this application Hooke's Law takes the form shown in Equation 1:

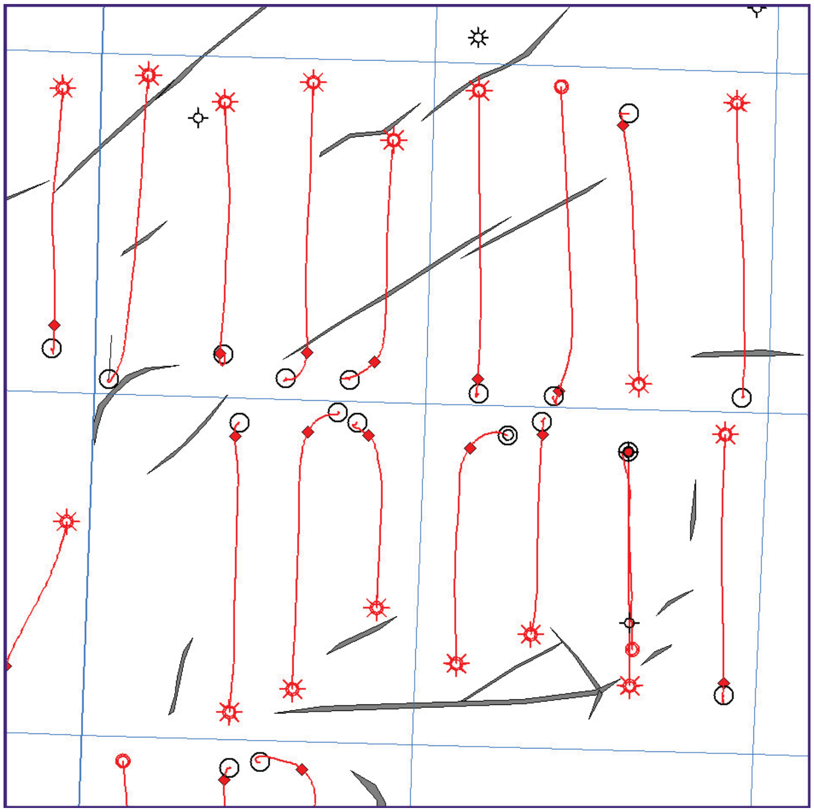

Figure 2 – Woodford structure showing an E-W fault/fracture network and a secondary NE-SW system. Wellbores are oriented N-S for most effective development. Blue squares denote 1 mile section lines.

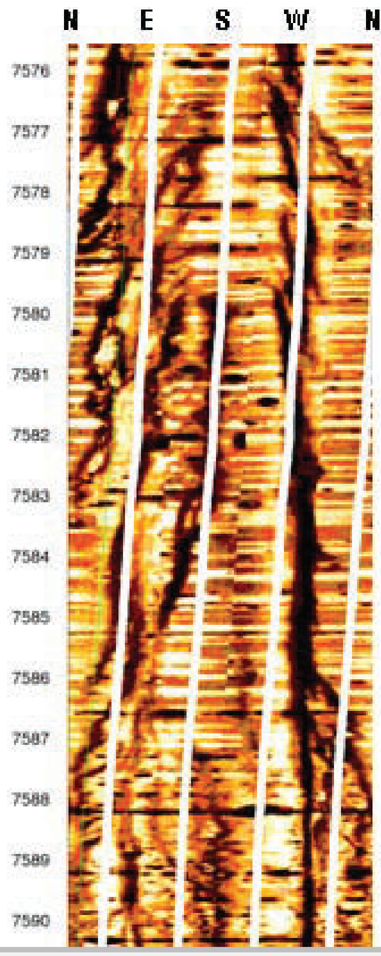

Figure 3 – Woodford FMI Log showing E-W Induced Fractures, the azimuth of the maximum horizontal stress (σ_H) and of hydraulic fractures.

$$\Delta\sigma = E(w/b) \quad (1)$$

where E = horizontal Young's Modulus, w = hydraulic fracture width, and b = hydraulic fracture spacing. Figure 7 portrays this stress increase

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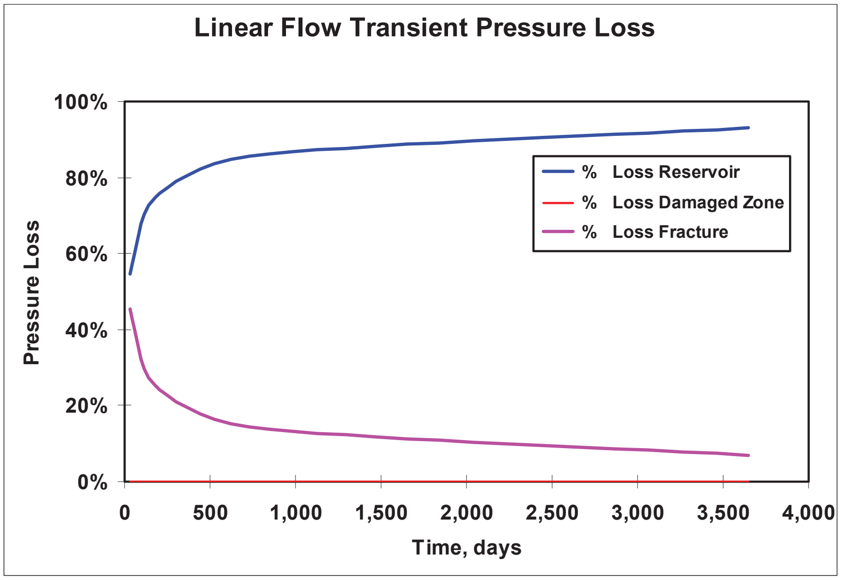
Figure 4 – Sources of pressure loss in a hydraulically fractured shale reservoir showing the majority of the system pressure loss is in the formation, near the fracture face.

Assumptions:
Fracture Length = 1,000 ft
Fracture Conductivity = 8.3 md-ft
Formation Perm = 200 nd
Fluid Viscosity = 0.02 cp
Porosity = 7%
Fluid Compressibility = 0.0001 psi^{-1}
No Fracture Face Skin



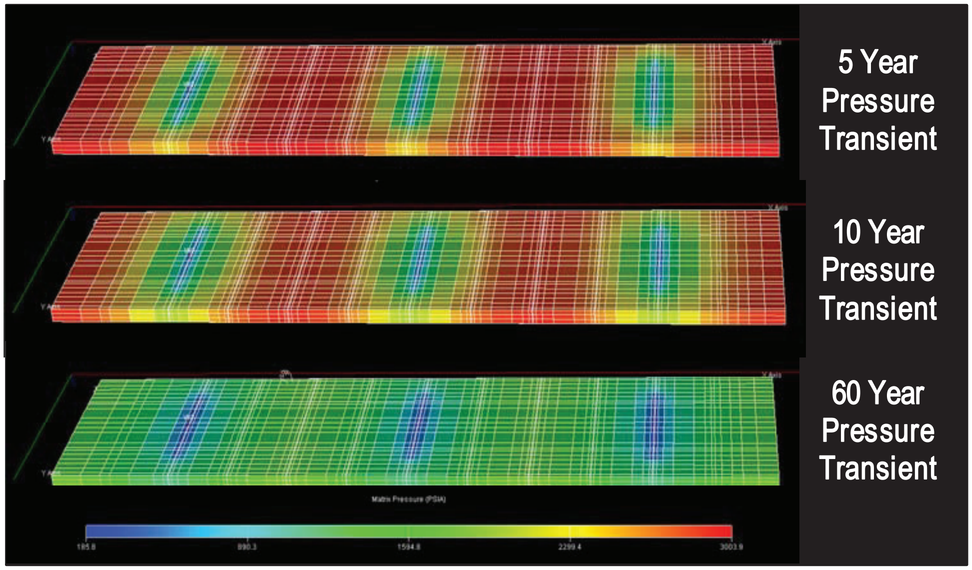


Figure 5 – Pressure Transient in a 400 nd shale gas reservoir with an initial reservoir pressure of 3,000 psi and 500 ft long hydraulic fractures spaced at 1,000 ft intervals.

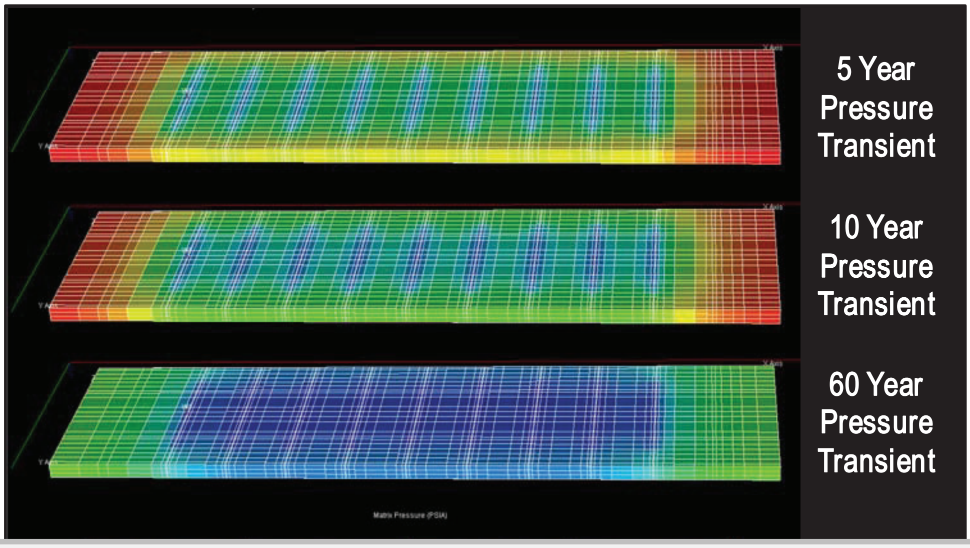


Figure 6 – Pressure Transient in a 400 nd shale gas reservoir with an initial reservoir pressure of 3,000 psi and 500 ft long hydraulic fractures spaced at 250 ft intervals.

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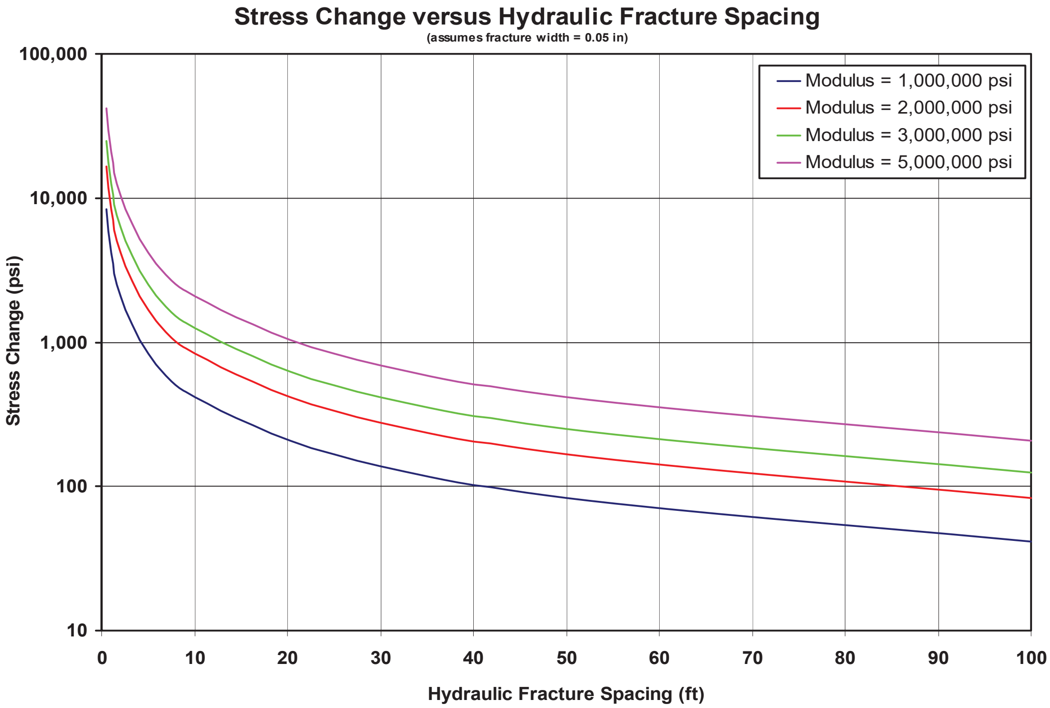

Figure 7 – Stress increase versus hydraulic fracture spacing for various Young's Moduli. The higher the Modulus the greater the stress increase. At very close fracture spacing the stress increases dramatically. A hydraulic fracture width of 0.05 inches is assumed.

Two conclusions are apparent:

- In order for hydraulic fractures to be very close together very high stresses are required. A fracture spacing of 1 ft requires stresses in excess of 4,000 psi for all listed moduli. This is unrealistic and will certainly lead to the truncation of most fractures and the creation of a dominant, single fracture at this spacing.
- The rock stiffness greatly influences the achievable fracture spacing. For example, at a fracture spacing of 25 ft the increase in stress is >800 psi for a rock with a Young's Modulus of 5×10^6 psi. Yet the stress increase is only 170 psi for a rock with a Young's Modulus of only 1×10^6 psi.

Fortunately organic-rich shales normally have relatively low Young's Modulus compared to conventional low permeability reservoirs that are candidates for hydraulic fracturing. Therefore, it is easier to place fractures closer together in these very low permeability rocks than in tight sands or carbonates where the Young's Modulus is frequently in excess of 6×10^6 psi. This example is a gross simplification yet it does provide a measure of scale of hydraulic fracture spacing.

Warpinski and Branagan[4] reviewed the stress alteration associated with hydraulic fracturing, comparing it to field results recorded in the U.S. DOE's Multiwell Experiment Site[5]. This paper focused on the rotation of minimum horizontal stress (σ_h) due to the stress perturbation created from a pre-existing fracture from an offset well. The analytical technique used in this paper[6,7] assumes an infinitely long planar fracture in a homogeneous, elastic and isotropic body. While these simplifying assumptions may be idealistic the method does provide some insight into the potential complexities associated with hydraulic fractures propagating in close proximity to each other. The reader is referred to Reference 4 for the pertinent equations.

Hydraulic fracture rotation is unlikely if there is a large difference in the horizontal stresses, a moderate Net Pressure build, and/or a relatively small fracture height. But this does not mean that the fracture geometry is not impacted by the adjacent fractures. The degree of stress increase associated with a hydraulic fracture varies vertically through the fracture with the highest stress increase occurring at the

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