REFRACTURE REORIENTATION ENHANCES GAS PRODUCTION IN BARNETT SHALE TIGHT GAS WELLS

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ABSTRACT

Refracturing can be used to increase production in poorly fractured wells. **A** different application of this technology is to refracture wells with strong initial fractures. In this paper, we provide evidence of increased production due to refracturing two tight gas wells having deeply penetrating initial fractures. Surface tiltmeter measurements show refracture orientations at oblique angles to the azimuth of the initial fractures.

INTRODUCTION

Refracture reorientation has previously been postulated [1, 2] and directly observed in soft, shallow formations [3, 4, 5]. We present the results of two refracture treatments *to* test the concept of orthogonal refracture reorientation in a tight gas formation. Previous work, based on theoretical considerations in tight gas reservoirs [6], shows that a refracture can orient at 90 degrees to an initial hydraulic fracture under certain conditions. In such cases, the refracture can penetrate untapped sections of the reservoir, significantly increasing production rate and reserves. Candidates for the field tests were those that exhibited production behavior indicative of a deeply penetrating highly conductive initial fracture. It is important to point out that such wells are not usually considered for refracturing. The field tests were carried out in the Barnett Shale, north of Fort Worth. The refracture treatments were monitored with an array of surface tiltmeters. Results indicate significant reorientation of the refracture treatment in Well **A,** and oblique reorientation in Well B. Production data indicates a substantial increase in production after both refracture treatments. Other wells in the area, not part of this study, have shown similar production increases after refracturing. In this paper, we summarize the field candidate selection process, results of production forecasts, and provide details and discussion on the refracture designs and treatments.

REFRACTURE REORIENTATION CONCEPT

Fig. 1 is a schematic representation of the concept of refracture reorientation. The figure shows a horizontal section through a vertical well containing an initial fracture, oriented west-east. Production, after placement of the initial fracture, will cause a local redistribution of pore pressure in an expanding elliptical region around the wellbore and initial fracture [6]. The pore pressure depletion changes the stress distribution in the reservoir. Numerical simulations [6] show that the total horizontal stress component parallel to the initial fracture reduces quicker than the orthogonal one as a function of time, at locations along the line of the proposed refracture direction.

If the induced stress changes are large enough to overcome the effect of the initial horizontal deviatoric stress, then the direction of the minimum horizontal stress becomes the maximum within an elliptical region around the wellbore and initial fracture (see **Fig. 1).** Under these conditions, a refracture will propagate at 90 degrees to the initial fracture azimuth, until it reaches the limit of the elliptical stress reversal region. The boundary of this region along the proposed refracture propagation direction is defined by isotropic points – points with equal horizontal stress. We can expect the refracture to start to reorient itself at some distance $L_{xf''}$ *beyond the isotropic point (at distance* $L_{xf'}$), as shown in **Fig. 1.** The isotropic point will typically locate at a distance less than half the initial fracture penetration. However, fracture toughness extends the orthogonal penetration of the refracture beyond this point.

The distance to the isotropic point depends on the magnitude of the initial horizontal stress contrast, initial fracture penetration, production rate, reservoir permeability, and the elastic moduli contrast between the pay and barrier zones [6]. These are parameters that should be considered in the selection of a candidate well.

FIELD CANDIDATE SELECTION AND EVALUATION

Initially we did not consider formations containing natural fractures because we were not sure how they might affect the reorientation. However, Mitchell Energy Corp. had been successful in refracturing a number of wells in the naturally fractured Barnett Shale. Well C was one of these wells, and its production history was analyzed to determine reasons for the success. The refracture was more than twice the size of the initial treatment, using approximately 500,000 gal of cross-linked fluid and more than 1 **MM** lb of proppant.

Fig. 2a shows the production history of Well C before and after refracturing. The log-log plot in **Fig. 2b** clearly shows the characteristic linear flow, indicative of a deeply penetrating initial fracture with finite acting fracture conductivity – one of our requirements for selection of a successful refracture reorientation candidate. The treatment parameters of this well, and others discussed in the paper, are summarized in **Table 1.**

Production history matching was performed in order to determine the likely orientation and magnitude of the refracture that was required to produce the incremental production benefits realized on this well. The best matches were achieved in the presence of a horizontal permeability anisotropy of $k_x/k_y = 12$. This magnitude of anisotropy could be expected in a formation that is naturally fractured. **Fig. 3** shows matches of the cumulative gas production with the measured data. Future production for three cases was simulated. The first case shows the simulated match and projection without a refracture. The second case, for refracture penetration twice that of the initial fracture propagated in the same plane as the initial fracture does not match the observed data. The final case is for a refracture penetration slightly less than that of the initial fracture, but propagated at 90 degrees to the initial fracture azimuth. These solutions are not unique, but for us they provided convincing evidence of reorientation. The operator chose to refracture Well A. A production match with projection of several refracture scenarios was made, and these are shown in **Fig. 8.** After the refracture of Well A, the operator decided to also refracture Well B. However, no detailed evaluation of the production data on Well B was performed prior to the refracturing treatment. It was refractured and the azimuth was measured with the same tiltmeter array as was used for Well A.

The initial fracture azimuth in the field is N40°E. This has been confirmed using several methods, including tiltmeter and microseismic data. A study of Well D about 3 miles to the east, indicated induced fractures at N60°E ± 15 degrees [7]. This study also showed that natural fractures are oriented at N65°W. Other unpublished borehole imaging data in the Barnett Shale showed different azimuths for the natural fractures on one well and none in others. However, there appears to be a dominance of natural fractures in the Bamett Shale.

WELL A REFRACTURE TREATMENT

Mitchell's current fracturing procedure, consisting of light sand fracs, using low concentrations and volumes of proppant, was pumped on Well A. The perforated interval, 7,090 to 7,280 ft, was re-perforated with 120 degree phasing, prior to performing the refracture treatment. A mini-frac was pumped consisting of 185 bbl, injected at 53 bpm. The main treatment consisted of 17,177 bbl injected at an average rate of 53 bpm over a 5.5 hr period. Proppant with a concentration of 0.2 ppg was added half way through the job, and ramped up to 1.6 ppg over the last 20 min. interval. Surface treating pressure held constant throughout the job at approximately 5,035 psi. **Fig. 4** shows the treatment schedule. Friction reducers at very low concentrations were added to the water, and the slight variations in treating pressure are attributed to variations in friction pressure. The bottom hole pressure was not measured.

A surface array of 24 tiltmeters, located on offset well locations in a radial pattern around the treatment well, was used to monitor the azimuthal growth of the refracture. The principle of tiltmeter fracture mapping is simply to infer hydraulic fracture geometry by measuring fracture-induced rock deformation. The induced deformation field radiates in all directions and can be measured with a surface array of tiltmeters and with wireline-conveyed downhole tiltmeter arrays (see **Fig. 13).** Details of surface and downhole tiltmeter mapping technology are well documented in the literature [8 - 12].

The data from Well A was subdivided into 5 intervals, corresponding to the mini-frac, followed by the main treatment, which was divided into 4 quarters (of 83 min each). **Table 2** summarizes the refracture characteristics for these intervals. Analysis of the tiltmeter data (see **Table 2)** shows that the refracture initiated in the N5°W direction, and gradually re-oriented to a final azimuth of N66°W. This can be deduced by noting the increasing percentage of total fracture growth contributing to the N60°W to N67°W azimuthal range in **Table 2.** In addition, analysis of the tiltmeter signals clearly shows a gradual azimuthal change **(Fig. 5)** rather than an abrupt one (e.g., see **Fig. 6,** from a tiltmeter survey in California). The latter might be expected to occur if the refracture intersected a natural fracture and immediately chose the natural fracture's preferential growth orientation, or if a second refracture initiated at a different orientation.

Fig. 7 is **a** schematic view of the refracture azimuth as a function of time, as interpreted from the tiltmeter data. Fracture length was not determined from the surface tilt data. Therefore, the figure accurately details the azimuth but does not infer length. The refracture initiated in N5°W direction, an angle of 45 degrees from the estimated azimuth of the initial fracture of N40°E. The refracture later curved gradually to a NW-SE direction, with a final azimuth range of N66°W, i.e., 106 degrees from the assumed initial fracture azimuth. The average refracture azimuth was calculated to be N28°W, 68 degrees from the initial fracture azimuth. The refracture azimuth thus provides partial validation of the orthogonality concept. The final refracture azimuth very closely matches the mapped azimuths of natural fractures about 3 miles to the east of Well A.

Of interest from a theoretical standpoint is the growth path of the refracture. The refracture did not initially propagate at 90 degrees to the initial fracture, as expected from theory. This could be due to any number of reasons, such as the perforation orientation or the fact that the well was shut in for a couple of weeks prior to the refracturing treatment. This shut-in period altered the pore pressure gradient near the wellbore, and may have contributed to the initial direction of the refracture. Also the natural fractures in the near wellbore vicinity may have filled with water during the shut-in period. Therefore, at the beginning of the fracture treatment these fluid filled fractures would be pressurized and then propagate away from the wellbore resulting in a complex fracture system near the wellbore. Thus, the initial azimuth of the fracture may have been affected by this early time complexity.

The initial production of Well A was history matched. The parameters for this match were used to forecast refracture lengths of about 40 and 80 percent of that of the original fracture length, as depicted in **Fig. 8.** After Well A was put back into operation, production increased from 50 to 100 Mscf/d to 750 Mscf/d **(Fig. 8)**. Gas production after six months was approximately 300 Mscf/d against slightly higher line pressure. Six months of post-refracture production data more accurately matches a refracture of length of 40 percent of the initial fracture length. The refracture stimulation cost has been recovered from the increased productivity.

WELL B REFRACTURE TREATMENT

Well B was not evaluated as an orthogonal refracturing candidate. It was part of a separate study in refracturing and infill drilling, but surface tilt data was available from the same array as was used for Well A. A diagnostic plot of Well B production did not show the long period of linear flow that was observed on Well **A (Fig. 11)**, indicating **a** shorter initial fracture. Its production rate was much higher, having produced about the same cumulative amount of gas in five yrs as Well A did in 11 yrs. Therefore, it appeared to have higher permeability either from matrix permeability or possibly due to the natural fracture system.

A similar treatment to that of Well A was used on Well **B.** The perforated interval, 7,004 to 7,242 ft, was re-perforated with 120 deg. phasing prior to performing the refracture treatment. A step rate test was performed, followed by two mini-fracs of 25 and 48 min. duration, at an injection rate of about 52 bpm. The main treatment consisted of 14,861 bbl injected **at** an average rate *of* 52 bpm over a 5 hr period. Proppant with a concentration of 0.12 to 0.25 ppg was added one third of the way through the job, and ramped up to 2 ppg over the last 7 min. of the treatment. The pressure response during the treatment **(Fig. 9)** was not as high as for typical refracture treatments.

There was no evidence of gradual reorientation as was observed on Well A. **Table 3** indicates that the azimuth during the first mini-frac was N55°W, an angle of **93** degrees from the azimuth range of N40°E for the initial fracture. The second mini-frac was oriented at N80°E or 40 degrees from the initial azimuth. The main refracture grew at an angle of 25 degrees from the assumed initial fracture azimuth. The main injection during the refracture showed reorientation. However, the magnitude is insufficient to validate the orthogonality concept. However there was still a substantial production increase as indicated in **Fig. 10.**

DISCUSSION

As stated earlier, we were hesitant to perform the field tests in formations containing natural fractures. During depletion of the reservoir, the total stresses all decrease, and hence the total magnitude of stress anisotropy also decreases. In addition, the two horizontal stress components deplete at different rates due to the initial fracture, as discussed earlier. These factors together with the presence of natural fractures can cause complex behavior during refracturing. Also, injection of the low viscosity water could allow more penetration of open natural fractures, with implications for the initial orientation *of* a refracture. In this study, there is a change in azimuth after each injection and shut down. We do not know the extent to which the natural fractures influence this. Changes in azimuth with subsequent injections have been reported in drill cutting disposal tests **[13,** 14]. However, these changes are not due to the orthogonal theory being tested in our study.

Fig. 12 is **a** schematic map of the neighboring wells in the area, giving an indication of the current drainage basin of the fractured wells, based on pressure transient estimates. In **Fig. 12,** the initial fracture azimuths, indicated by the dark lines with arrows, are oriented at an azimuth of N40°E. The azimuth ranges of the initial injection or mini-frac during the refracturing treatment are shown by the dashed lines with square symbols. The azimuth range of the second mini-frac on Well B is indicated by the triangles. The orientation of the main refracture is indicated by the long grey line for each well. Note that the length of each line does not represent fracture length. Reorientation of the refractures is clearly evident for both wells.

The reorientation theory in this project is based purely on an infinite acting homogeneous medium affected by the pressure drawdown. This same mechanism was observed in a study of injector and producer wells where fractures grew toward the injector well [15, 16]. This implies that under certain conditions fractures should grow away from producers. The path taken by both main refractures indicates that each seems to have avoided existing drainage basins of neighboring wells although this could be purely coincidental.

CONCLUSIONS

Refracture reorientation can be applied in suitable tight gas formations to increase production at the cost of a fracture treatment. The technology is equally applicable to oil reservoirs. The field tests were successful in terms of increasing production, and in obtaining some validation of the orthogonality concept, despite the wells being less than optimum candidates. This is encouraging for future treatments utilizing this technology.

NOMENCLATURE

k_x	permeability in horizontal x direction
k_y	permeability in horizontal y direction
L_{xf}	initial fracture half length
L'_{xf}	distance to isotropic point from wellbore
L''_{xf}	distance to first curvature point of refracture

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SI METRIC CONVERSION FACTORS

ft	x 3.048	E-01	= m
mi	x 1.609	E+03	= m
psi	x 6.895	E+03	= Pa
lb	x 4.536	E-01	= kg
gal	x 3.785	E+00	= l
scf	x 2.832	E-02	= m^3
bbl	x 0.159	E+03	= l
bpm	x 2.649	E-03	= m^3/s
ppg	x 1.198	E+02	= kg/m^3

Table 1
Summary of Initial Frac and Refracture Treatments on Wells A, B, and C

Well		Volumes		Fluid Type
		Proppant lb	Fluid Gal	
Well C	Initial	360,000	225,000	75% N2 Foam
	Refrac	1,060,000	515,000	Crosslinked Gel
Well A	Initial	Unknown	Unknown	Crosslinked Gel
Well B	Initial	1,291,000	437,000	Crosslinked Gel
	Refrac	92,000	715,000	Light Sand Frac

Table 2
Summary of Surface Tiltmeter Mapping Results for Well **A**

Stage	Difference From N40E		Fracture Azimuth Refracture		Percent of Refracture	
	Main deg.	Secondary deg.	Main deg.	Secondary deg.	Main %	Secondary %
Mini-frac	45	N/A	N5W	None	100	0
Main 1st Q	107	34	N67W	N6E	72	28
Main 2nd Q	100	33	N60W	N7E	75	25
Main 3d Q	103	47	N63W	N7W	97	3
Main 4th O	106	N/A	N66W	None	100	0
		Accuracy	±10 deg.	±10 deg.		

Table 3
Summary of Surface Tiltmeter Mapping Results for Well B

Stage	Difference From N40E deg.	Fracture Azimuth deg.
Mini-frac I	93	N53W
Mini-frac II	40	N80E
(Main Treatment	**25**	N65E
	Accuracy	±8 to **15** deg.

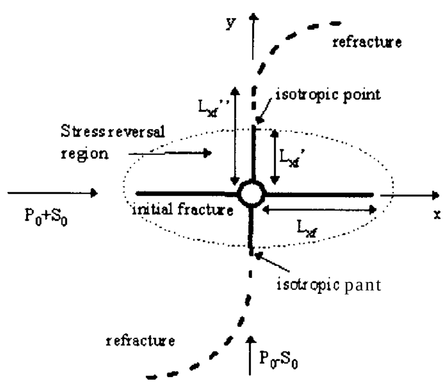

Figure 1 - Refracture Reorientation Concept

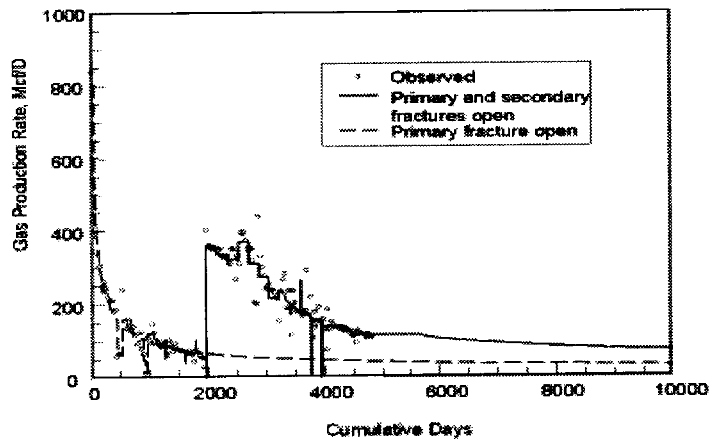

Figure 2a - Production History of Well C Before and After Successful Refracture Treatment

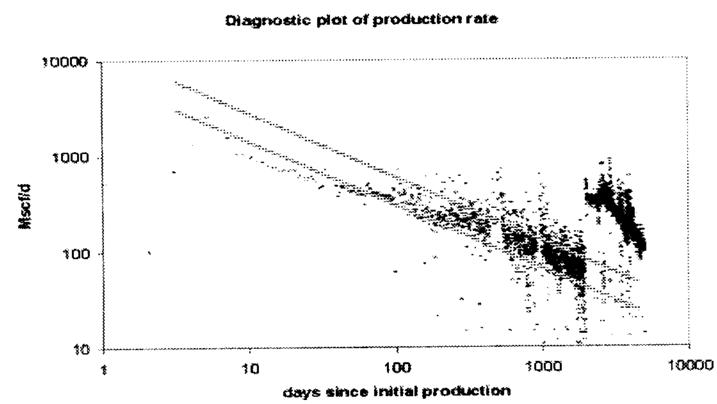

Figure 2b - Log-Log Plot of Production History of Well C Before and After Successful Refracture Treatment

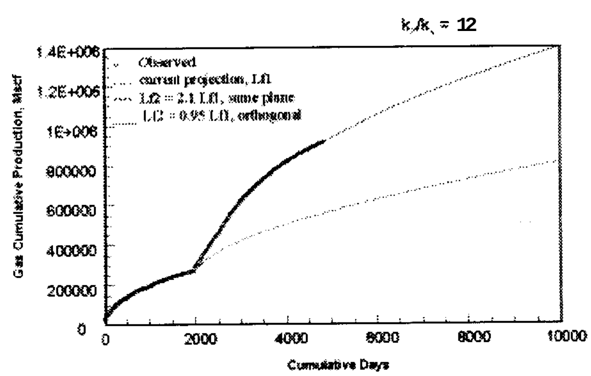

Figure 3 - Production history match on refractured Well C in Barnett shale for parallel and orthogonal refractures (L_{f1} *is initial fracture length,* L_{f2} is refracture length)

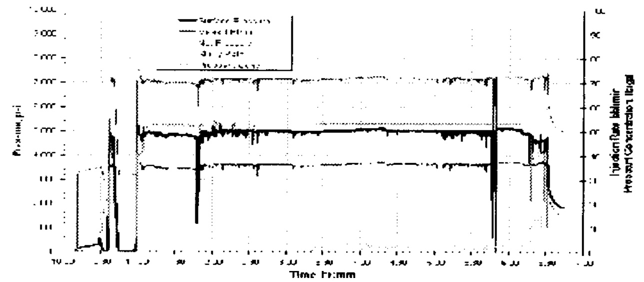

Figure 4 - Treatment Schedule for Well A Refracture **Job**

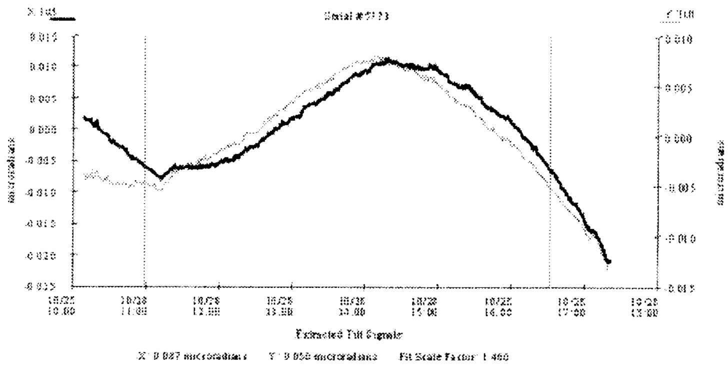

Figure 5 - Raw Tiltmeter Signal for Main Frac Treatment on Well A Showing Gradual Azimuth Change

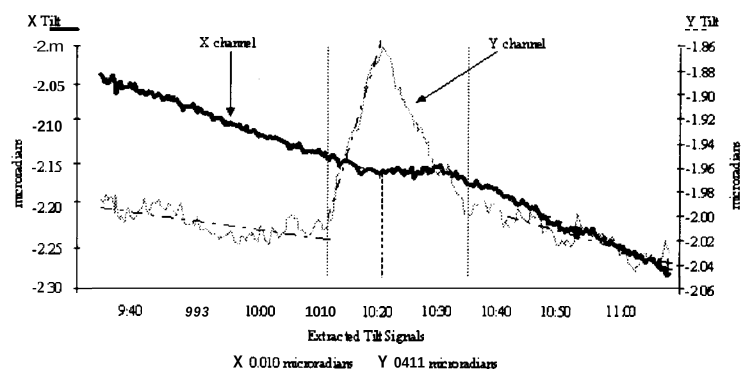

Figure 6- Raw Tiltmeter Signal for Main Frac Treatment on a Lost Hills, CA, Site Showing Abrupt Azimuth Change at Time 10:20

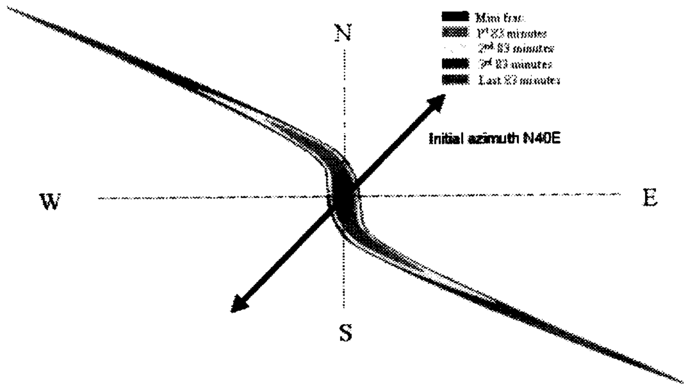

Figure 7 - Plan View of Well A Refracture Azimuth Growth as a Function of Time

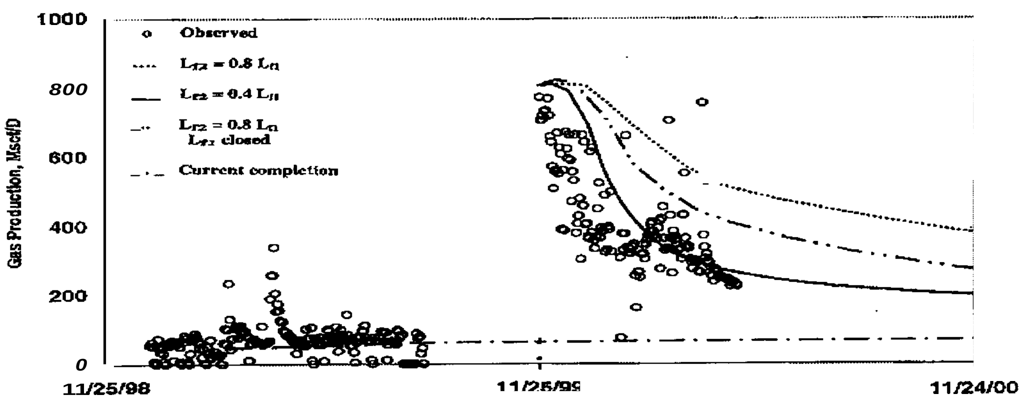

Figure 8 - Production History Match on Well A in Barnett Shale for Parallel and Orthogonal Refractures (L_{f1} is initial fracture length, L_{f2} is refracture length)

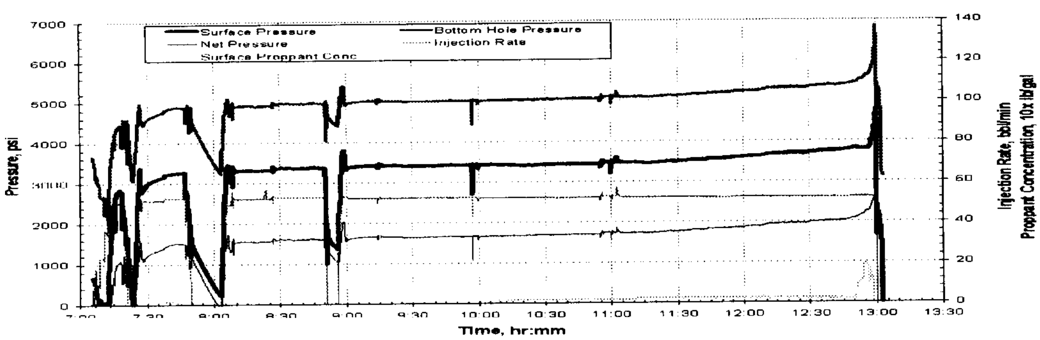

Figure 9 - Treatment Schedule for Well B Refracture **Job**

job

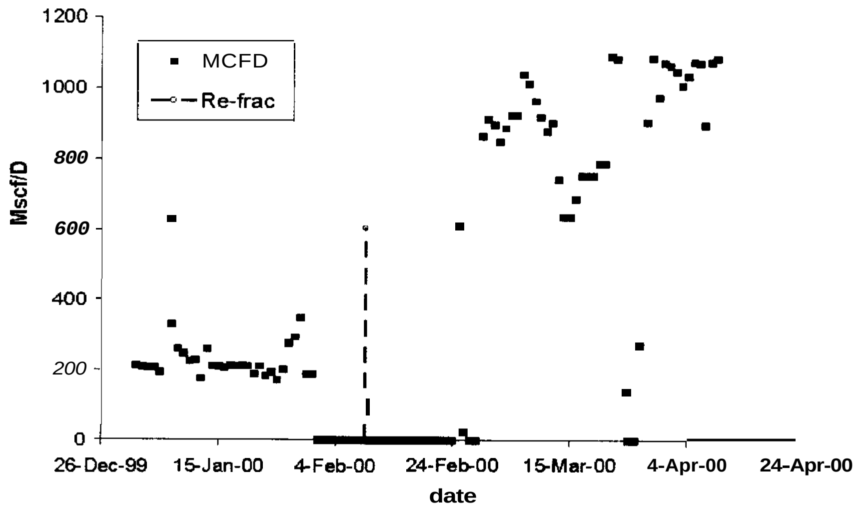

Figure 10 - Gas Production Versus Time, Before and After Refracture Treatment. From Well B

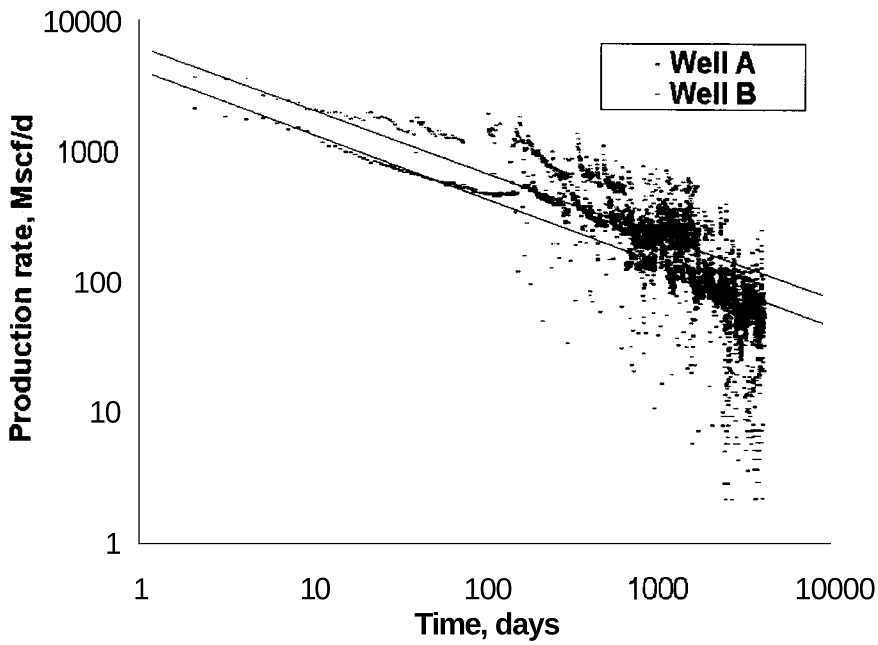

Figure 11- Log-Log Plot of Production History of Well A and Well B Before Refracture Treatment

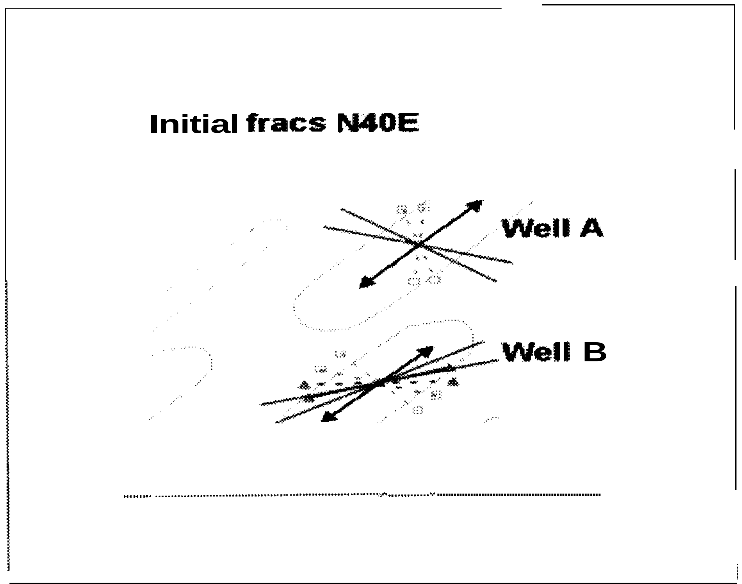

Figure 12 - Neighboring Wells of Wells A and B, Showing Their Drainage Basins, with Estimated Initial Fracture (N40E arrows) and Measured Refracture Azimuths

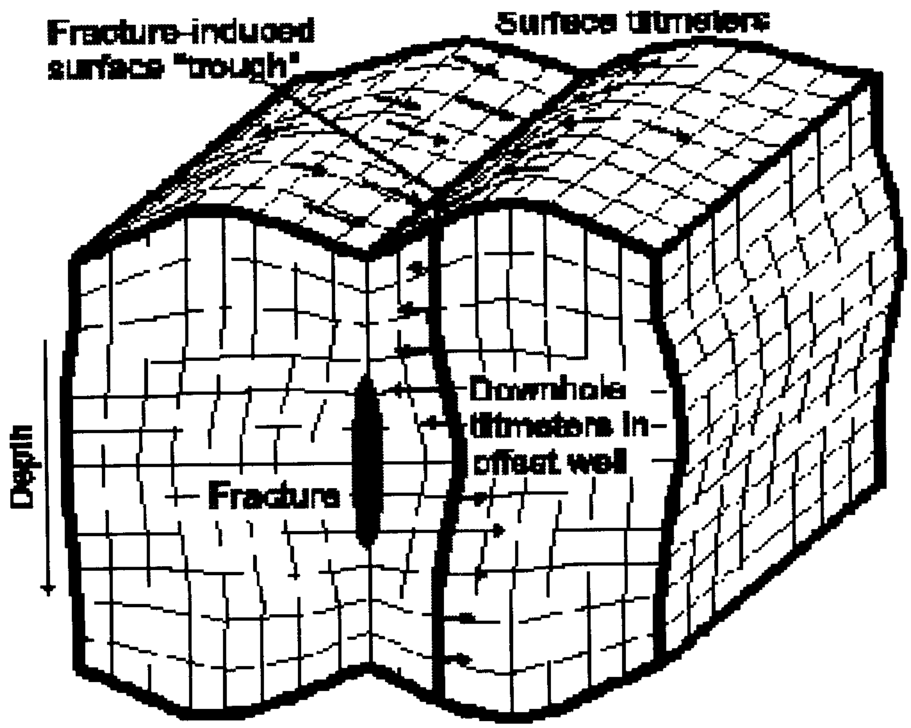

Figure 13 - Displacement Field in the Earth Around a Vertically Oriented Hydraulic Fracture, Showing Induced Surface and Downhole Tilt Vector Directions