APPENDIX 2-B

FRACTURE TREATMENT SUMMARIES

POST TREATMENT REPORT

GE Engine Services
United Nuclear Church Rock Project RW 11
Sec 37, Twn 17 N, Rng 16 W
Gallup

Treatment Date - September 11, 2004
Farmington, New Mexico
505-327-6222

BJ Services Company

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Please Reply: (505) 327-6222
Farmington, New Mexico (505) 327-5766
505-327-6222

September 11,2004

Mr. Pat Pontoriero
GE Engine Services
Mactec Engineering & Consulting, Inc. 700N Bell Ave, Suite 200
Pittsburg, PA 15106

Re:
Treatment Summary
United Nuclear Church Rock Project RW 11
Gallup

Dear Mr. Pontoriero:

This post treatment summary contains information that was gathered through BJ Services Company's real time data acquisition system. The stimulation treatment on the above reference well was performed by our Farmington district on September 11, 2004.
The information presented consists of the well data, proposed vs. actual treatment, treatment graphs, discussion, and treatment data.
Thank you for the opportunity to evaluate this treatment. If you have any questions or comments, please call me at 505-327-6222.

Sincerely,

Frank Culler
BJ Services Company
Field Tech. Rep.

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SECTION I

WELL DATA

WELL DATA

Operator	GE Engine Services	
Well Name	United Nuclear Church Rock Project RW 11	
Well Orientation	Vertical	
Formation	Gallup	
Location	Sec 37, Twn 17 N, Rng 16 W	
Total Depth	175	ft
Perforation Interval	171-175	ft
Depth to Middle Perforation	173	ft
Number of Perforation	80	
Perforation Diameter	0.500	in
Casing/Liner Size	7.000	in
Frac Gradient	0.500	psi/ft
Bottom Hole Fracture Pressure	204	psi
Bottom Hole Temperature	82	°F
Anticipated Fracture Height	4	ft
Net Fracture Height	4	ft

SECTION II

PROPOSED & ACTUAL TREATMENT

TREATMENT PARAMETERS

Parameters	Proposed	Actual	Unit
Treating Conductor	7.000	7.000	in
Injection Rate	35.00	35.50	bpm
Average Surface Treating Pressure	132	330	psi
FLUID VOLUME			
Treating Fluid Volume	25000	16632	gals
Flush Volume	291	504	gals
PROPPANT			
20/40 Brady	25000	9540	lbs

TREATMENT SCHEDULE

Stage No.	Gel Volume, gals Proposed	Actual	Fluid Type	Proppant Conc., ppg Proposed	Actual
1	5000	5000	Fresh Water	0.0	0.0
2	5000	5000	Fresh Water	0.5	0.5
3	5000	5000	Fresh Water	1.0	1.0
4	5000	1176	Fresh Water	1.5	1.5
5	5000	0	Fresh Water	2.0	2.0
6	291	504	Fresh Water	0.0	0.0

TREATMENT REPORT

Date September 11, 2004 District Farmington F.Receipt 216431801 Operator GE Engine Services
Lease United Nuclear Church Rock Project Well No. RW 11 Field Chuch Rock Location Sec 37, Twn 17 N, Rng 16 W
County Mckinley State New Mexico Stage No. 1 Treatment Target(s) This zone

WELL DATA

Well Type: ☒New Well ☐Old Well Well Class: ☐Oil ☒Gas ☐Disposal ☐Injection ☐Misc.
Prev. Treatment N/A Prev. Production N/A Well Dep.TD/PB 175 ft Formation Gallup
Perf.: Size 0.500 in Total No. 80 Interval 171-175(ft)

String/TypePacker/OpenHole Description	Size (in)	Weight (lbm/ft)	Set at (ft)	From (ft)	To (ft)	Length (ft)	Capacity (bbls/ft)	Total Capacity (bbls)
Casing	6.456	20.00			175		0.0405	7

TREATMENT DATA

Treating via: ☐Tubing ☒Casing ☐Annulus ☐Tubing & Annulus Fluid to load 6
Pad Used: ☒Yes ☐No Pad Type Fresh Water Pad Volume 5000 gals Ball Sealers: in stages of
Treating Fluid Type: ☐Foam ☒Water ☐Acid ☐Oil ☐Other Volume 11632 gals Base Fluid Type: Fresh Volume 64000 gals
Foam Type: ☐Mitchell Surface ☐Mitchell Downhole ☐Slurry Surface ☐Slurry Downhole Foam Quality Hole Loaded with Fresh Water

Proppant Type	Size	Quantity (lbs)	Proppant Type	Size	Quantity (lbs)	Proppant Type	Size	Quantity (lbs)
Brady	20/40	9540						

TOTAL LIQUID/GAS PUMPED

Pad Volume: 119 bbls Treating Fluid Volume: 277 bbls Flush Volume: 12 bbls
Over Flush Volume: Fluid to Recover: 396 bbls Total CO2: Total N2:
Pumps Used(Type/Number): 3BL-2000
Auxiliary Material:
Procedure Summary:

TREATMENT SUMMARY

Treating Pressure: Min. Max. 370 psi Ave. 330 psi Operator's Max. 3000 psi
Injection Rate: Treating Fluid 35.00 bpm Flush 20.00 bpm Average 35.50 bpm Flush Fluid Density 8.34 ppg
ISDP: Pre-Job Post-Job 100 psi Final Shut in Pressure in 5.0 min
Recommendation ID# 216454887A Job Number 216431801 Customer Representative L.Bush Service Representative V.Eldridge
Distribution Normal

TREATMENT LOG

Time	Treating Pressure		Stage Surface Fluid Pumped			Total Surface Fluid Pumped			Surface Fluid Pumping Rate			Comments
	STP	Annulus	Slurry	CO2	N2	Slurry	CO2	N2	Slurry	CO2	N2	
am/pm	psi	psi	bbls	bbls	scf	bbls	bbls	scf	bpm	bpm	scf/min	
09.00												SAFETY MEETING
09.20	4000											PT LINES
09.39									36.00			ST FRESH H2O PAD
09.44	343		119			119			35.90			ST .50# 20/40 BRADY
09.47	333		122			241			35.70			ST 1.00#
09.51	353		124			365			35.70			ST 1.50#
09.51	70		29			394						S/D FRACTURING VERTICAL
09.52	275					394			20.00			ST CROSS OVER FLUSH
09.53	100		12			406						S/D,ISIP

SECTION III

TREATMENT GRAPHS & INTERPRETATION

Engineering Analysis

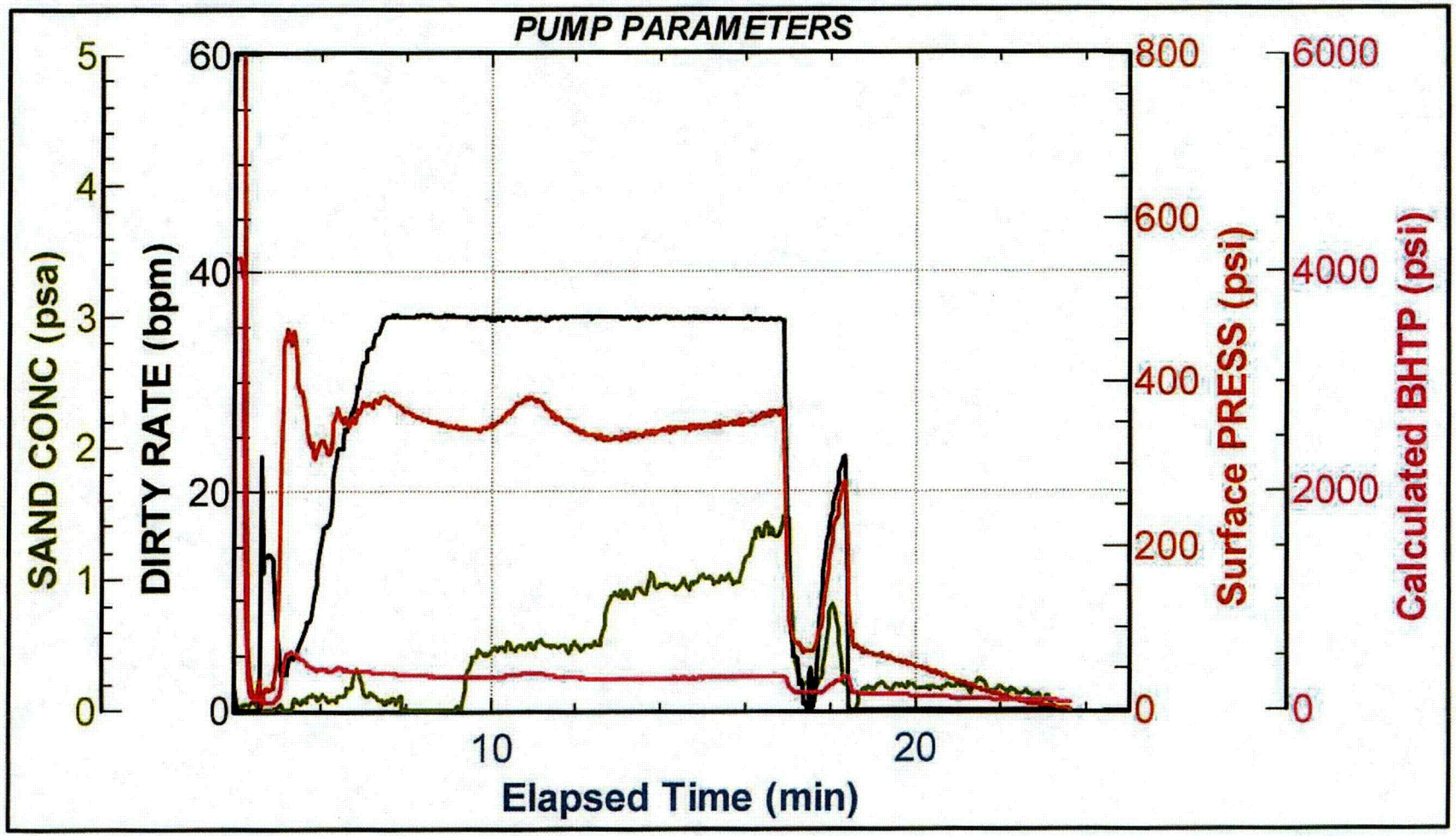
Net-P Calculations:

1. Net Pressure = BHTP - Closure Pressure
2. Closure Pressure = 00 psi for calculations

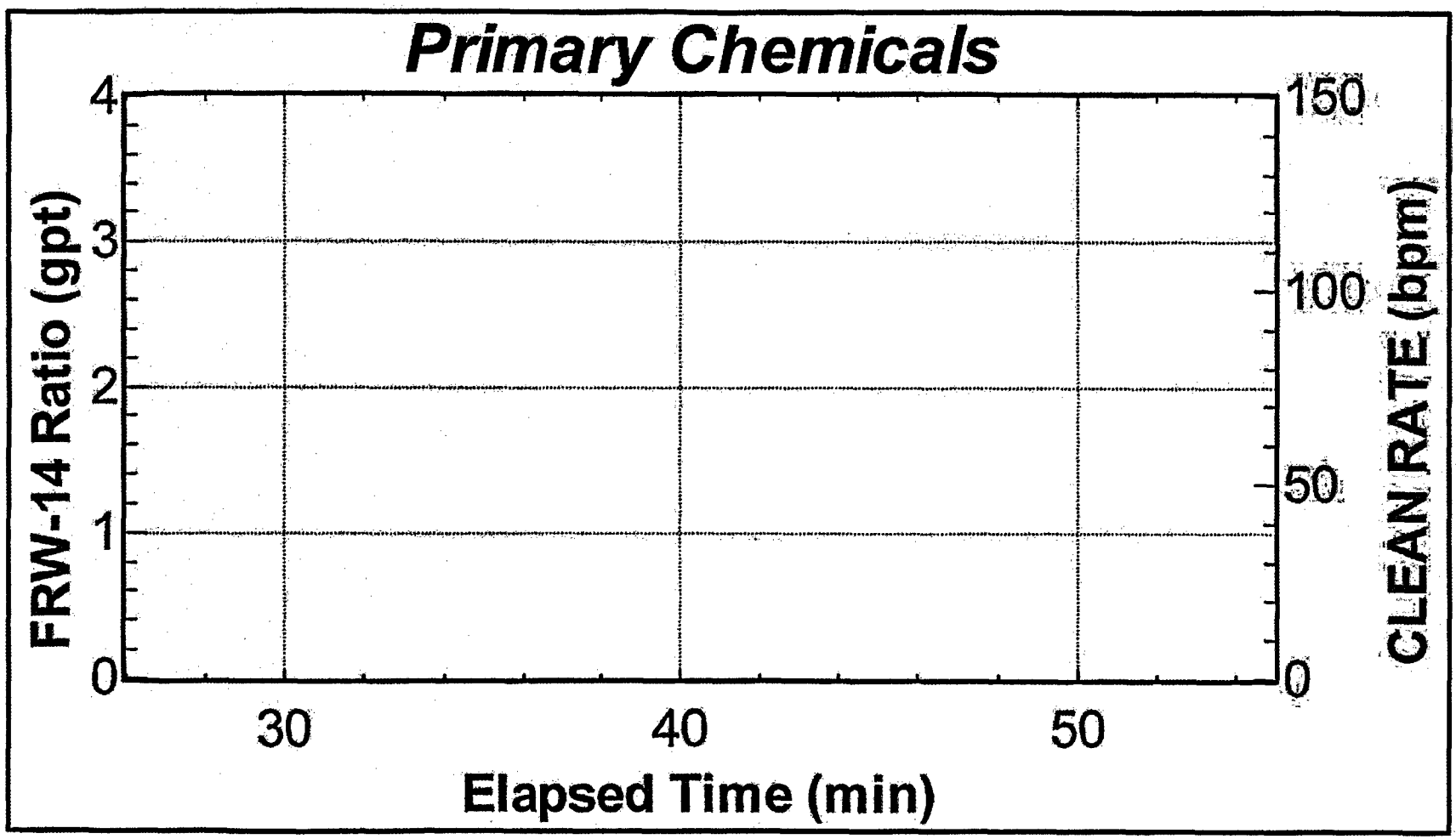
SECTION IV

TREATMENT DATA

BJ Services JobMaster Program Version 3.00
Job Number: 216431801
Customer: GE Engine Services INC
Well Name: United Nuclear Rw11C

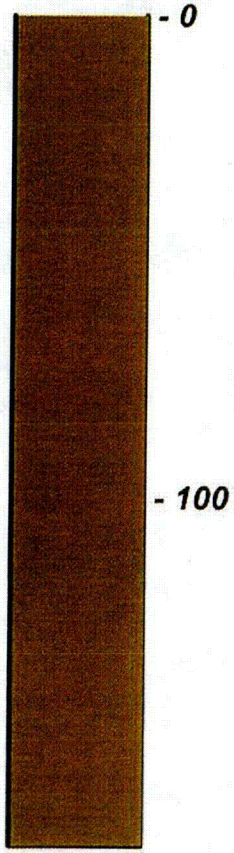


BJ Services JobMaster Program Version 3.00
Job Number: 216431801
Customer: GE Engine Services INC
Well Name: United Nuclear Rw11C



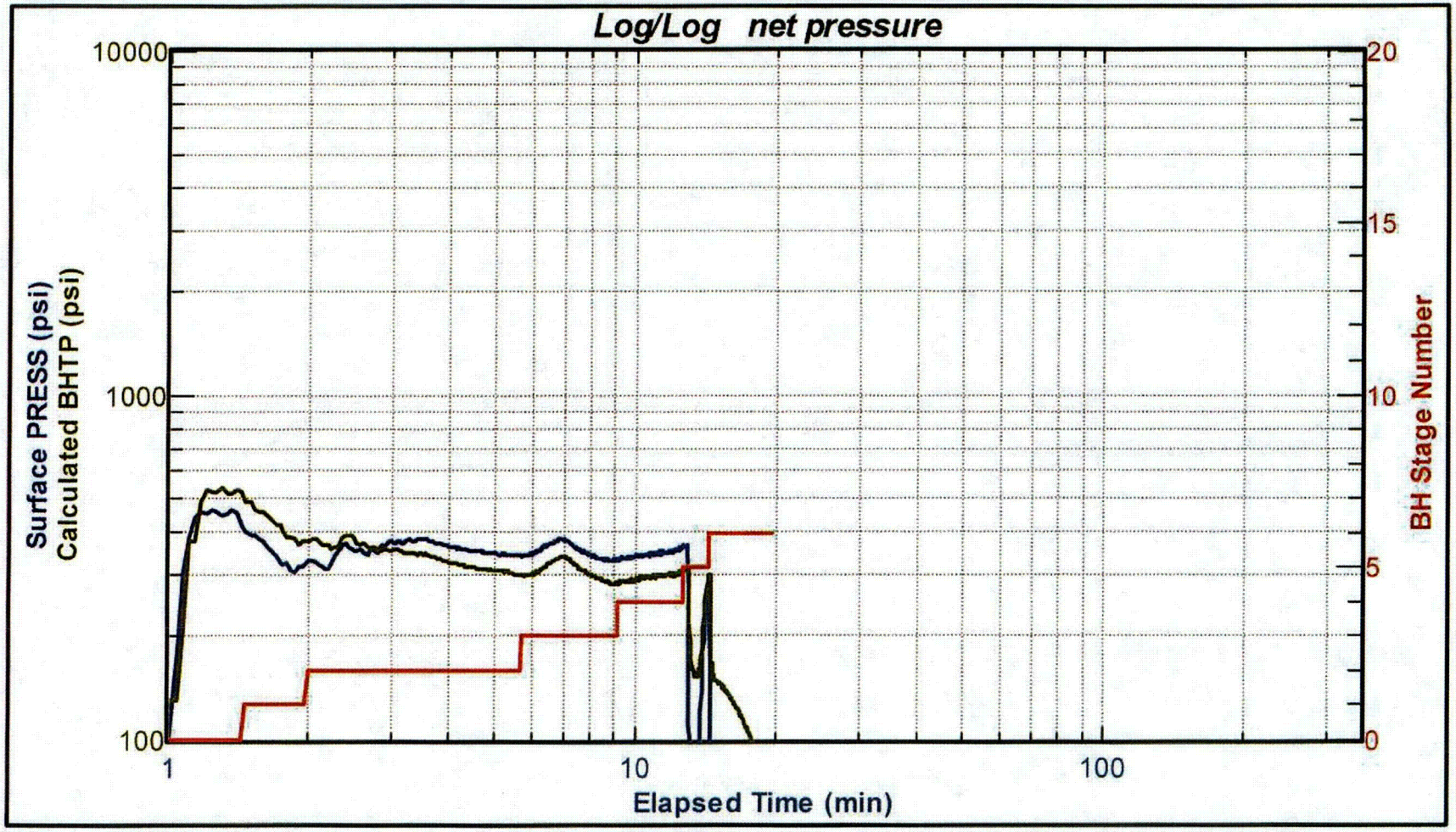
BJ Services JobMaster Program Version 3.00
Job Number: 216431801
Customer: GE Engine Services INC
Well Name: United Nuclear Rw11C

MD=171 ft, Slurry/Sand are bbl/lbm



Design	Actual	Stage
728.9	410.6	Slurry
25272	9239	Sand
100.0	4.3	01. Test
119.0	119.5	02. Pad
121.7	121.8	03. .50
124.4	124.4	04. 1.00
127.1	28.3	05. 1.50
129.8	12.2	06. 2.00
6.9	0.0	07. Flush

BJ Services JobMaster Program Version 3.00
Job Number: 216431801
Customer: GE Engine Services INC
Well Name: United Nuclear Rw11C



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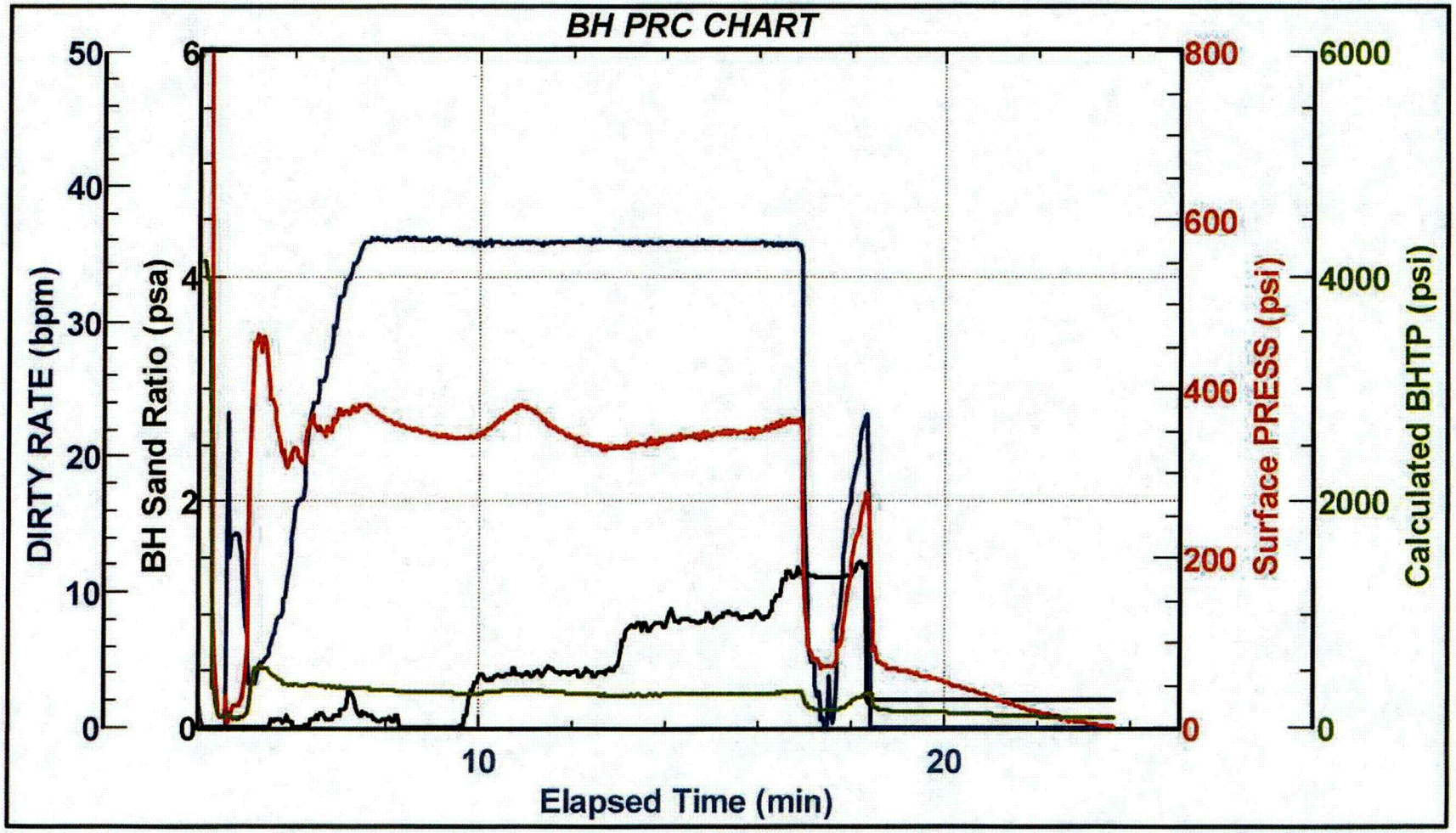
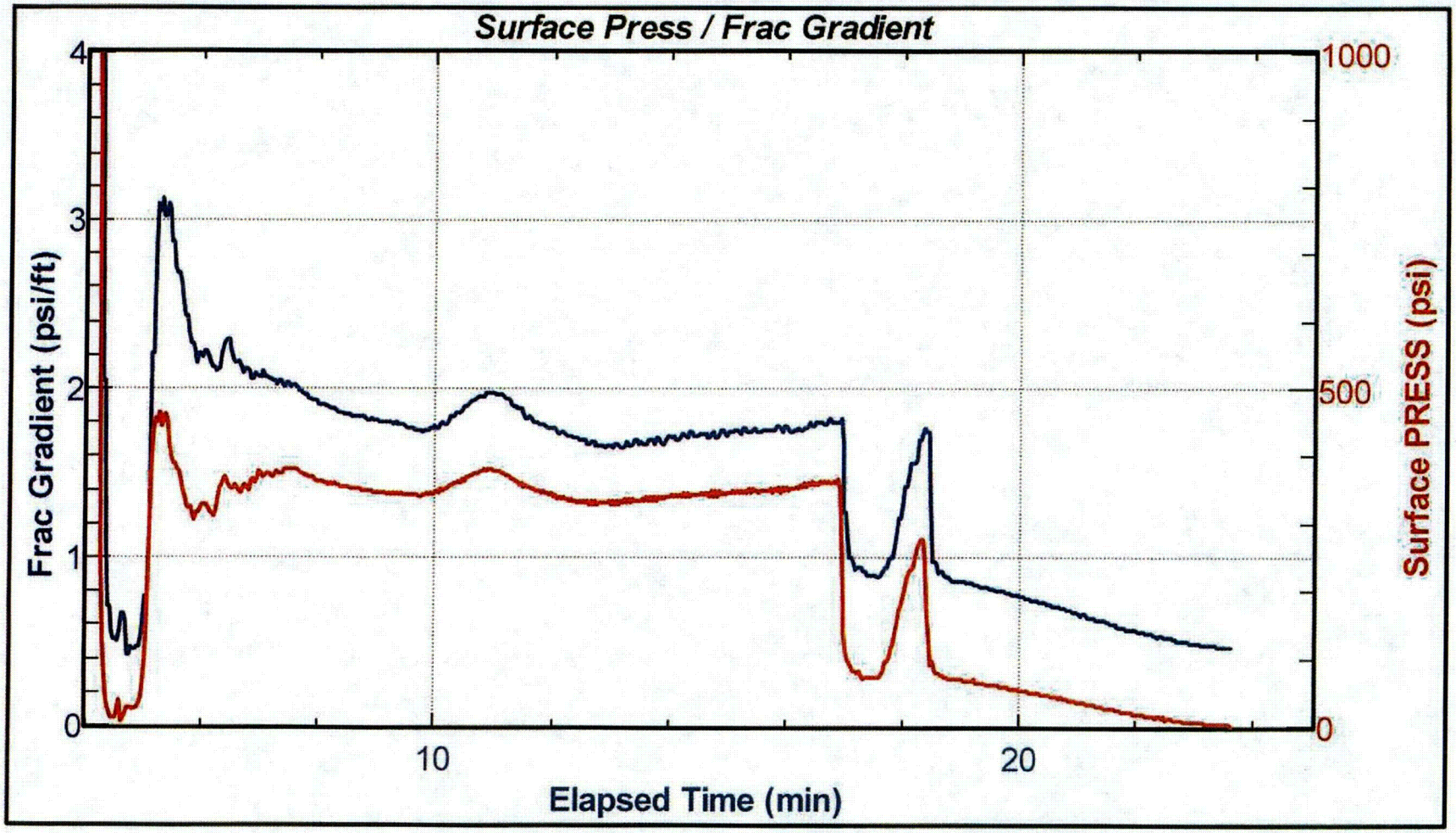
BJ Services JobMaster Program Version 3.00
Job Number: 216431801
Customer: GE Engine Services INC
Well Name: United Nuclear Rw11C



C64

BJ Services JobMaster Program Version 3.00
Job Number: 216431801
Customer: GE Engine Services INC
Well Name: United Nuclear Rw11C



CG5

POST TREATMENT REPORT

GE Engine Services
United Nuclear Church Rock Project RW12
Sec.37,T17N,R16W
Gallup

Treatment Date - September 18,2004
Farmington, New Mexico
505-327-6222

BJ Services Company

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Please Reply: (505) 327-6222
Farmington, New Mexico (505) 327-5766
505-327-6222

September 18, 2004

Mr. Pat Pontoriero
GE Engine Services
Mactec Engineering & Consulting, Inc. 700N Bell Ave, Suite 200
Pittsburg, PA 15106

Re:
Treatment Summary
United Nuclear Church Rock Project RW12
Gallup

Dear Mr. Pontoriero:

This post treatment summary contains information that was gathered through BJ Services Company's real time data acquisition system. The stimulation treatment on the above reference well was performed by our Farmington district on September 18,2004.
The information presented consists of the well data, proposed vs. actual treatment, treatment graphs, discussion, and treatment data.
Thank you for the opportunity to evaluate this treatment. If you have any questions or comments, please call me at 505-327-6222.

Sincerely,

Frank Culler
BJ Services Company
Field Tech. Rep.

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SECTION I

WELL DATA

WELL DATA

Operator	GE Engine Services	
Well Name	United Nuclear Church Rock Project RW12	
Well Orientation	Vertical	
Formation	Gallup	
Location	Sec.37,T17N,R16W	
Total Depth	173	ft
Perforation Interval	169-173	ft
Depth to Middle Perforation	171	ft
Number of Perforation	80	
Perforation Diameter	0.500	in
Casing/Liner Size	7.000	in
Frac Gradient	1.180	psi/ft
Bottom Hole Fracture Pressure	202	psi
Bottom Hole Temperature	82	°F
Young's Modulus	6.00e+006	psi
Anticipated Fracture Height	4	ft
Net Fracture Height	4	ft

SECTION II

PROPOSED & ACTUAL TREATMENT

TREATMENT PARAMETERS

Parameters	Proposed	Actual	Unit
Treating Conductor	7.000	7.000	in
Injection Rate	35.00	35.30	bpm
Average Surface Treating Pressure	139	480	psi
FLUID VOLUME			
Treating Fluid Volume	25000	15206	gals
Flush Volume	288	588	gals
PROPPANT			
20/40 Brady	25000	10000	lbs

TREATMENT SCHEDULE

Stage No.	Foam Volume, gals Proposed	Actual	Fluid Type	Proppant Conc., ppg Proposed	Actual
1	5000	4998	Fresh Water	0.0	0.0
2	5000	5011	Fresh Water	0.5	0.5
3	5000	4862	Fresh Water	1.0	1.0
4	5000	0	Fresh Water	1.5	1.5
5	5000	0	Fresh Water	2.0	2.0
6	288	288	Fresh Water	0.0	0.0

TREATMENT REPORT

Date September 18,2004 District Farmington F.Receipt 216430802 Operator GE Engine Services
Lease United Nuclear Church Rock Project Well No. RW12 Field Church Rock Location Sec.37,T17N,R16W
County Mc Kinley State New Mexico Stage No. 1 Treatment Target(s) This zone

WELL DATA

Well Type: ☒New Well ☐Old Well Well Class: ☐Oil ☒Gas ☐Disposal ☐Injection ☐Misc.
Prev. Treatment N/A Prev. Production N/A Well Dep.TD/PB 173 ft Formation Gallup
Perf.: Size 0.500 in Total No. 80 Interval 169-173(ft)

String/TypePacker/OpenHole Description	Size (in)	Weight (lbm/ft)	Set at (ft)	From (ft)	To (ft)	Length (ft)	Capacity (bbls/ft)	Total Capacity (bbls)
J-55	7.000	20.00			175		0.0405	7

TREATMENT DATA

Treating via: ☐Tubing ☒Casing ☐Annulus ☐Tubing & Annulus Fluid to load 0
Pad Used: ☒Yes ☐No Pad Type Fresh Water Pad Volume 5000 gals Ball Sealers: in stages of
Treating Fluid Type: ☒Foam ☒Water ☐Acid ☐Oil ☐Other Volume 10206 gals Base Fluid Type: water Volume 33600 gals
Foam Type: ☐Mitchell Surface ☐Mitchell Downhole ☐Slurry Surface ☒Slurry Downhole Foam Quality 0.0 % Hole Loaded with Fresh Water

Proppant Type	Size	Quantity (lbs)	Proppant Type	Size	Quantity (lbs)	Proppant Type	Size	Quantity (lbs)
Brady	20/40	10000						

TOTAL LIQUID/GAS PUMPED

Pad Volume: 119 bbls Treating Fluid Volume: 243 bbls Flush Volume: 7 bbls
Over Flush Volume: Fluid to Recover: 366 bbls Total CO2: Total N2:
Pumps Used(Type/Number): 3 Frac Pumps,
Auxiliary Material:
Procedure Summary: See actual vs proposed

TREATMENT SUMMARY

Treating Pressure: Min. 50 psi Max. 960 psi Ave. 480 psi Operator's Max. 3000 psi
Injection Rate: Treating Fluid 35.30 bpm Flush 35.00 bpm Average 35.30 bpm Flush Fluid Density 8.23 ppg
ISDP: Pre-Job Post-Job 151 psi Final Shut in Pressure in 15.0 min
Recommendation ID# 216451887A Job Number 216430802 Customer Representative. L.Bush Service Representative Leo_Pacheco
Distribution normal

TREATMENT LOG

Time	Treating Pressure		Stage Surface Fluid Pumped			Total Surface Fluid Pumped			Surface Fluid Pumping Rate			Comments
am/pm	STP psi	Annulus psi	Slurry bbls	CO2 bbls	N2 scf	Slurry bbls	CO2 bbls	N2 scf	Slurry bpm	CO2 bpm	N2 scf/min	
12:00												Safety meeting
12:15	4500											Pressure test lines
12:30	380								35.60			St Pad
12:34	360		119			119			35.70			St .5#
12:38	870		122			241			35.10			St 1#
12:42	460		121			362			35.00			St Flush
12:42	151		14			376						Shutdown

SECTION III

TREATMENT GRAPHS & INTERPRETATION

Engineering Analysis

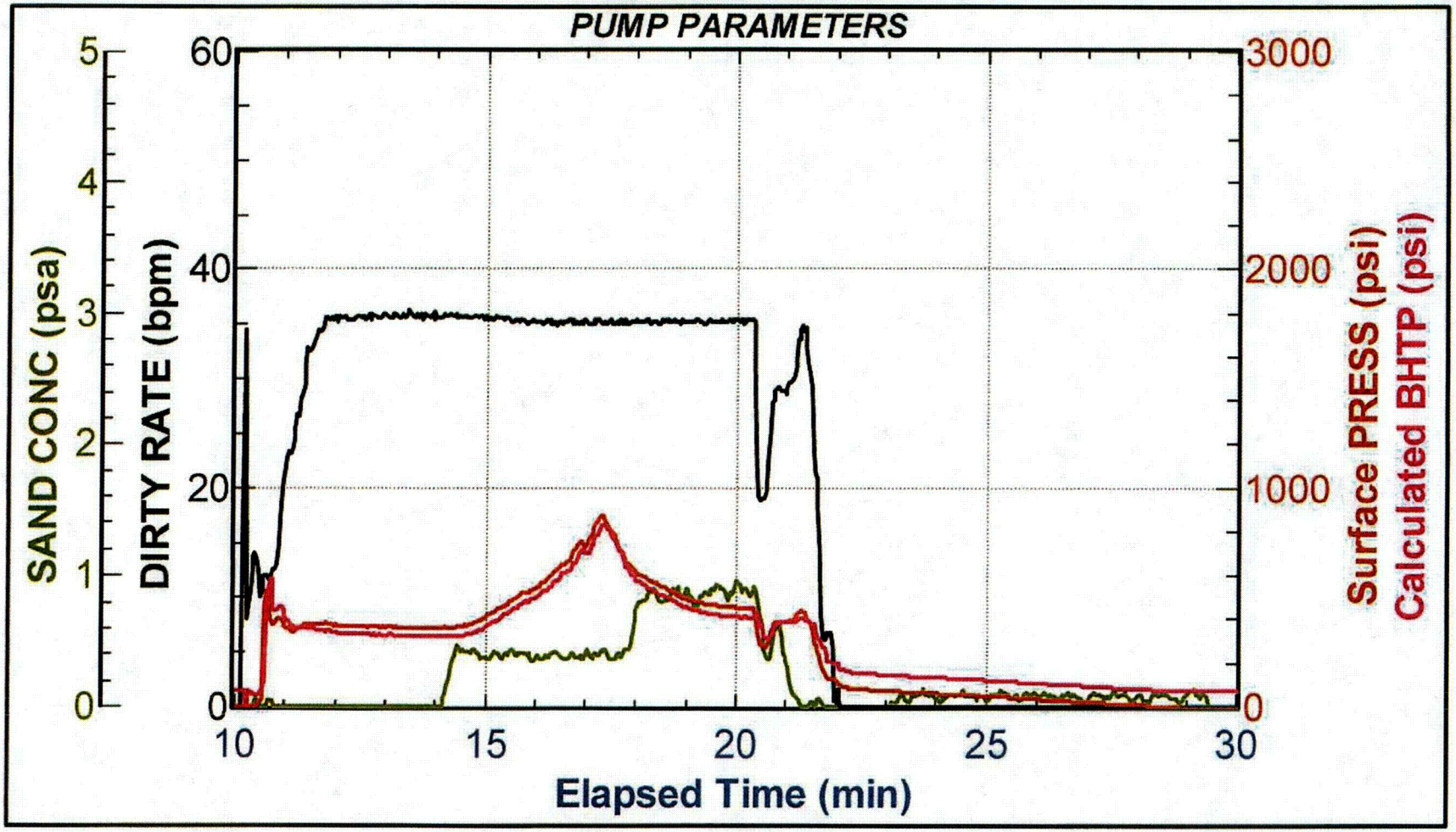
Net-P Calculations:

1. Net Pressure = BHTP - Closure Pressure

SECTION IV

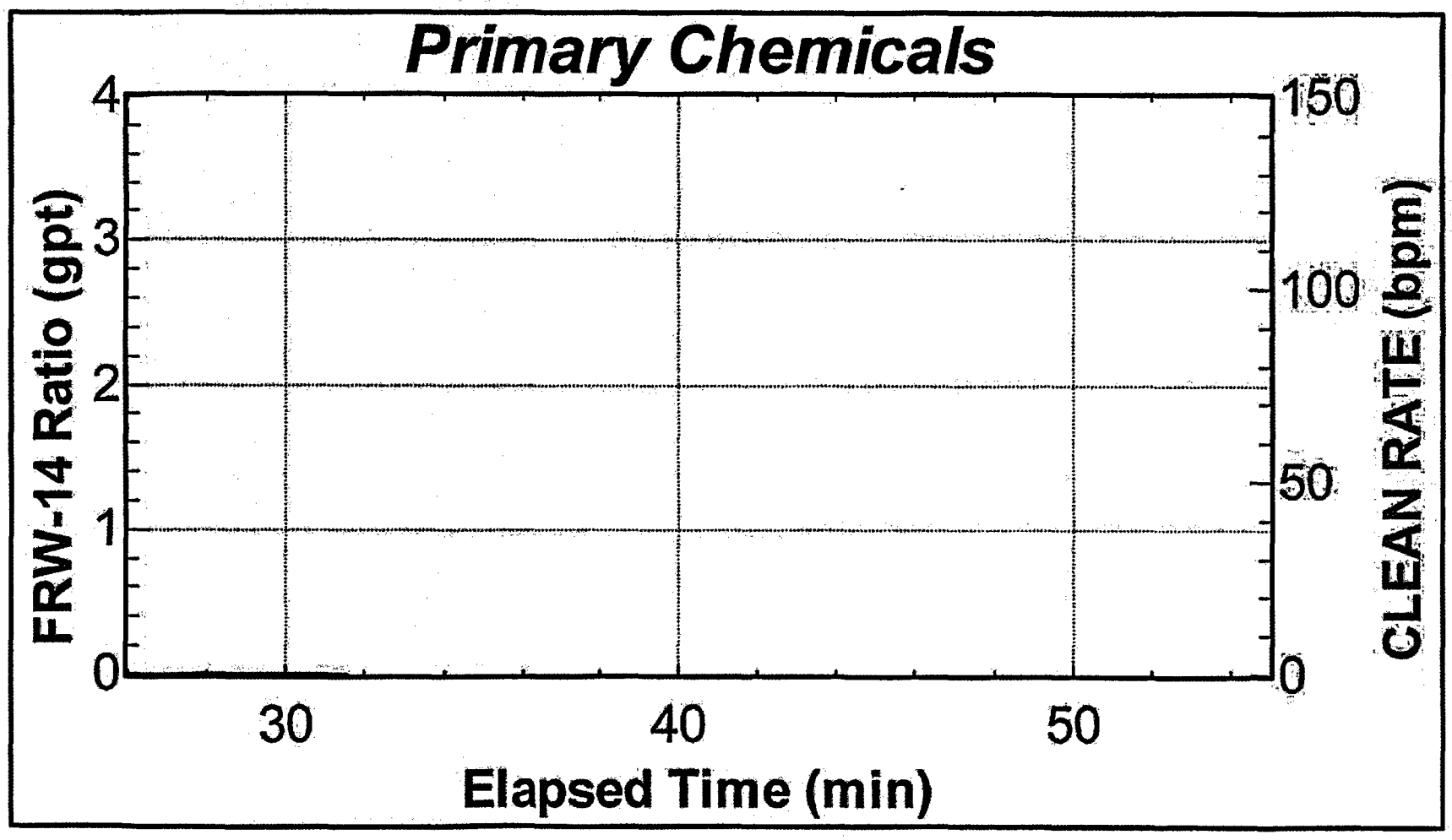
TREATMENT DATA

BJ Services JobMaster Program Version 3.00
Job Number: 216431802
Customer: G.E. Engine Services,Inc.
Well Name: United Nuclear Rw12

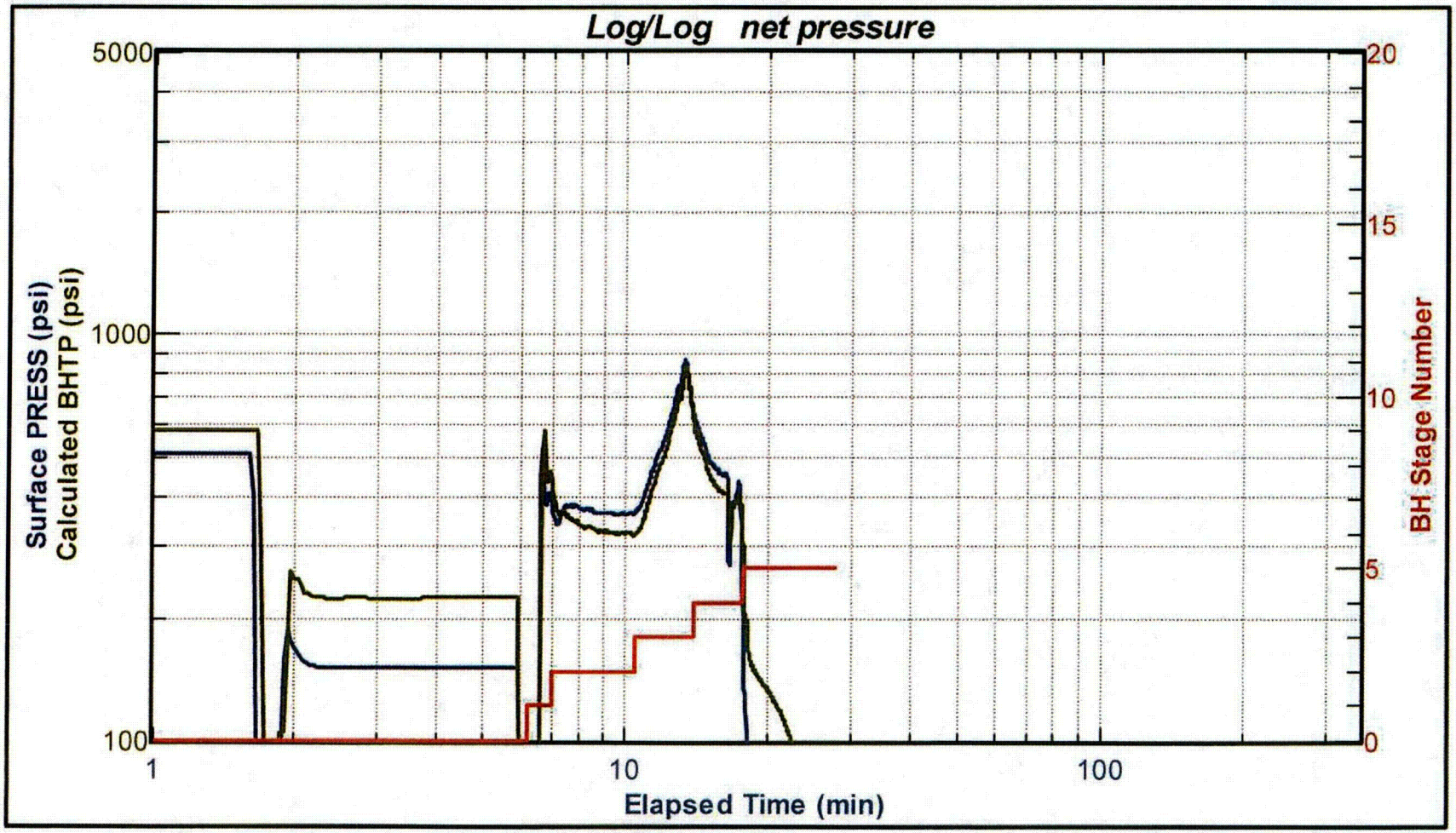


C66

BJ Services JobMaster Program Version 3.00
Job Number: 216431802
Customer: G.E. Engine Services,Inc.
Well Name: United Nuclear Rw12

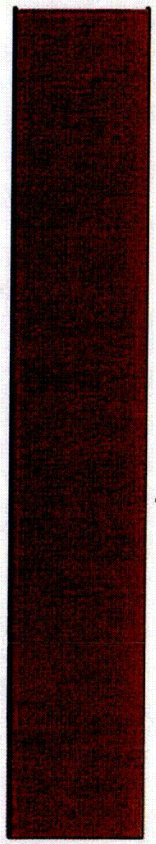


BJ Services JobMaster Program Version 3.00
Job Number: 216431802
Customer: G.E. Engine Services,Inc.
Well Name: United Nuclear Rw12



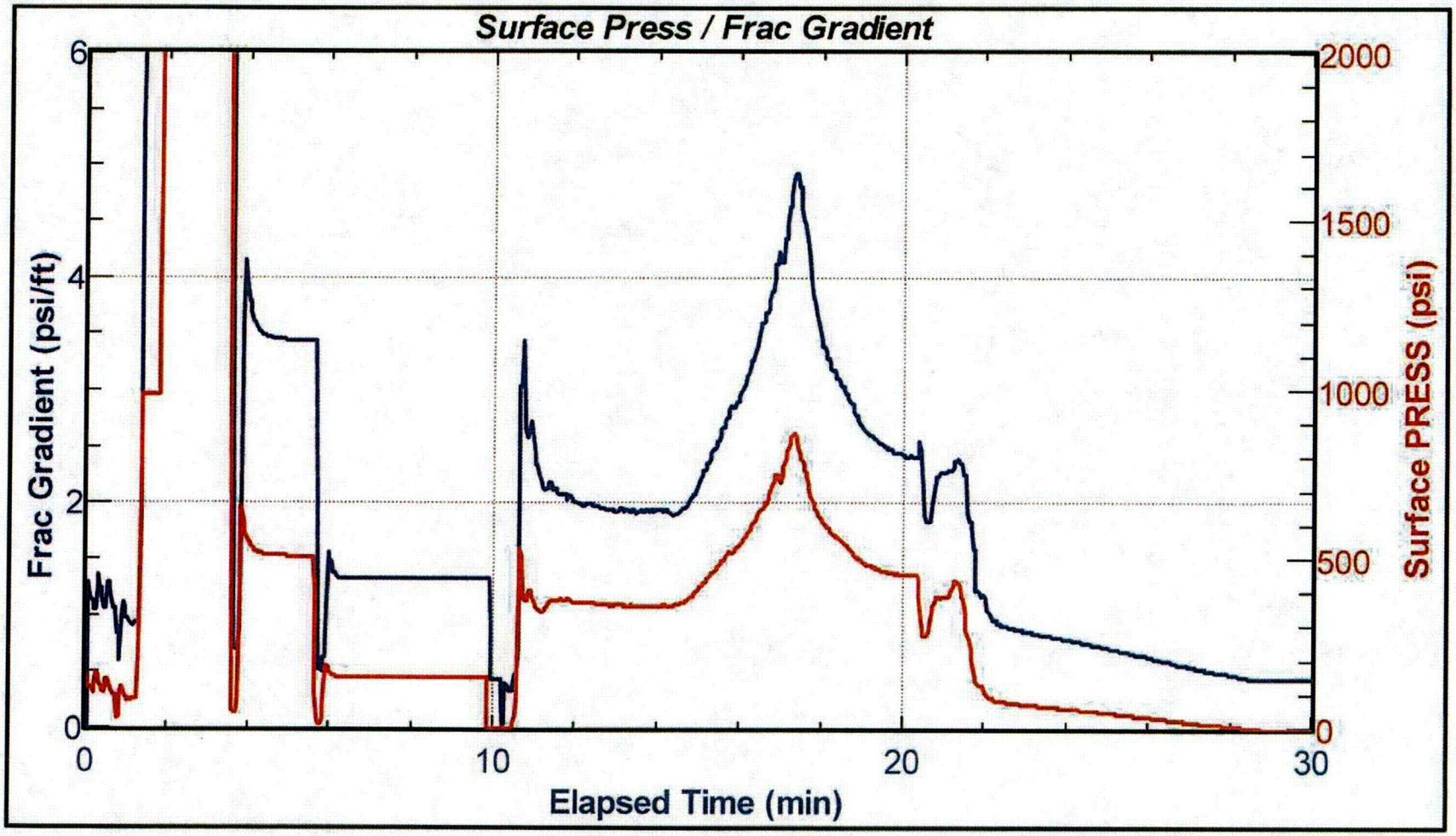
BJ Services JobMaster Program Version 3.00
Job Number: 216431802
Customer: G.E. Engine Services,Inc.
Well Name: United Nuclear Rw12

MD=169 ft, Slurry/Sand are bbl/lbm



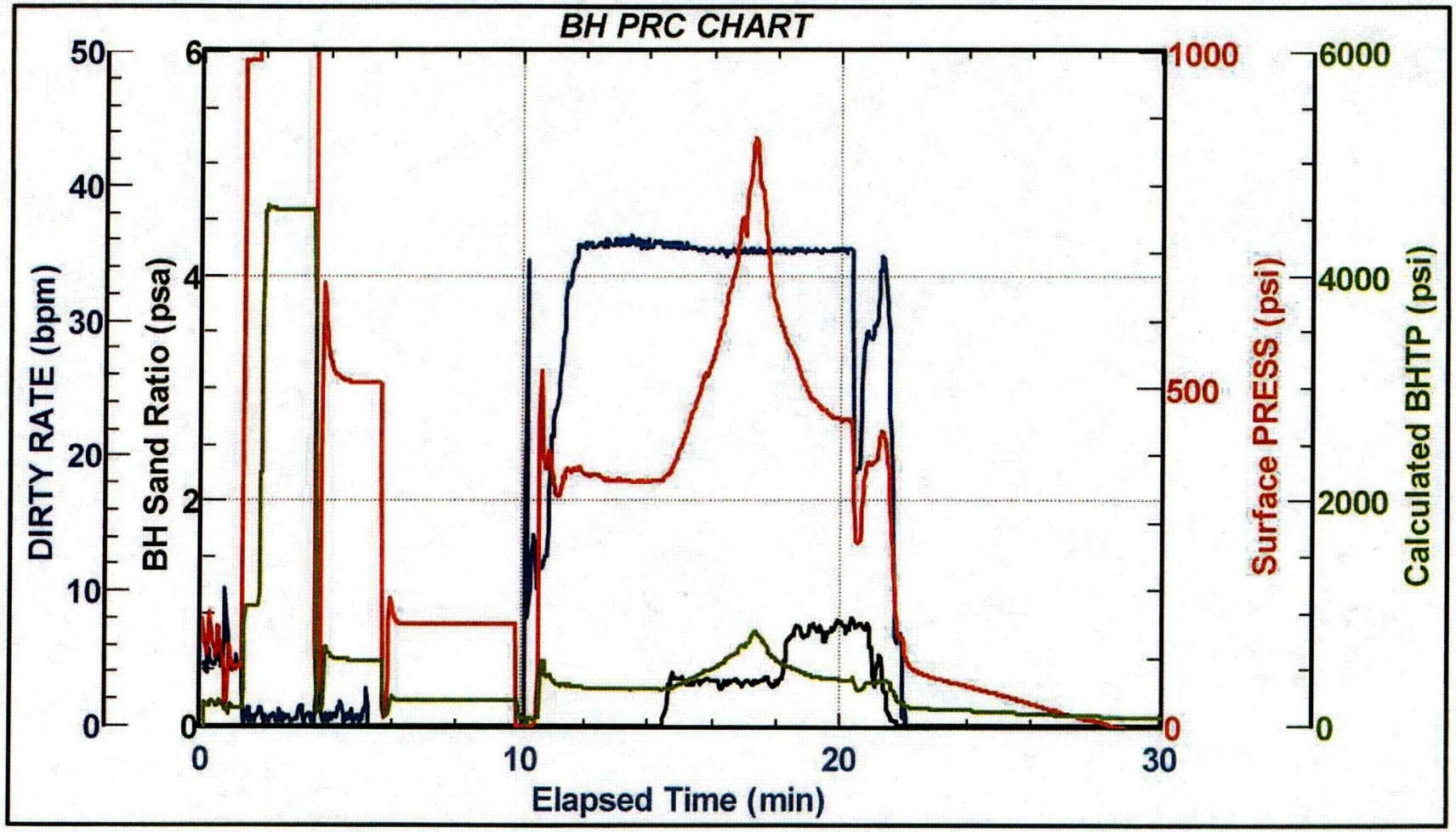
Design	Actual	Stage
728.9	385.9	Slurry
24995	5484	Sand
100.0	9.6	01. Test
119.0	120.2	02. Pad
121.7	122.5	03. .50
124.4	120.2	04. 1.00
127.1	13.4	05. 1.50
129.8	0.0	06. 2.00
6.9	0.0	07. Flush

BJ Services JobMaster Program Version 3.00
Job Number: 216431802
Customer: G.E. Engine Services,Inc.
Well Name: United Nuclear Rw12



CG9

BJ Services JobMaster Program Version 3.00
Job Number: 216431802
Customer: G.E. Engine Services,Inc.
Well Name: United Nuclear Rw12



C70

APPENDIX 2-C

PINNACLE FRACTURE DIAGNOSTIC REPORT

Pinnacle

Surface Tilt Fracture Mapping for Church Rock Project McKinley County, New Mexico

Final Report for MACTEC Engineering & Consulting, Inc.

Report Date: September 2004

By
Pinnacle Technologies
15579 E. Hinsdale Circle, Suite 102
Centennial, CO 80112

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- assumes any liability with respect to the use of, or for damages resulting from the use of, any information, apparatus, method, or process disclosed in this report.

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1. Executive Summary

Pinnacle Technologies conducted surface tiltmeter hydraulic fracture mapping for MACTEC Engineering & Consulting, Inc. (MACTEC), to help ascertain the growth and extent of hydraulic fractures in the Lower Gallup Sandstone formation. This was part of an ongoing program by United Nuclear Corporation (UNC) and its contractors to remediate ground water impacts from previous mining and milling operations at the Church Rock site near Gallup, New Mexico. MACTEC is the general contractor for current activities and Pinnacle Technologies subcontracted under MACTEC to provide hydraulic fracture tiltmeter mapping services.

In 2003, a test Recovery Well (the HF-3) was drilled and hydraulically fractured outside the area of proposed remediation. To monitor the growth and coverage of the created hydraulic fracture, an array of 32 surface tiltmeters was installed covering a surface area surrounding the HF-3 well. This array extended out from the wellbore approximately 250% the depth of the hydraulic fracture. For example, a drainhole having a hydraulic fracture initiated at a depth of 160 ft from the surface would have a surface tiltmeter array surrounding the wellhead approximately 400+ ft in all directions.

For the 2004 project, two separate surface tiltmeter arrays of approximately 60 sites each were required to image seven Recovery Wells inside the area of remediation. Wells RW11, RW12, RW13, & RW14 were imaged with one array and wells RW15, RW16, & RW17 were imaged with the second array. Pinnacle staked and installed the ±120 surface tiltmeter sites several weeks prior to the hydraulic fracturing program.

The table below outlines the results from the 2004 hydraulic fracturing campaign in the Church Rock project. Seven wells were stimulated with several wells experiencing multiple fracture growth. A single openhole interval was hydraulic fracture stimulated in the each of the Recovery Wells. The results below are the final values at the conclusion of each injection. A and B in wells RW15 and RW17 refer to treatments that were shutdown between the pad and main injection.

Table 1. Fracture Orientation at End of Pumping

Well Name	Openhole Interval (ft)	Volume Pumped Fluid (gals)	Volume Pumped Proppant (lbs)	Volume Pumped Rate (bpm)	Fracture Orientation	Fracture Depth (ft) (± uncertainty)	Fracture Dimensions (ft) (± uncertainty)	Location to Frac Wellbore (ft) (± uncertainty)
RW11	171-175	17,136	9,540	35.5	Horizontal$_1$	150 ± 20	60 ± 15	30 ± 15 N
					Horizontal$_2$	95 ± 20	80 ± 15 N-S 40 ± 15 E-W	100 ± 15 E
RW12	169-173	15,794	7,500	35.3	Horizontal	100 ± 20	80 ± 15	75 ± 15 SW
RW13	169-173	27,112	31,540	35.8	Horizontal	160 ± 20	120 ± 20	155 ± 15 NE
RW14	164-168	22,273	21,000	35.8	Horizontal	145 ± 20	100 ± 20	100 ± 20 SW
RW15 A	140-144	23,329	10,570	32.0	Vertical	130 ± 20	NA	± 10 NE
RW15 B					Horizontal	50 ± 20	50 ± 15	40 ± 15 NE
RW16	149-152	31,080	27,667	35.0	Horizontal	130 ± 20	80 ± 15	70 ± 15 SE
RW17 A	174-180	25,368	11,554	33.0	Horizontal	130 ± 20	50 ± 15	40 ± 15 NE
RW17 B					Vertical	60 ± 20	100 ± 20	± 15 NE

In an effort to increase production of contaminated water from the Lower Gallup Sandstone, vertical drainholes completed with hydraulic fracture stimulation are being evaluated. Measurement of the hydraulic fracture growth pattern is critical to understanding radial coverage/contact of the hydraulic fracture. Knowledge of the hydraulic fracture growth dictates vertical drainhole density for optimal coverage.

2. Background

The United Nuclear Corporation Church Rock Project is located approximately 21 miles northeast of Gallup, New Mexico on the southern border of the Navajo reservation. The site is underlain by a series of sand and shale sequences with some coal layers and an overlying alluvium.

In 2003, a test Recovery Well (the HF-3) was drilled and hydraulically fractured outside the area of proposed remediation. To monitor the growth and coverage of the created hydraulic fracture, an array of 32 surface tiltmeters was installed covering a surface area surrounding the HF-3 well extending out from the wellbore approximately 250% the depth of the hydraulic fracture. The test area for the project was adjacent to a known plume of contaminated ground water, which is migrating to the north and emanates from the tailing ponds located at the site. Previous attempts to drain this area have proven not to be overly efficient and hydraulic fracture stimulation is now being considered as a way to improve performance of the contaminate removal.

The 2003 test project was designed (from a surface tiltmeter mapping perspective) to determine:

1. the vertical component (if any) created from the hydraulic fracturing operations,
2. the radial extent of the created horizontal fracture(s), and
3. whether the surface deformation caused by the hydraulic fracturing would affect a nearby LPG pipeline.

The answers found to the above questions in 2003 were:

1. no vertical growth was observed;
2. the radial extent of the hydraulic fracture was between 35 and 45 ft in radius; and
3. surface ground movements of <0.1 inch were within pipeline design limits.

The 2004 project included seven Recovery Wells named RW11, RW12, RW13, RW14, RW15, RW16, and RW17. The wells were drilled and cased with a small interval (±4 feet) of openhole barefoot interval at the bottom of the hole. Single hydraulic fracture treatments were pumped in each Recovery Well and monitored with Pinnacle's Surface Tiltmeters. Descriptions of each treatment are detailed below.

RW11 - Pumped September 11, 2004
The treatment was started at 09:31 and ended at 09:44. A total of 408 barrels (17,136 gallons) of fluid carrying 9,540 lbs of proppant was injected into the openhole interval. From the surface tiltmeters, a horizontal fracture was initiated to the north, which grew for 7 minutes at depth of 150 feet from surface. The created fracture was centered approximately 50 feet to the north of the RW11 wellbore and was elliptical in shape. Approximately 7 minutes into the treatment, tiltmeter signals increased to the ESE with a secondary horizontal fracture indicated at a shallower depth (~95 feet from surface). The treatment was shut down after 12 minutes due to upward movement of the second fracture.

RW12
Unable to treat as the wellbore had silted up and required additional cleanout.

RW13 – Pumped September 11, 2004
The treatment was started at 15:53 and ended at 16:13. A total of 645.5 barrels (27,112 gallons) of fluid carrying 31,540 lbs of proppant was injected into the openhole interval. From the surface tiltmeters, a horizontal fracture was initiated to the north of the wellbore and continued with radial growth for the entire injection period. The depth of the fracture was 160 ± 20 feet from surface and 80 ± 15 feet in diameter.

RW14 – Pumped September 11, 2004
The treatment was started at 17:46 and ended at 18:01. A total of 530 barrels (22,273 gallons) of fluid carrying 21,000 lbs of proppant was injected into the openhole interval. From the surface tiltmeters, a horizontal fracture was initiated to the south of the wellbore and continued with radial growth for the entire injection period. The treatment was terminated due to running out of proppant. The depth of the fracture was 145 ± 20 feet from surface and 100 ± 20 feet in diameter.

RW12 – Pumped September 18, 2004
The treatment was started at 12:29 and ended at 12:40. A total of 376 barrels (15,794 gallons) of fluid carrying 7,500 lbs of proppant was injected into the openhole interval. From the surface tiltmeters, a vertical fracture in the vicinity of the openhole section (azimuth N17E) was initiated, which grew for six minutes. Approximately six minutes into the treatment, tilt signals indicated a secondary horizontal fracture was created at a depth of ~100 feet from surface. The treatment was shut down after 12 minutes due to upward movement of the second fracture.

RW15 – Pumped September 18, 2004
The pad was started at 15:57 and ended at 16:03. A total of 164 barrels (6,888 gallons) of fluid was injected into the openhole interval. At the conclusion of the pad, surface tilt data were analyzed. The interpreted fracture geometry was vertical and centered at ±130 feet from surface. Injection was resumed and growth was monitored with the tiltmeters. Two vertical fractures were initiated with the center of the vertical fractures at 120 feet and 150 feet from surface, respectively. Azimuths of the vertical fractures were N12E and N82W, respectively. At nine minutes into the treatment, tiltmeters indicated that one of the fractures developed a horizontal component. At 12 minutes, tiltmeter analysis indicated upward movement of the horizontal component and it was advised to cease injection. Following flush, a small surface breach was noted just east of the RW15 wellhead shortly after the treatment was complete. A total of 555 barrels (23,329 gallons) of fluid carrying 10,570 lbs of proppant was injected into the well.

RW16 – Pumped September 18, 2004
The treatment was started at 19:00 and ended at 19:26. A total of 740 barrels (31,080 gallons) of fluid carrying 27,667 lbs of proppant was injected into the interval. From the surface tiltmeters, a horizontal fracture was centered on the wellbore and continued with radial growth for the entire injection period. The depth of the fracture was 130 ± 20 feet from surface and 80 ± 15 feet in diameter.

RW17 – Pumped September 19, 2004
The pad was started at 10:15 and ended at 10:23. A total of 206 barrels (8,652 gallons) of fluid was injected into the openhole interval. At the conclusion of the pad, surface tilt data were analyzed. The interpreted fracture geometry was horizontal and centered on the wellbore at ±160 feet from surface. Injection was resumed at 11:19 and growth was monitored with the tiltmeters. Fourteen minutes into the treatment, it was advised to cease injection due to upward movement of a horizontal component. The horizontal component moved to ±130 feet from surface NE of the wellbore with a smaller horizontal component approximately 60 feet from surface and 100 feet to the SW.

The surface tiltmeters were demobilized on September 20 with the PVC casing and caps left for later recovery.

3. Results and Conclusions

1. In all treatments images, no downward growth was measured, i.e., no coal was fractured.

2. All movement of the created fracture growth was up. It is not known if the upward movement was due to existing vertical networks, existing boreholes, and/or poor primary cement bonding in the Recovery Wellbores.

3. Fracturing complexity was much greater than in the 2003 hydraulic fracturing program.

4. The created hydraulic fractures were not all centered at the Recovery Wellbore. This is likely a result of existing channels and/or natural fractures.

5. The goal of fracturing the saturated zone will be born out of post-treatment production data.

6. The cement quality in the Recovery Wellbores remains a large unknown and potential cause of the lack of zonal isolation.

4. Fracture Orientation

Fracture orientation is presented for the seven Recovery Wells mapped in September 2004. In addition to fracture orientation (azimuth, dip, and horizontal and/or vertical components), the depth to the center of the created fracture along with its relation to the treatment well is given. **Appendices A** and **B** contain details on surface tiltmeter mapping background and theory. **Appendix C** includes plots for each Recovery Well showing surface deformation at the end of pumping. **Appendix D** includes plots for each stage with the observed and theoretical tilt vectors along with individual tiltmeter plots showing actual movement measurement for select treatment and tiltmeters.

Table 2. Fracture Orientation at end of Pumping

Well Name	Openhole Interval (ft)	Volume Pumped: Fluid (gals)	Volume Pumped: Proppant (lbs)	Volume Pumped: Rate (bpm)	Fracture Orientation	Fracture Depth (ft) (± uncertainty)	Fracture Dimensions (ft) (± uncertainty)	Location to Frac Wellbore (ft) (± uncertainty)
RW11	171-175	17,136	9,540	35.5	$Horizontal_1$	150 ± 20	60 ± 15	30 ± 15 N
					$Horizontal_2$	95 ± 20	80 ± 15 N-S 40 ± 15 E-W	100 ± 15 E
RW12	169-173	15,794	7,500	35.3	Horizontal	100 ± 20	80 ± 15	75 ± 15 SW
RW13	169-173	27,112	31,540	35.8	Horizontal	160 ± 20	120 ± 20	155 ± 15 NE
RW14	164-168	22,273	21,000	35.8	Horizontal	145 ± 20	100 ± 20	100 ± 20 SW
RW15 A	140-144	23,329	10,570	32.0	Vertical	130 ± 20	NA	± 10 NE
RW15 B					Horizontal	50 ± 20	50 ± 15	40 ± 15 NE
RW16	149-152	31,080	27,667	35.0	Horizontal	130 ± 20	80 ± 15	70 ± 15 SE
RW17 A	174-180	25,368	11,554	33.0	Horizontal	130 ± 20	50 ± 15	40 ± 15 NE
RW17 B					Vertical	60 ± 20	100 ± 20	± 15 NE

Recovery Wells 11, 15, and 17 each experienced multiple planes of hydraulic fracture growth. Discussion of individual wells follows. **Figure 1** and **Figure 2** illustrate plan views of the 2004 Church Rock Tiltmeter mapping project. The small blue dots represent actual tiltmeter sites that surround the Recovery Wells fractured in this campaign. The colored circles represent the estimated radial extent and location of the center of the created hydraulic fracture.

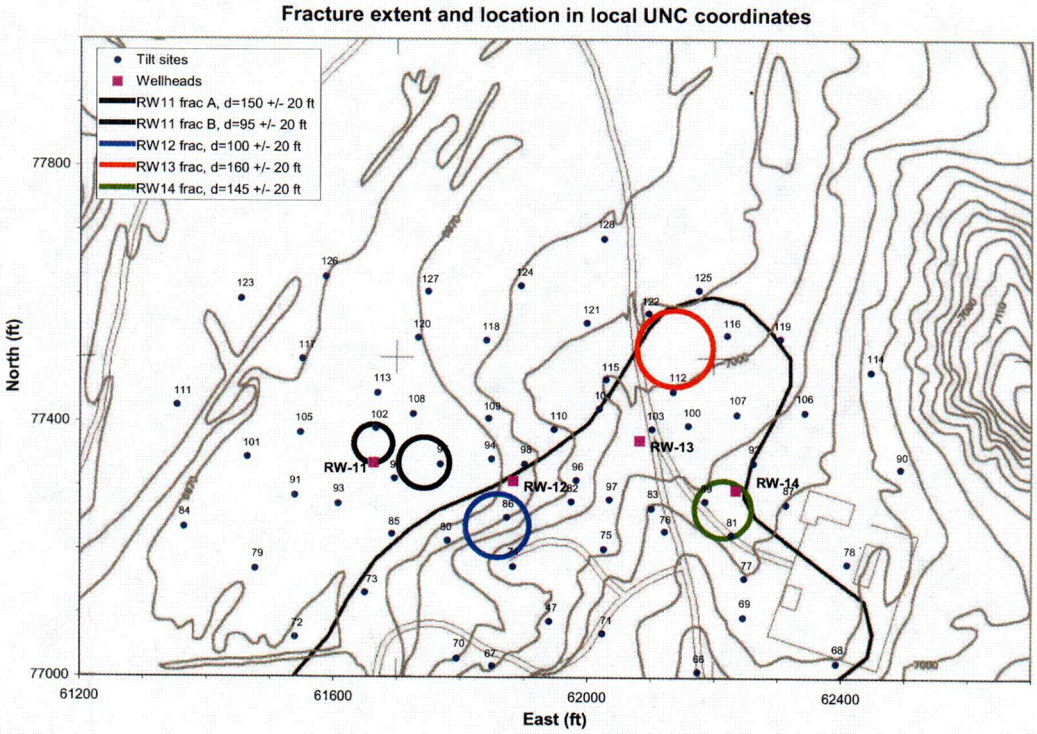

Figure 1. Plan view of the 2004 Church Rock Hydraulic Fracturing program – Array #1

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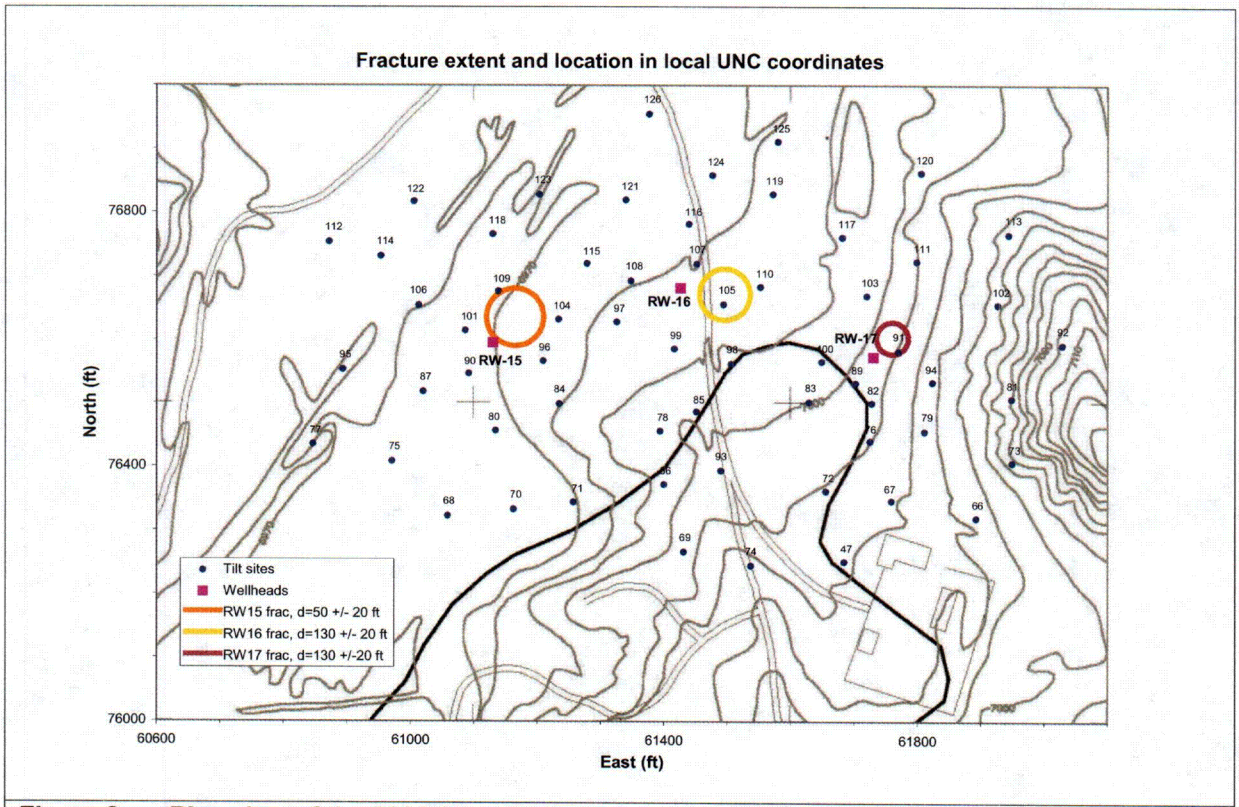

Figure 2. Plan view of the 2004 Church Rock Hydraulic Fracturing program – Array #2

CT2

5. Recommendations

- Pump a minifrac or pad with a scheduled shutdown to ascertain created hydraulic fracture geometry and be prepared to not stimulate a well if growth behavior is unacceptable, i.e., not treat the saturated zone.
- Closer spacing and smaller treatments may aid in achieving consistent hydraulic fracture growth.

Appendix A – Introduction to Surface Tilt Fracture Mapping

A.1 Description

Creation of a hydraulic fracture, by definition, involves parting of the rock and displacing the fracture faces to create fracture width. The principle of tiltmeter fracture mapping is simply to infer hydraulic fracture geometry by measuring this fracture-induced rock deformation. The induced deformation field radiates in all directions and can be measured either downhole with wireline-conveyed tiltmeter arrays or with a surface array of tiltmeters. **Figure 3** shows a schematic diagram of the induced deformation field from a vertical fracture as seen both downhole and at the surface. As shown, measuring the deformation field at the surface with a two-dimensional array gives a very different view of the deformation field than a one-dimensional (line) array downhole in an offset wellbore. Horizontal fractures exhibit slightly different surface deformation patterns but are easily recognized. **Figure 3** shows surface deformation patterns from horizontal and vertical hydraulic fractures.

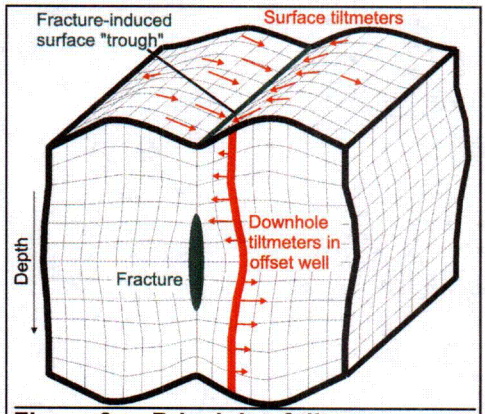

Figure 3. Principle of tiltmeter fracture mapping

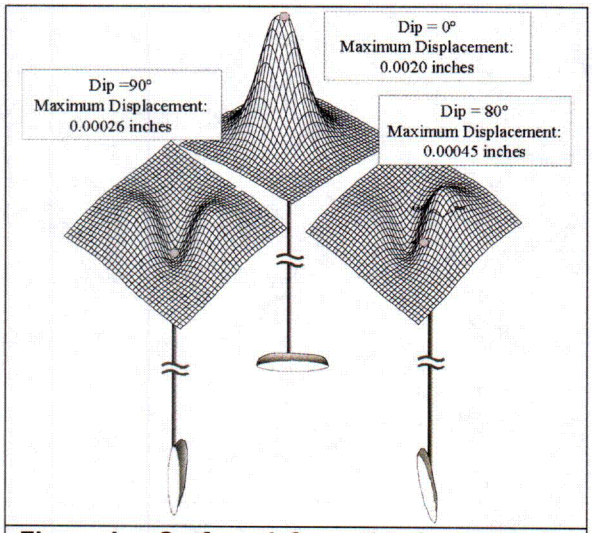

Figure 4. Surface deformation for hydraulic fractures of different orientations at 3000 ft depth

At the surface, the induced deformation magnitudes are so small – typically on order of one ten-thousandth of an inch – that they are impossible to measure. Fortunately, measuring the gradient of the displacement field, or the tilt field, is far easier. The induced deformation field at the surface is primarily a function of fracture azimuth, dip, depth to fracture center, and total fracture volume (**Figure 4**). The induced deformation field is almost completely independent of reservoir mechanical properties and in-situ stress state. For example, a north-south growing vertical hydraulic fracture of a given size yields the same surface deformation pattern whether the fracture is in low modulus diatomite, extremely hard carbonate, or even unconsolidated sandstone. The deformation pattern is simply a north-south trending trough surrounded by symmetrical ridges (the ridges are asymmetrical if the fracture is dipping) whose magnitude depends on the created fracture volume and whose separation depends on the depth-to-fracture-center.

The simplicity of the concept allows robust and unambiguous determination of a few primary fracture parameters like fracture azimuth and dip and, with somewhat less precision, created fracture volume,

C73

depth-to-fracture-center and fracture offset due to asymmetric growth. The characteristic shape and orientation of the tilt field is not altered with increasing fracture depth. The magnitude of the tilt is, of course, attenuated with increasing fracture depth, which serves to limit the practical surface mapping depth.

The greatest limitation of surface tilt mapping is that some critical details, like individual fracture dimensions, cannot be resolved at fracture depths far greater than the created fracture dimensions. This is because, at greater depth, not only do the induced surface tilts get smaller, but there is also an inherent blurring of the fracture source "edges" as the measurement distance gets large compared to the separation of the fracture edges (i.e., fracture dimensions). Downhole tiltmeter mapping was developed to get around the fracture dimension resolution limitation by bringing the measurement distance down to the same order of magnitude as the created fracture dimensions.

A.2 Sensor Location and Placement

Pinnacle Technologies placed 120 surface tiltmeter sites in two arrays to map the seven Recovery Wells. **Figure 5** shows a map of the area that was implemented with surface tiltmeters.

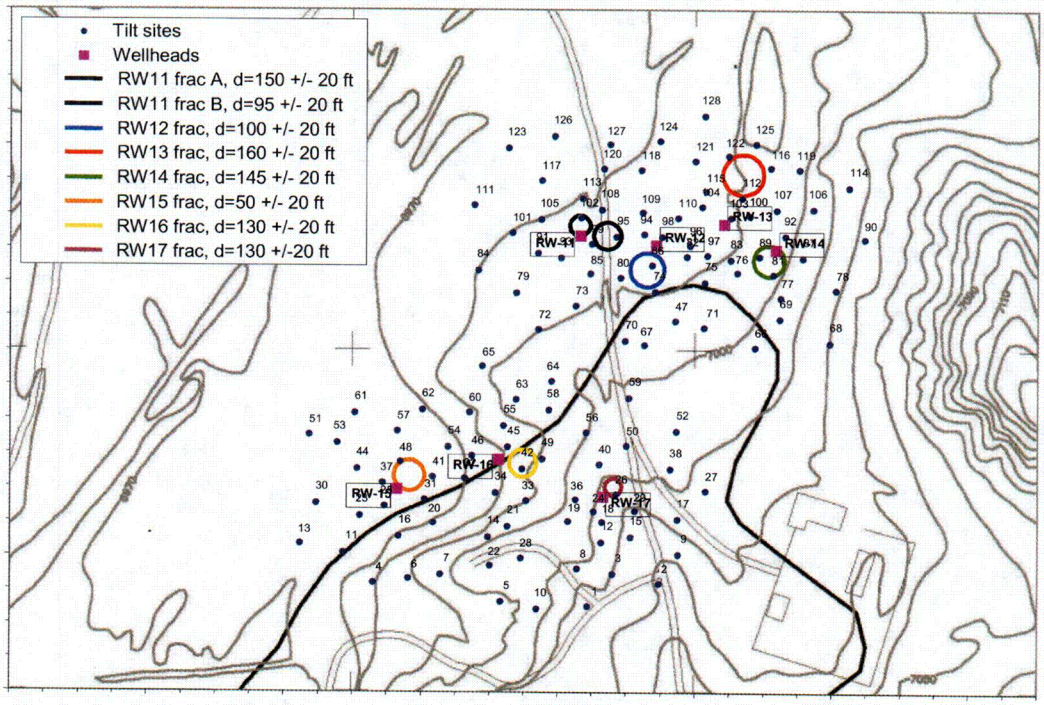

Figure 5. Plan view of the 2004 Church Rock Hydraulic Fracturing program – Both Arrays

Pinnacle Technologies worked with UNC to choose the most convenient locations for the tiltmeter sites, and avoid building sites too close to roads or existing power or data lines. Instruments were also placed so as to ascertain any possible movement of an LGP pipeline running through the NE quadrant of the array.

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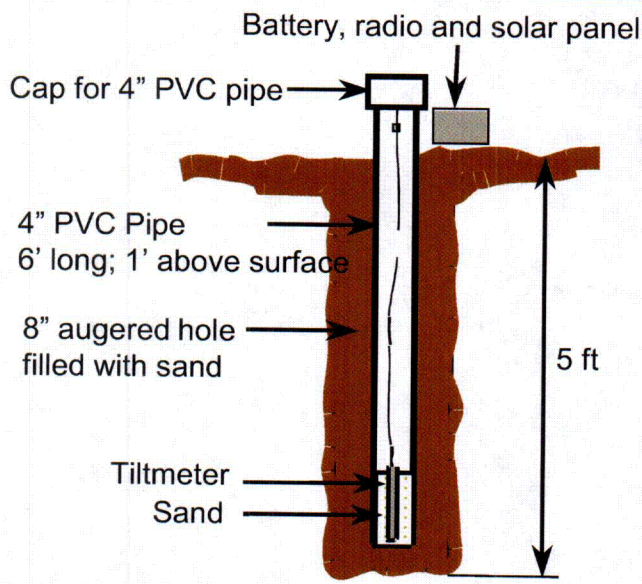

Figure 6. Schematic view of a surface tiltmeter site. A 4" PVC pipe is placed in an 8" augered hole that is filled on the backside with sand. The tiltmeter instrument is placed inside the 4" pipe and is held in place by a shallow layer of sand.

Figure 7. Example of a surface tiltmeter site. A capped PVC pipe sticks out about 2 ft above surface. A solar panel is attached to the tiltmeter site to charge the battery of the instrument.

Pinnacle staked the surface tilt site locations for approval by UNC on July 17th, and then constructed the 32 sites on July 29th. As shown in the schematic in **Figure 6**, each tiltmeter site consists of a 4-inch diameter 6-ft long PVC pipe set in a 5-ft hole. **Figure 7** shows the tiltmeter site above surface, with a 2 ft capped pipe protruding out of the ground. The backside between the hole and the pipe was filled with sand. A bottom cap was installed at the bottom of the 6 ft pipe to prevent sand from coming in at the bottom. Once the sites were constructed, tiltmeters were installed by lowering them to the bottom of the hole, then pouring a small amount of sand in the wellbore to lock the instruments in place. After the pilot project was completed, the tiltmeter instruments were removed and the sites reclaimed.

C75

A.3 Processing

Surface tiltmeter mapping involves measuring the fracture-induced tilt at many points above a hydraulic fracture, and then solving the geophysical inverse problem to determine the fracture parameters that must have been created in order to produce the observed deformation field. While the concept is simple, the magnitudes of the induced surface deformations are quite small and require highly sensitive measurement. A typical hydraulic fracture treatment at 7,000 ft depth results in induced surface tilts of only about 10 nanoradians – or about 10 parts in a billion. These minute tilts are measured with highly sensitive tiltmeters that operate on the same principle as a carpenter's level. Tiltmeters are metal cylinders roughly 30 inches long and 2 inches in diameter, which measure their own tilt on two orthogonal axes. As the instrument tilts, a gas bubble contained within a conductive-liquid-filled glass casing moves to maintain its alignment with the local gravity vector. Precision electronics detect changes in resistivity between electrodes mounted on the glass sensor that are caused by motion of the gas bubble. The latest generation of high-resolution tiltmeters, developed jointly by Pinnacle Technologies and Lawrence Livermore National Laboratory, were awarded a prestigious *R & D 100 Award* in 1997 and can detect tilts of less than one nanoradian.

For typical deep fracture mapping purposes, an array of 12 to over 24 tiltmeters are placed around the well to be fractured at radial distances from 15% to 75% of the fracture depth, as this is the region of maximum induced surface tilt. Fortunately, the exact layout of the monitoring array is not critical. Fracture mapping resolution is primarily dependent on the number of tiltmeter sites employed and the signal-to-noise ratio of the measurements. Resolution of fracture orientation is typically better than +/- 5 degrees at depths of less than 5,000 ft, and can drop to +/- 10 degrees as depth approaches 10,000 ft. Resolution of fracture center location ranges from 20 to 200 feet for fractures shallower than 3,000 ft, and drops to many hundreds of feet for fractures approaching 10,000 ft.

The tilt signals from shallow hydraulic fractures are much larger than those of deep fractures and thereby tend to increase the signal to noise ratio (S/N) helping to overcome the environmental noise around the array.

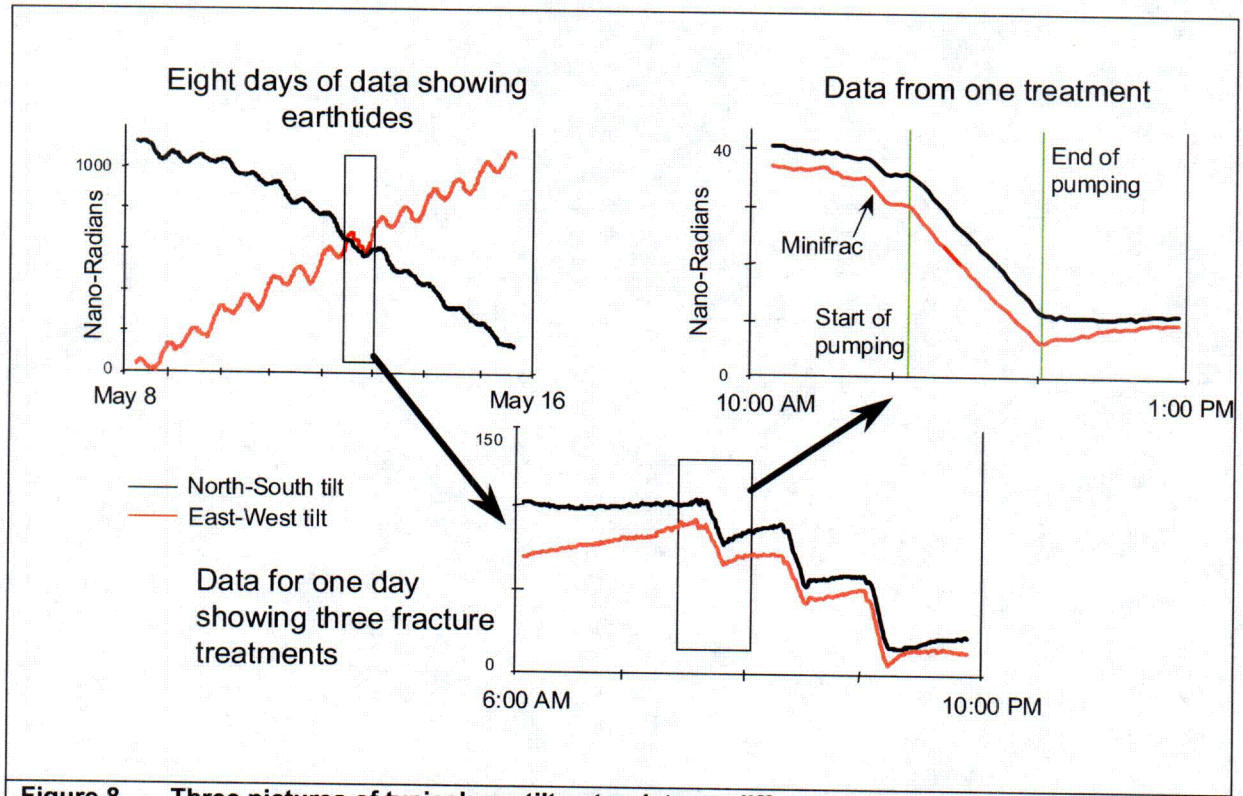

Figure 8. Three pictures of typical raw tiltmeter data on different time scales, ranging from one week with clear earth tides to a few hours around a fracture treatment

Each tiltmeter site has an instrument surrounded by sand within PVC pipe (3" to 9" diameter) that is cemented in a relatively shallow borehole (10 to 40 ft deep). **Figure 8** shows a sample record of tilt data versus time on many different time scales. The first view shows the daily swings of the tilt data in response to the solid earth tides caused by the earth's rotation with respect to the sun and moon, and a long-term drift due to surface subsidence. The next zoom-in shows an 18-hour time period when three hydraulic fracture treatment stages (seen clearly in the data) were pumped in the well being monitored. The final zoom-in illustrates a two-hour time period that clearly shows the recording of fracture-induced tilt from one of the propped fracture treatments. The three fracture treatments shown were in a relatively shallow depth range of approximately 3,000 ft and, therefore, yielded induced tilts on order of 100 nanoradians. The fracture-induced tilt is then extracted at each instrument site to yield an array of observed surface tilt vectors.

The observed tilt data is inverted to find the hydraulic fracture parameters that yield the best fit to the observed data, and a Monte-Carlo technique is employed to estimate parameter uncertainty. The top view in **Figure 9** compares the observed and theoretical fracture-induced tilt vectors from a best-fit fracture solution and shows a tabular listing of the mapped fracture orientation and depth. Note how a careful visual inspection of the observed tilt vectors alone reveals a trough that runs roughly northeast-southwest (fracture azimuth of N 45° E) and that both ridges are of roughly equal magnitude implying a fracture dip that is almost perfectly vertical (90 degrees). In simple single-plane-fracturing cases like this, visual inspection alone reveals the essential results.

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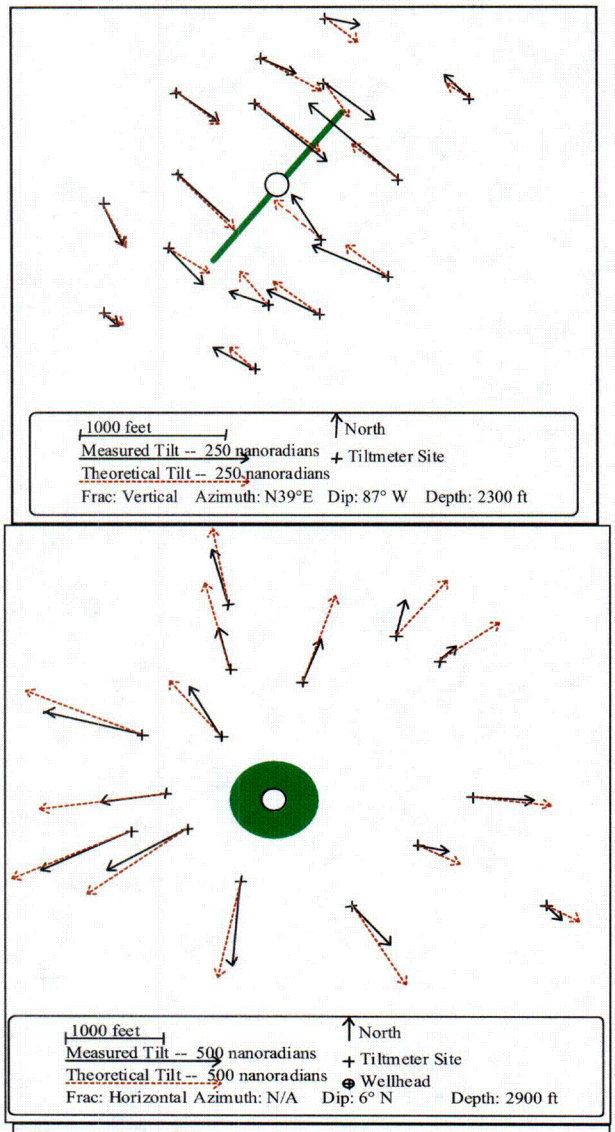

Figure 9. Observed and theoretical fracture-induced tilt vectors for a vertical (top) and horizontal (bottom) fracture; Curiously, the mapped horizontal fracture is in the same field as the vertical fracture shown, and the horizontal fracture is created in a structurally deeper part of the reservoir.

The lower view of **Figure 9** shows another overlay of observed and theoretical tilt vectors for the case of a horizontal fracture. Note the dramatic difference in the induced surface tilt patterns. Curiously, the mapped horizontal hydraulic fracture is in the same field as the vertical fracture shown, and the horizontal fracture is created in a structurally deeper part of the reservoir.

As the fracture-induced tilt is measured as a function of time, fracture mapping can be performed throughout the course of the treatment. In some cases fractures may initiate in one plane and then twist into another orientation, or initiate secondary fracture growth in another plane at some point in time during a treatment. Other parameters like depth-to-fracture-center may also change significantly during a treatment if, for example, the fracture breaks through a barrier and begins rapid upward or downward height growth.

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Appendix B – Conventions in Describing Fracture Orientation

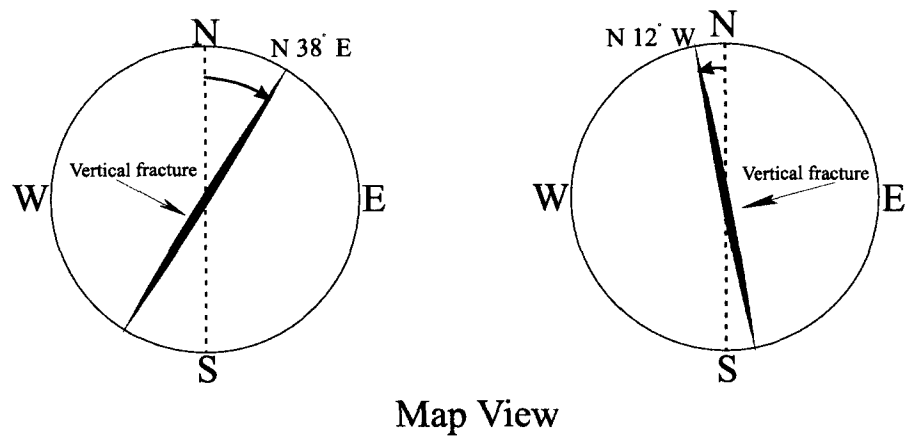


Figure 10. Conventions for describing fracture azimuth orientation. Value is measured as degrees from due North. Last letter designation (E or W) specifies direction of rotation from North (E being clockwise towards the East, W being counter-clockwise towards the West).

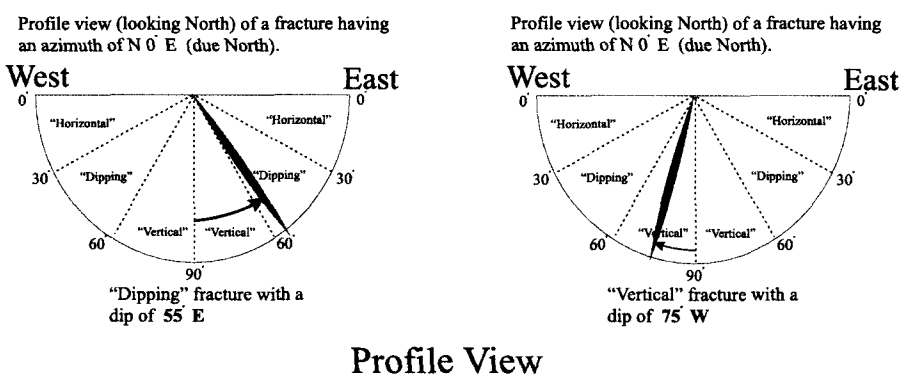


Figure 11. Conventions for describing fracture dip. A horizontal fracture has a dip of zero. A vertical fracture has a dip of 90°. The last letter designates which direction the fracture is dipping towards. For example, a fracture dip of 55° E should be understood as a fracture dipping 55° down towards the East. The range of possible dips (0°- 90°) as been divided into three parts; "horizontal", "dipping" and "vertical". This helps describe the fracture within Pinnacle reports. For example, a fracture with a dip of 82° E would be understood as a vertical fracture dipping 82° down towards the East.

Appendix C – Surface Vector Plots

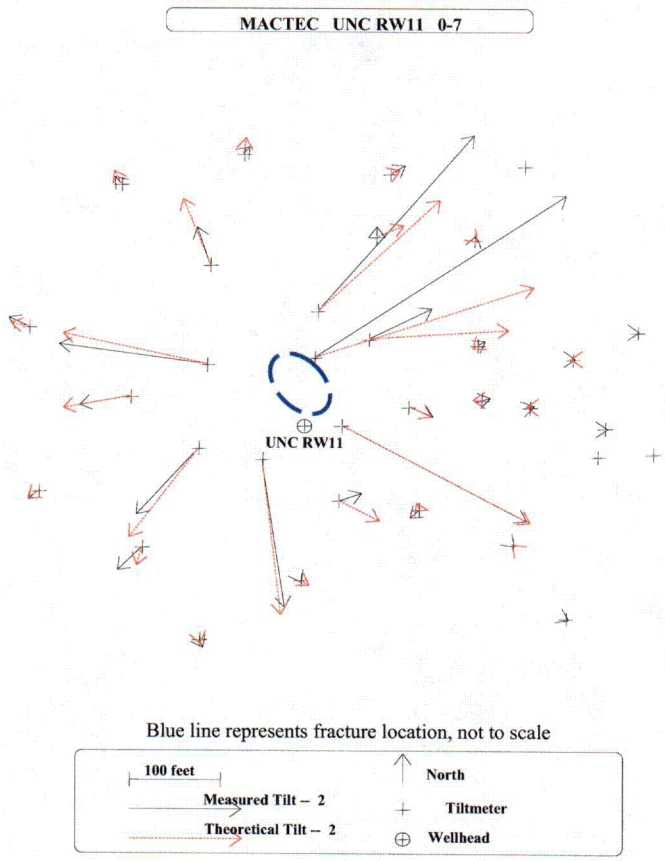


Figure 12. Observed and Theoretical tilt vectors for the best-fit fracture system at well RW 11 (t = 7 minutes)

C78

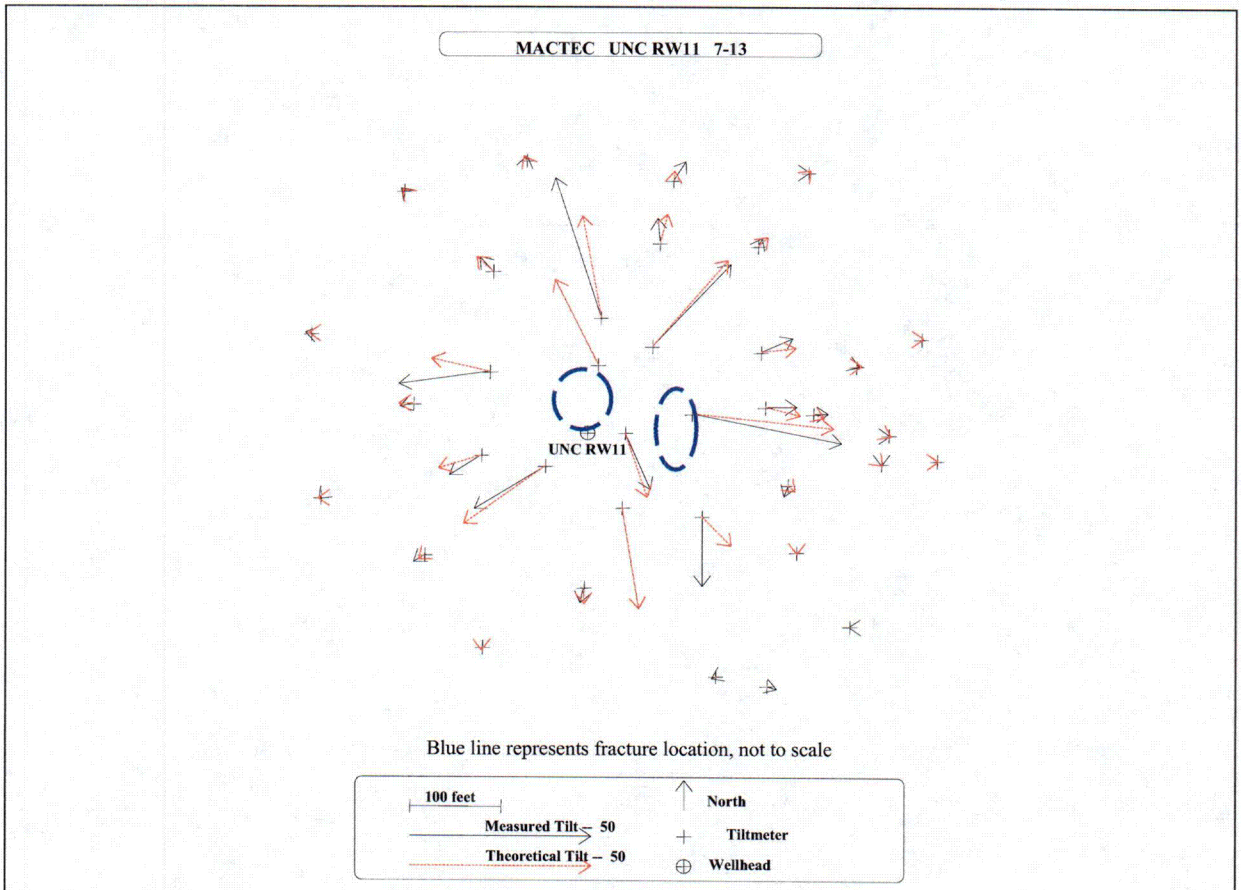


Figure 13. Observed and Theoretical tilt vectors for the best-fit fracture system at well RW 11 (t = 13 minutes, end of job)

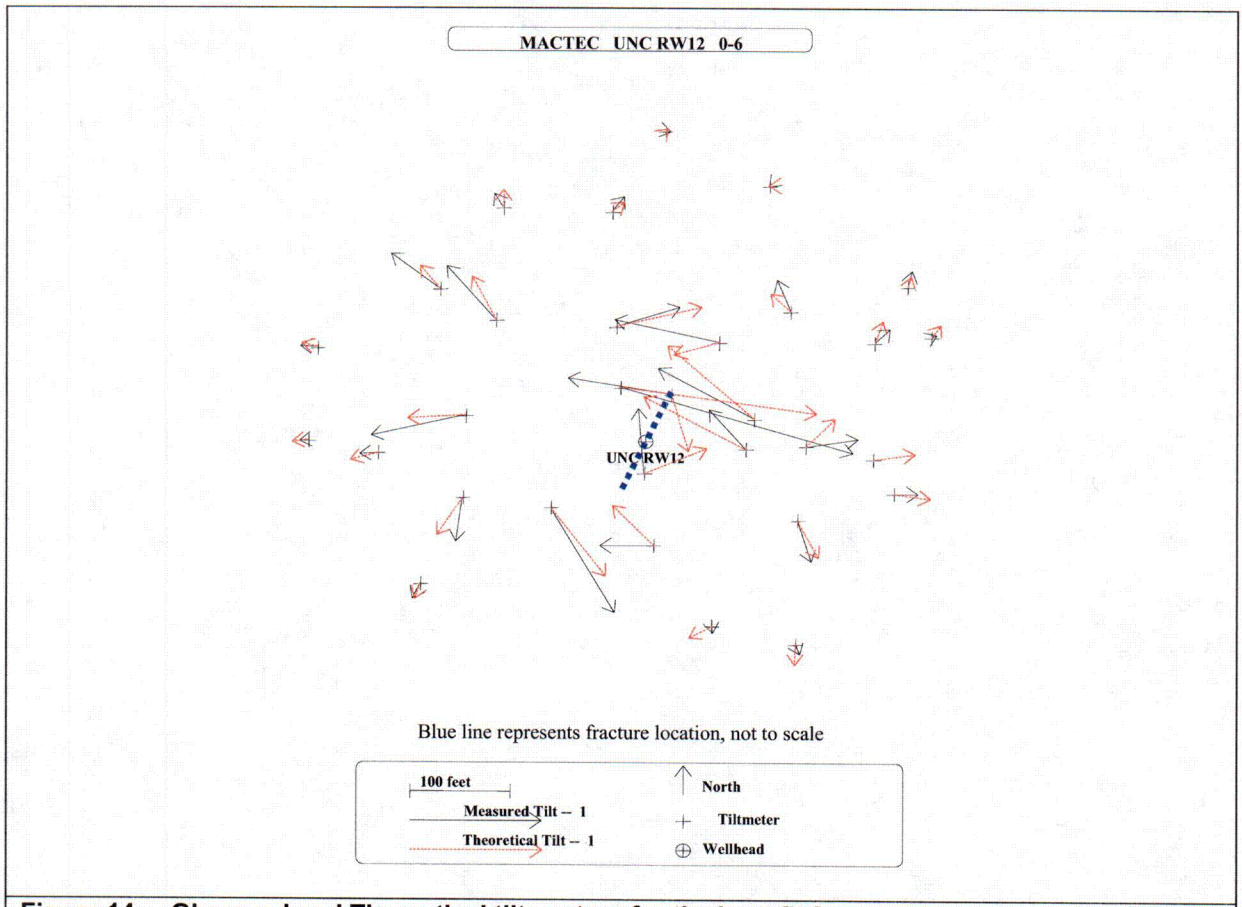
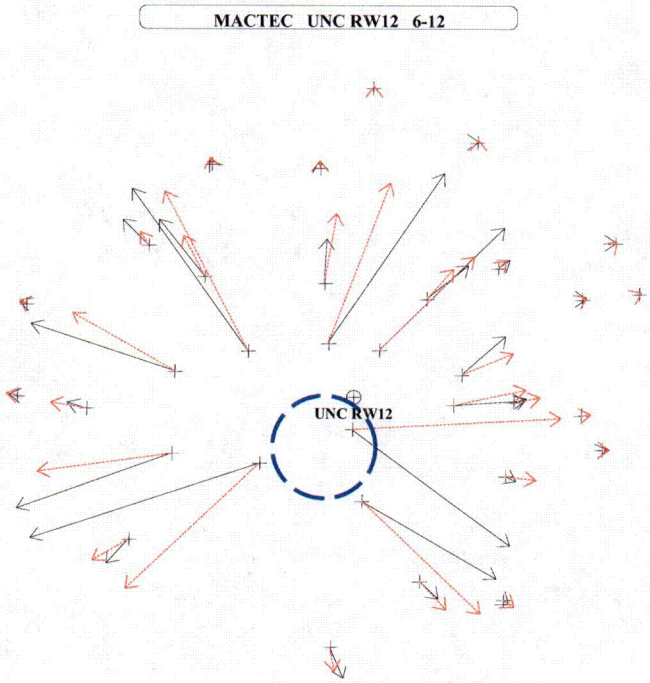


Figure 14. Observed and Theoretical tilt vectors for the best-fit fracture system at well RW 12 (t = 6 minutes)

C80



Blue line represents fracture location, not to scale

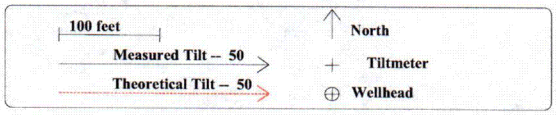


Figure 15. Observed and Theoretical tilt vectors for the best-fit fracture system at well RW 12 (t = 12 minutes, end of job)

C81

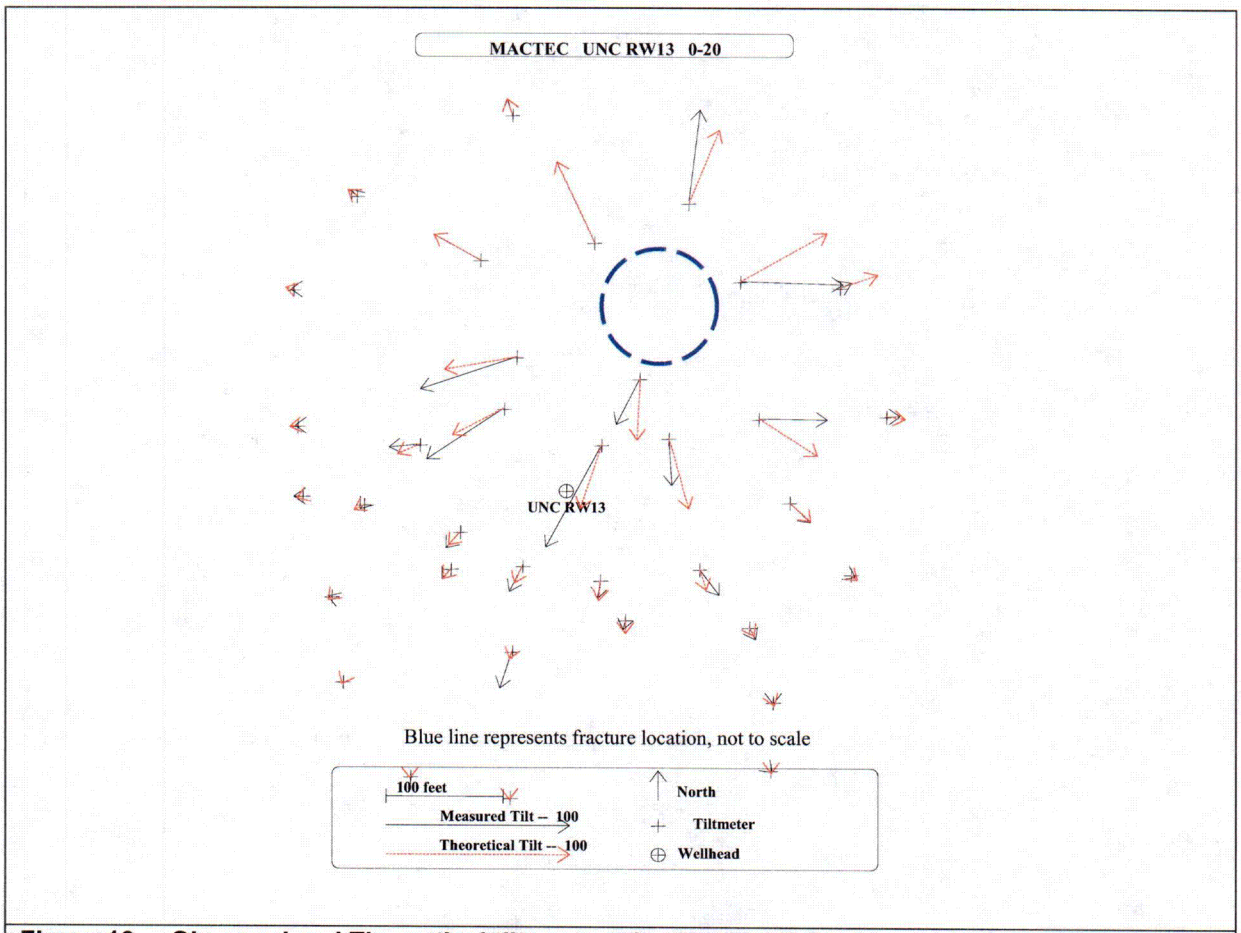


Figure 16. Observed and Theoretical tilt vectors for the best-fit fracture system at well RW 13 (t = 20 minutes, end of job)

C82

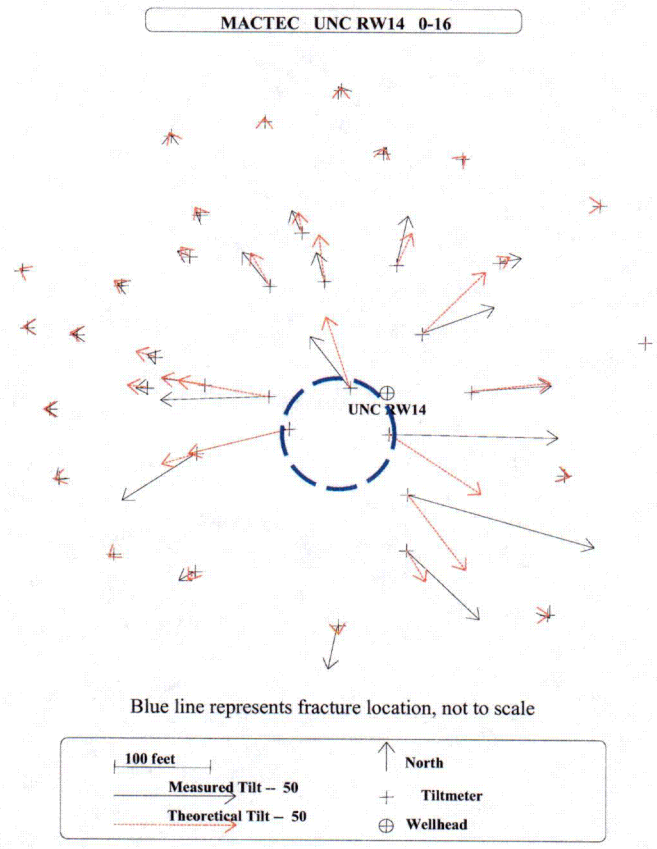


Figure 17. Observed and Theoretical tilt vectors for the best-fit fracture system at well RW 14 (t = 16 minutes, end of job)

C83

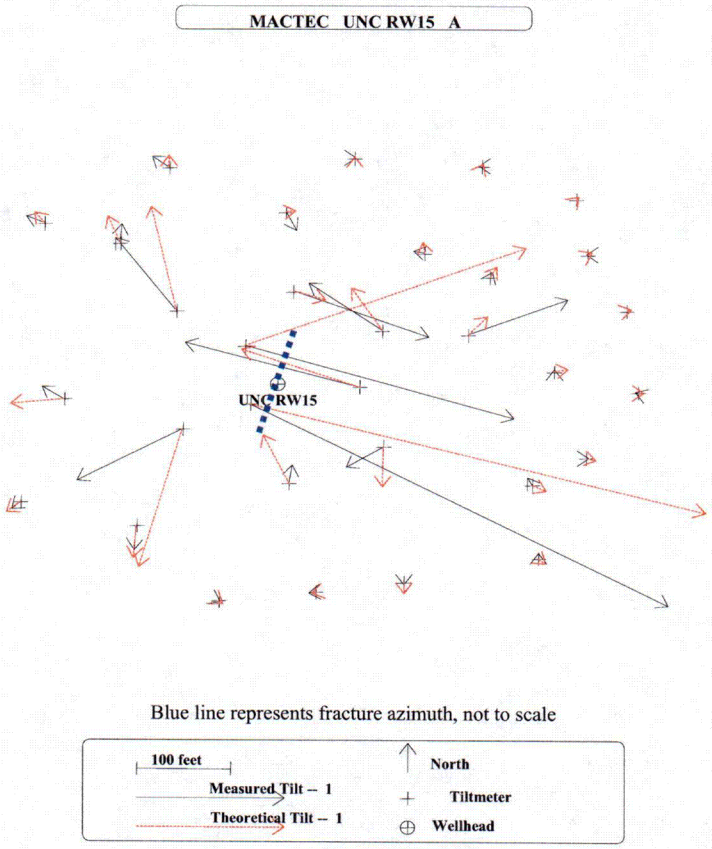


Figure 18. Observed and Theoretical tilt vectors for the best-fit fracture system at well RW 15A (t = 6 minutes, end of pad)

C84

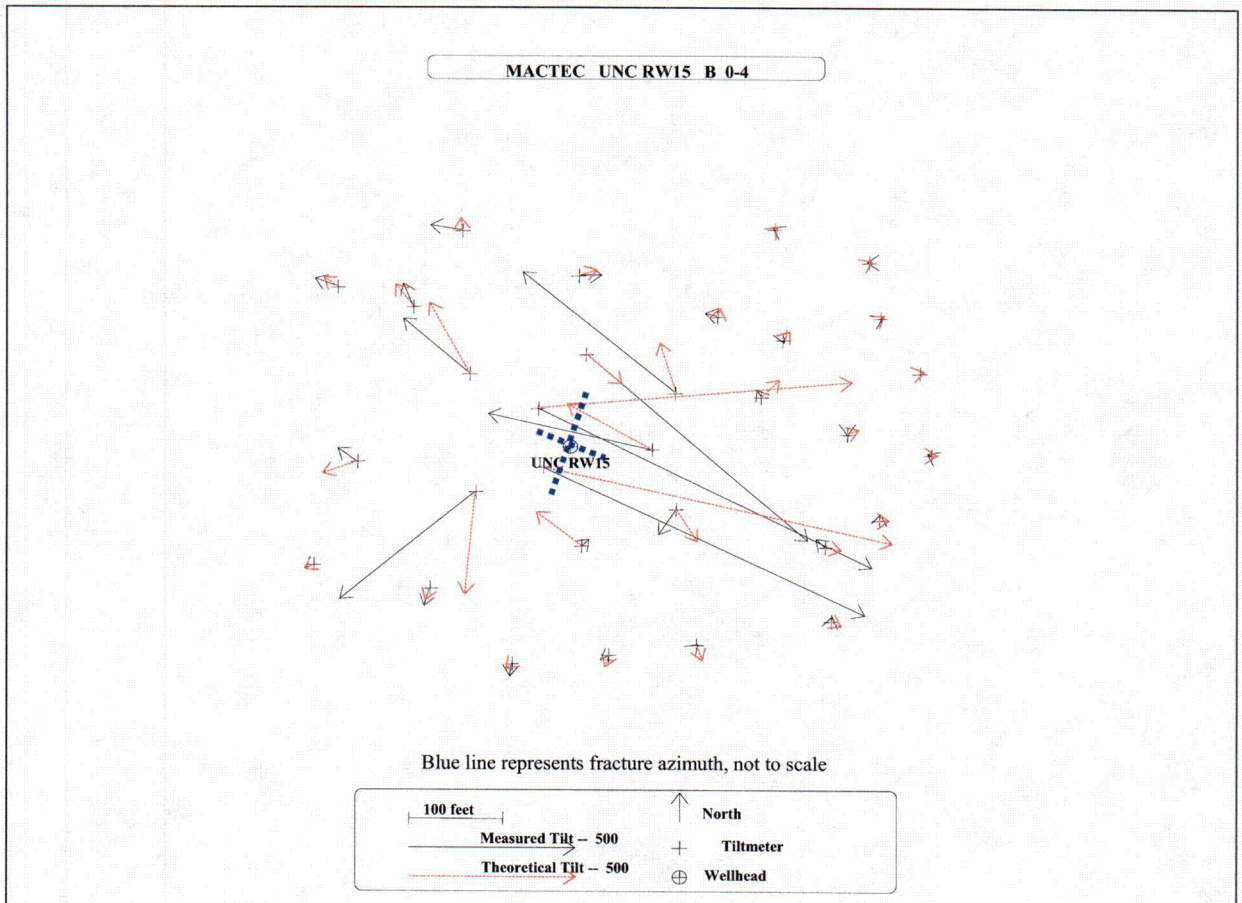


Figure 19. Observed and Theoretical tilt vectors for the best-fit fracture system at well RW 15B (t = 4 minutes)

C85

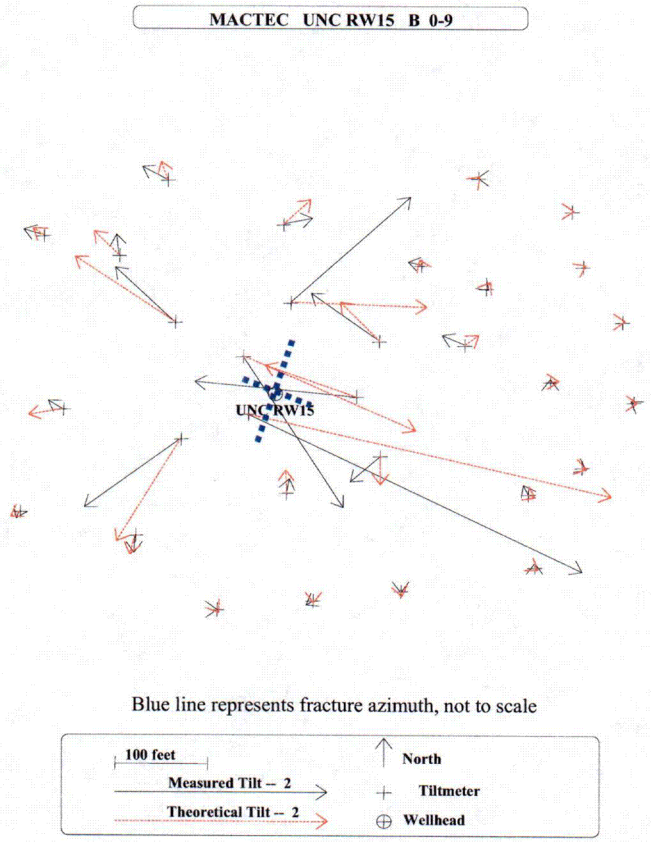


Figure 20. Observed and Theoretical tilt vectors for the best-fit fracture system at well RW 15B (t = 9 minutes)

C86

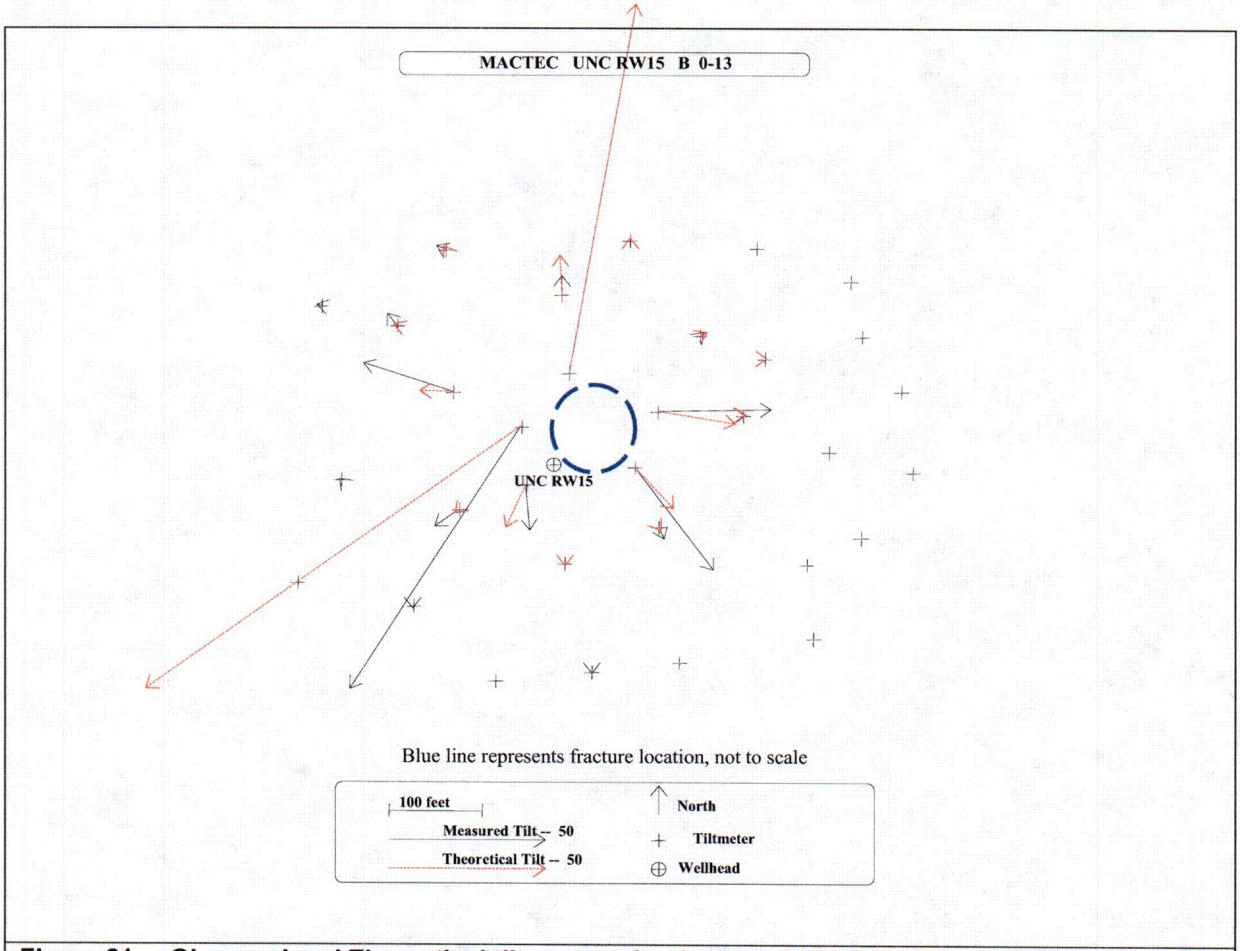


Figure 21. Observed and Theoretical tilt vectors for the best-fit fracture system at well RW 15B (t = 13 minutes, end of job)

C87

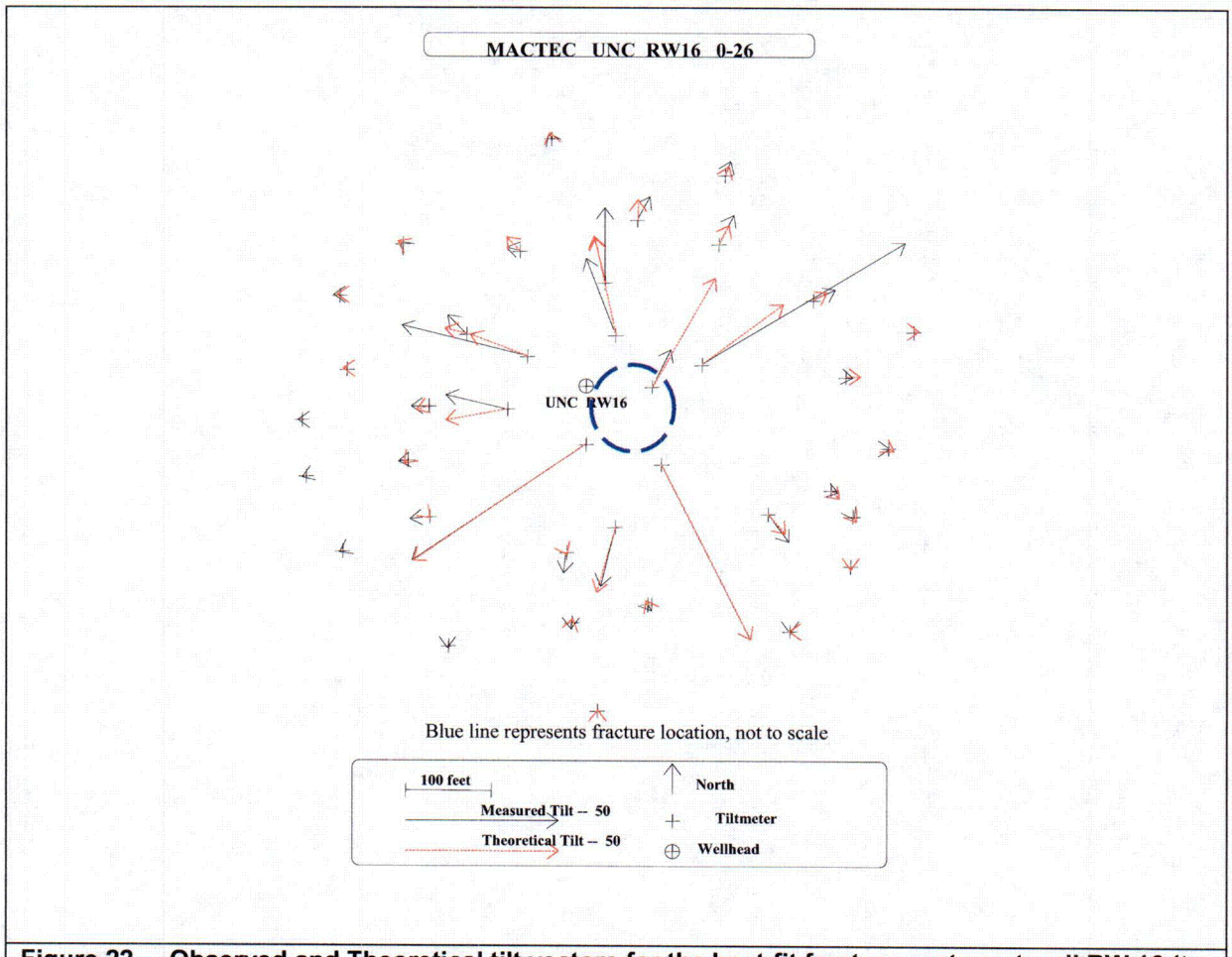


Figure 22. Observed and Theoretical tilt vectors for the best-fit fracture system at well RW 16 (t = 26 minutes, end of job)

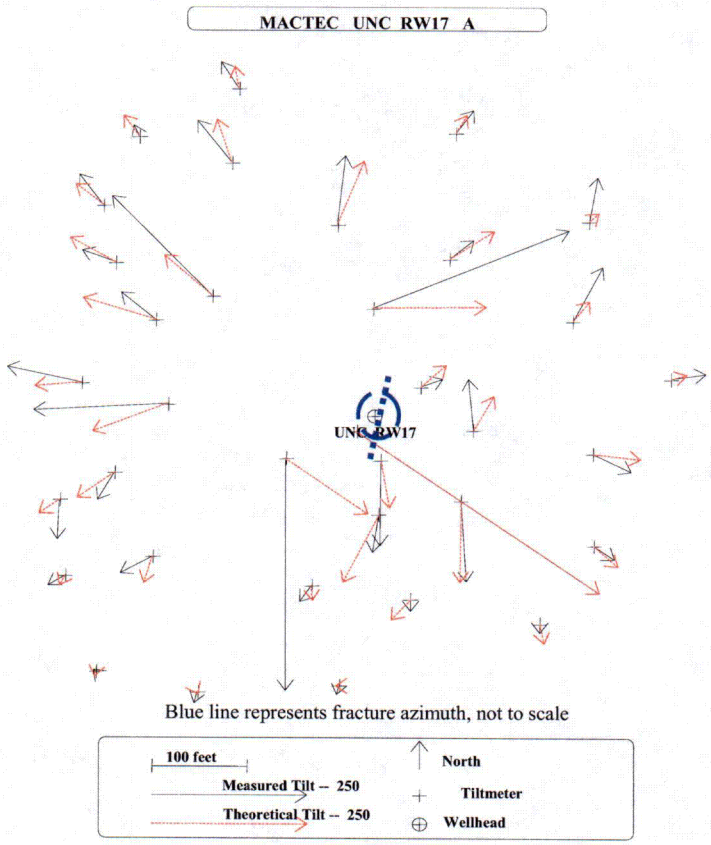


Figure 23. Observed and Theoretical tilt vectors for the best-fit fracture system at well RW 17A (t = 9 minutes, end of pad)

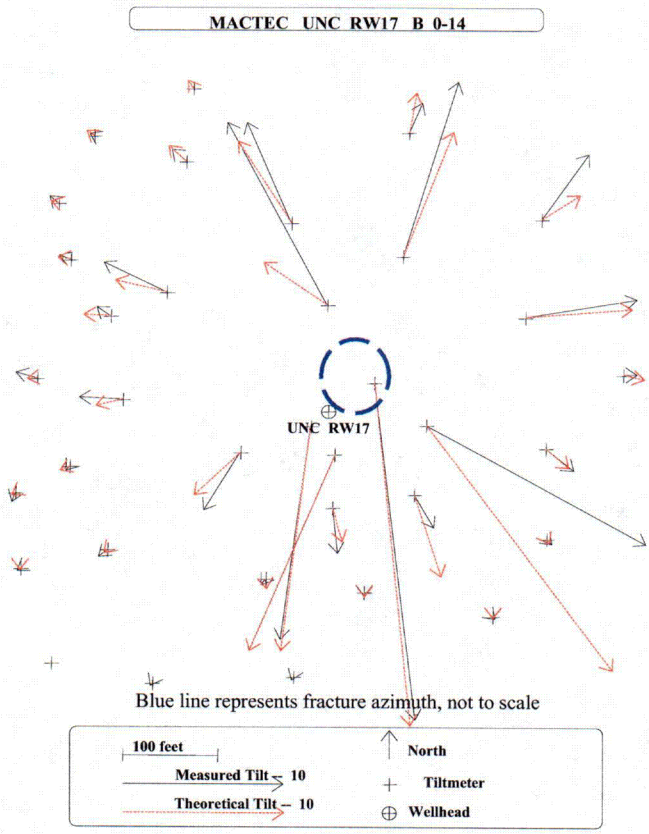


Figure 24. Observed and Theoretical tilt vectors for the best-fit fracture system at well RW 17B (t = 14 minutes, end of job)

Appendix D – Surface Deformation Plots

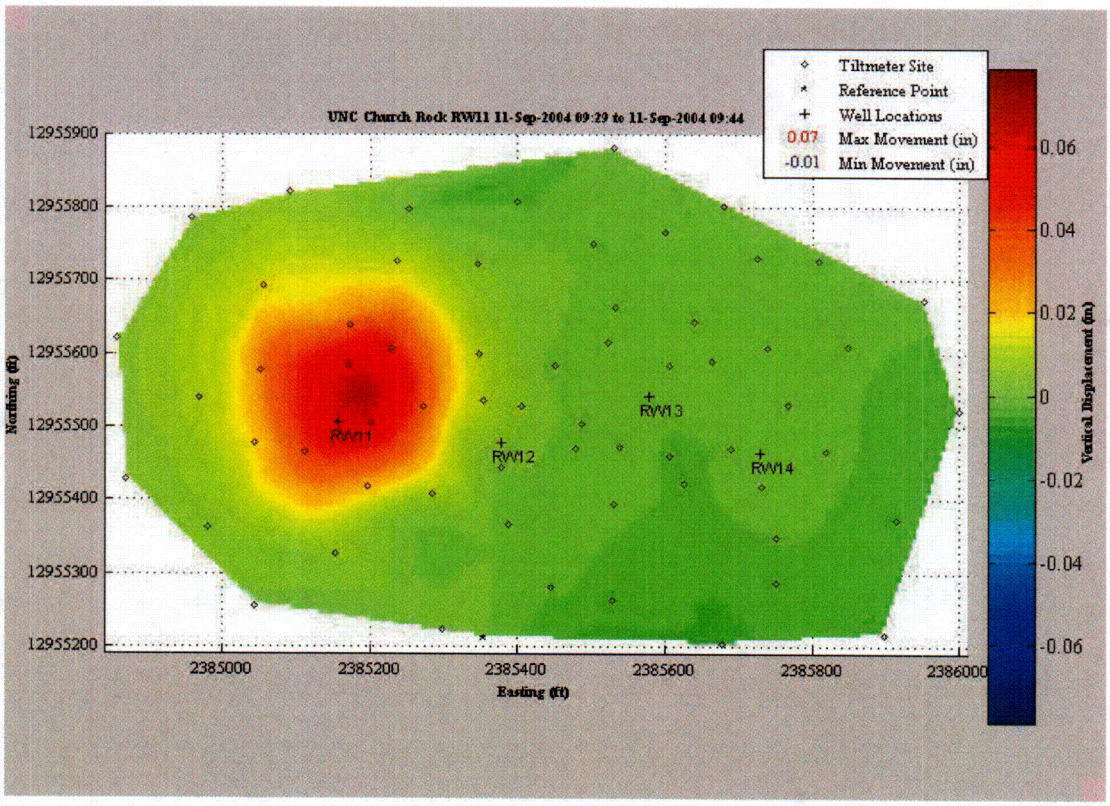


Figure 25. Maximum Surface Deformation for the treatment pumped in RW11

C91

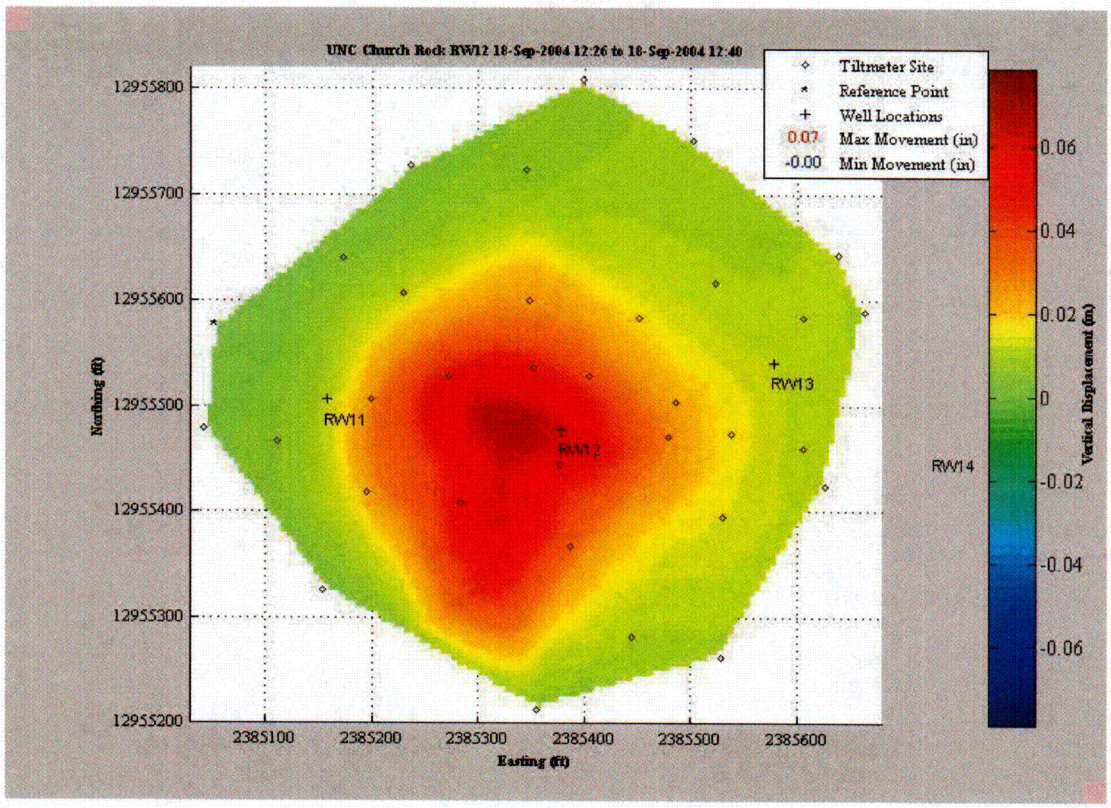


Figure 26. Maximum Surface Deformation for the treatment pumped in RW12

C92

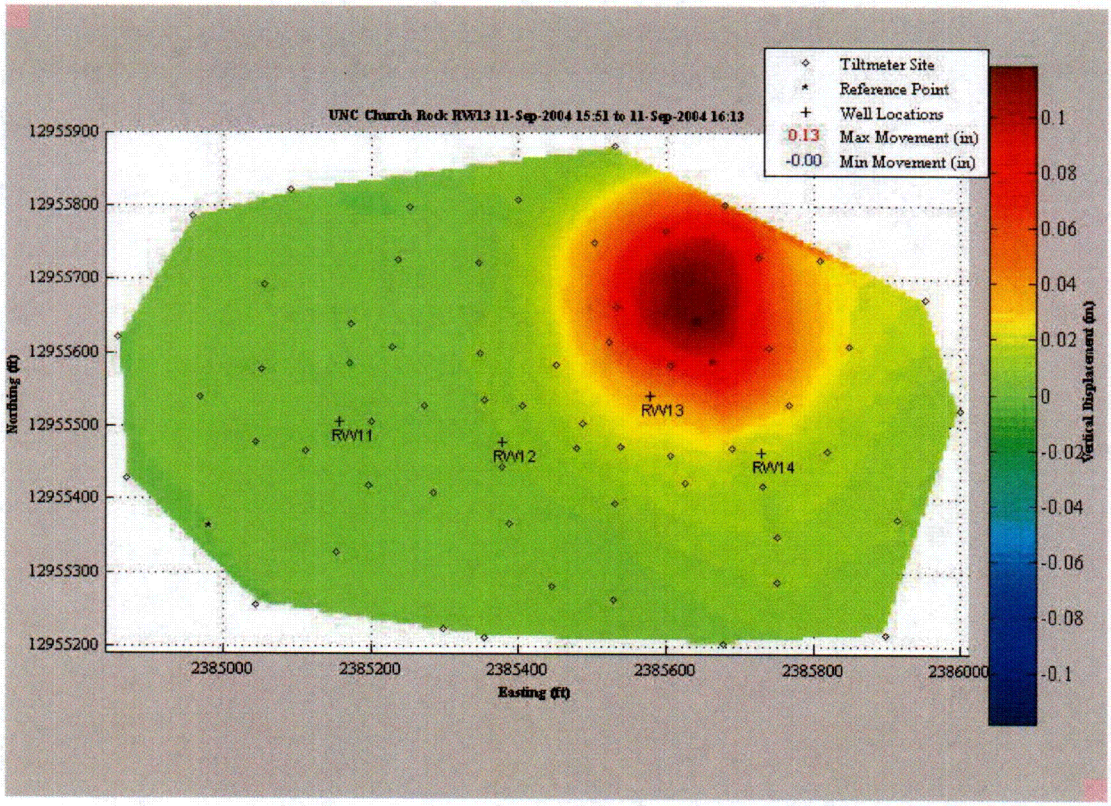


Figure 27. Maximum Surface Deformation for the treatment pumped in RW13

C93

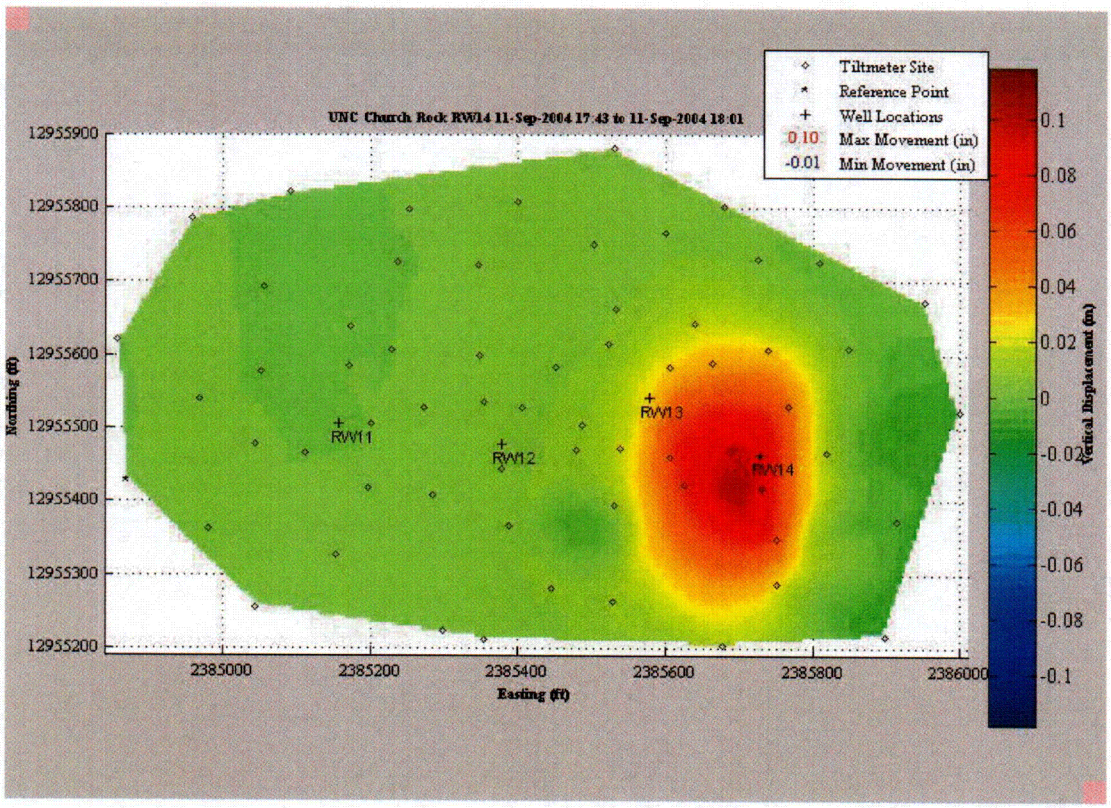


Figure 28. Maximum Surface Deformation for the treatment pumped in RW14

C94

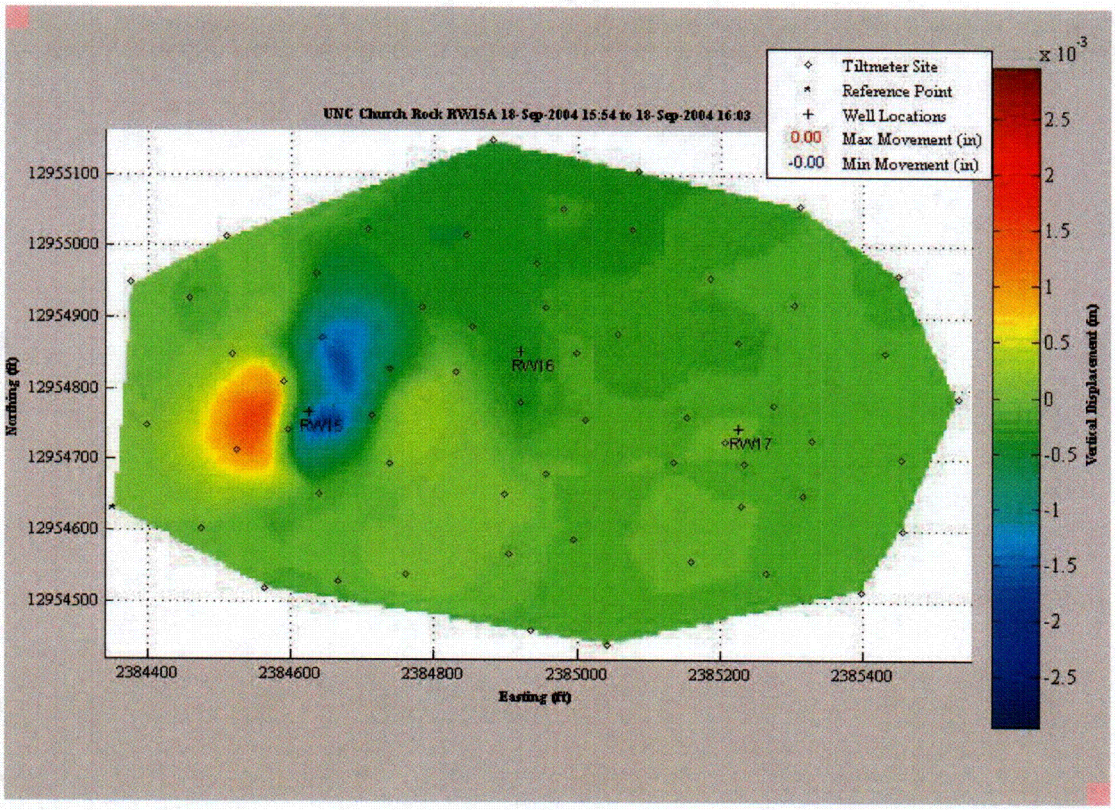


Figure 29. Maximum Surface Deformation for the treatment pumped in RW15 – Horizontal Fracture #1

C95

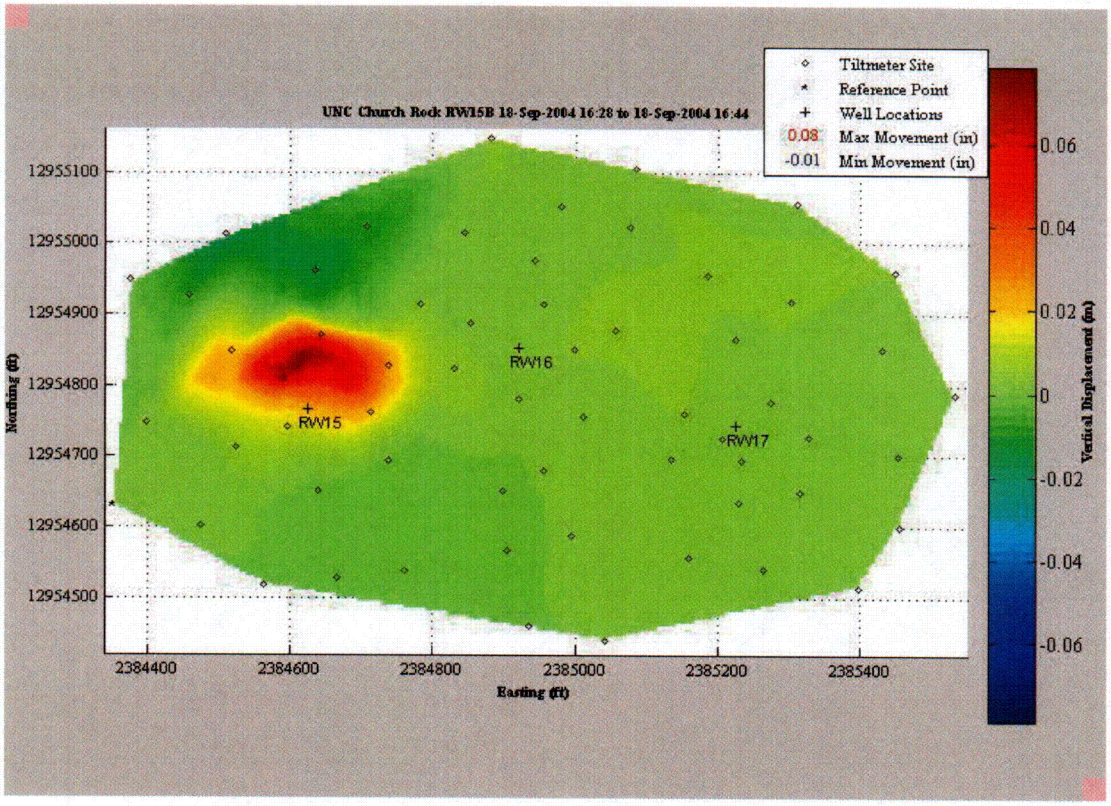


Figure 30. Maximum Surface Deformation for the treatment pumped in RW15 – Horizontal Fracture #2

C96

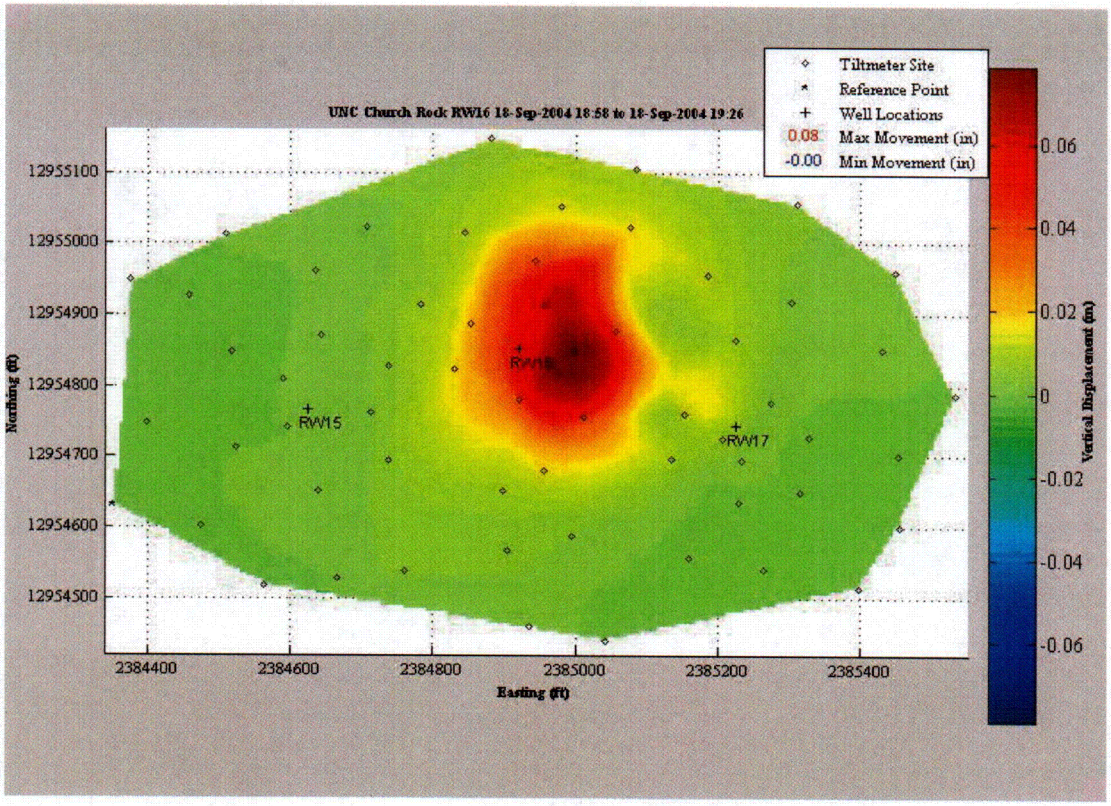


Figure 31. Maximum Surface Deformation for the treatment pumped in RW16

C97

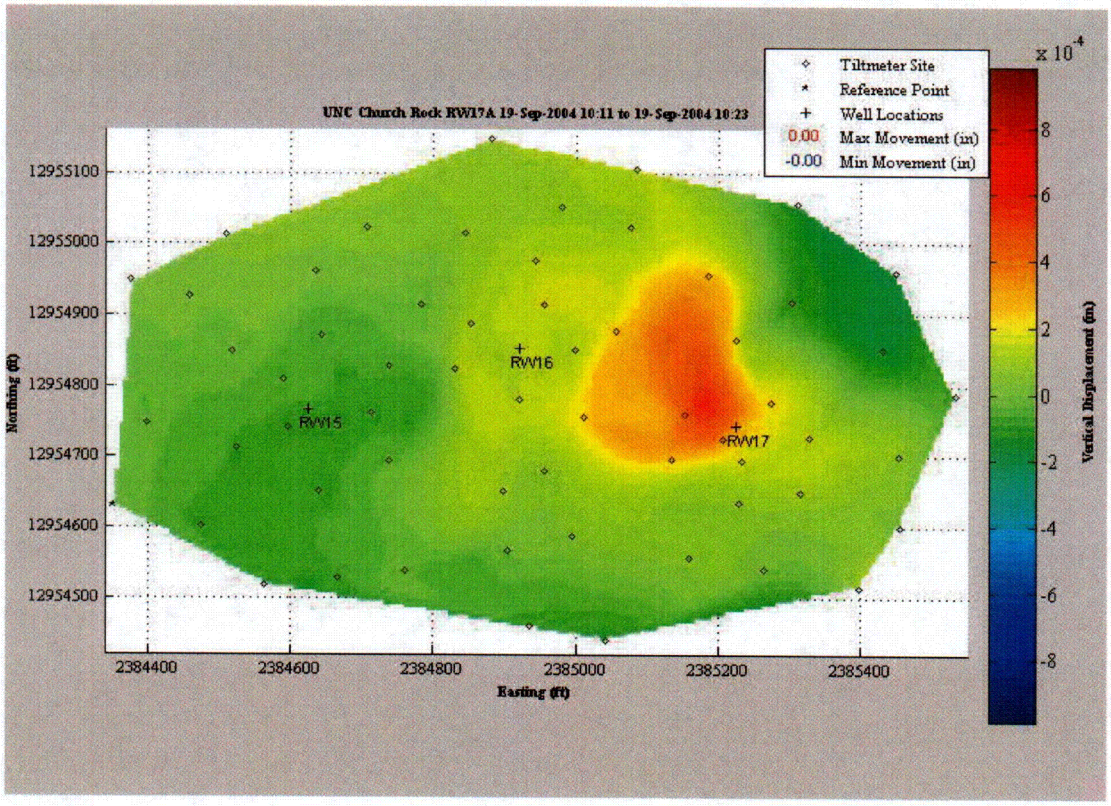


Figure 32. Maximum Surface Deformation for the treatment pumped in RW17 – Horizontal Fracture #1

C98

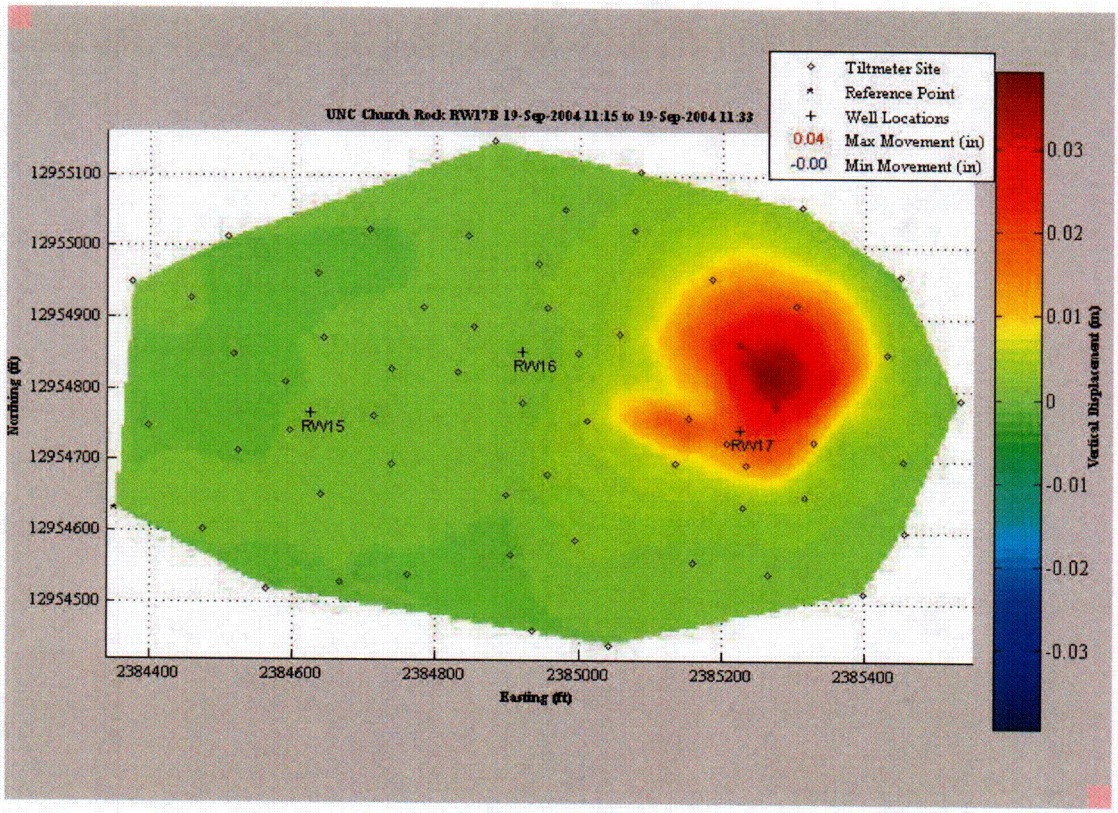


Figure 33. Maximum Surface Deformation for the treatment pumped in RW17 – Horizontal Fracture #2

C99