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Hydraulic-fracture growth in dipping anisotropic strata as viewed through the surface deformation field*

Gary R. Holzhausen
Applied Geomechanics Inc., 1336 Brommer, Santa Cruz, CA 95062

C.S. Haase and S.H. Stow
Environmental Sciences Division, Oak Ridge National Laboratory, P.O. Box X, Oak Ridge, TN 37831

George Gazonas
Center for Tectonophysics, Texas A&M University, College Station, TX 77843

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ABSTRACT

In 1983 and 1984 Oak Ridge National Laboratory conducted a series of precision ground deformation measurements before, during, and after the generation of several large hydraulic fractures in a dipping member of the Cambrian Conasauga Shale. Each fracture was produced by the injection of approximately 500,000 L of slurry on a single day. Injection depth was 300 m. Leveling surveys were run several days before and several days after the injections. An array of eight high-precision borehole tiltmeters monitored ground deformations continuously for a period of several weeks. Analysis of the leveling and the tilt measurements revealed surface uplifts as great as 25 mm and tilts of tens of microradians during each injection. Furthermore, partial recovery (subsidence) of the ground took place during the days following an injection, accompanied by shifts in the position of maximum resultant uplift. Interpretation of the tilt measurements is consistent with stable widening and extension of hydraulic fractures with subhorizontal orientations.

Comparison of the measured tilt patterns with fracture orientations established from logging of observation wells suggests that shearing parallel to the fracture planes accompanied fracture dilation. This interpretation is supported by measured tilts and ground uplifts that were as much as 100 percent greater than those expected from fracture dilation alone. Models of elastically anisotropic overburden rock do not explain the measured tilt patterns in the absence of shear stresses in the fracture planes. This work represents the first large-scale hydraulic-fracturing experiment in which the possible effects ~~of material anisotropy and fracture~~-parallel shears have been measured and interpreted.

1 INTRODUCTION

At Oak Ridge National Laboratory (ORNL) low-level liquid nuclear wastes are routinely disposed of by mixing them with cement and

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injecting the slurry under pressure into highly impermeable shale at a depth of 300 m. Past experience has shown that the slurry spreads radially from the injection well to form thin sheets millimeters to centimeters thick approximately parallel to bedding planes and then sets to form a grout. During 1983 and 1984, efforts were made to develop methods of mapping the sizes and orientations of the subsurface grout sheets. This work was motivated by a need to verify that geologic isolation had occurred. This paper represents work done in 1983 and 1984 in measurement of surface deformation resulting from the injections and an assessment of the effectiveness of leveling and tiltmeter surveys for mapping the grout sheets.

2 THE HYDROFRACTURE PROCESS

The disposal process is termed "hydrofracturing" because it is based on the same principle underlying the method used by the petroleum industry to fracture reservoir rocks to increase oil and gas production. At ORNL the objective is to provide geologic containment of nuclear wastes. The process has been used for waste disposal at ORNL for almost two decades. Over 1.5 million curies of radionuclides has been disposed of; Sr^{90} and Cs^{137} are the principal nuclides. A complete description of the process and site selection considerations are found in de Laguna et al. (1968).

The process at ORNL is a large-scale batch operation. The wastes are mixed with cement and other additives, such as illite, which helps retard nuclides by sorption, forming a slurry that is pumped down the cased injection well. The casing is slotted at the bottom of the well so that the slurry can be injected into the shale.

Prior to injection of the slurry, fracturing of the shale is initiated by injection of several thousand liters of water. Because the shale is finely bedded and structurally anisotropic and because the depth of the injection is relatively shallow, the fractures follow bedding planes which dip about 15° SE at the site. The diameters of the grout sheets are up to a few hundred meters; the minimum dimensions of the grout sheets can be determined by gamma-ray logging of the cased observation wells. Systematic logging of observation wells at two former hydrofracture sites and at the current site provides postinjection verification that the grout sheets are subparallel to bedding planes. The grout sheets are known to branch in places, but the branches tend to parallel each other at slightly different depths. Logging and coring of the grout sheet produced in an experimental, nonwaste-bearing hydraulic-fracturing experiment at ORNL revealed that the grout had cut about 15 m upward across bedding planes to the southeast (down-dip) of the injection point. The upward migration was apparently in steps, with the subhorizontal portion of each step parallel to bedding. This first injection was at a depth of 88 m.

3 GEOLOGIC SETTING

The ORNL hydrofracture site is located in the Valley and Ridge province of the Appalachian orogenic belt. The Valley and Ridge province in east Tennessee is characterized by a series of regional thrust faults that strike northeast-southwest and extend from Alabama to Virginia. Motion along these thrust faults during the Alleghanian orogeny (approximately 250 m.y. ago) resulted in southeast-to-northwest crustal shortening of approximately 100 to 150 km. This shortening resulted in the formation of a series of imbricate thrust fault blocks that repeat a stratigraphic package of sandstones, shales, and carbonates as many as seven times within the province.

The ORNL site is located on the leading edge of the Copper Creek fault block. Strata at the site strike N 45° to 55° E and dip 10° to 20° to the southeast. They consist of sandstones, shales and limestones, and dolostones of the Rome Formation, the Conasauga Group, and the Knox Group, respectively. Injections from the ORNL hydrofracture facility are made into the Pumpkin Valley Shale, which is the basal formation of the Conasauga Group. At the site, the Pumpkin Valley Shale is 100+10 m thick and consists of complexly interstratified, thinly bedded siltstones, laminated shales with siltstone stringers, and massive mudstones. The formation contains a pervasive structural fabric defined by multiple joint sets and several generations of folds and faults (Haase et al., 1985).

4 THE 1983 DEFORMATION MEASUREMENT PROGRAM

4.1 Leveling

Ground surface uplift resulting from slurry injection was monitored with a network of 75 benchmarks surrounding the injection well. Some benchmarks were located around the facility to distances of 650 m on roads extending radially outward from the well. The remainder of the benchmarks were placed within 200 m of the injection well at the nodes of a 60-m orthogonal grid centered at a point directly above the bottom of the well. Leveling was performed with an AGA Geodimeter, Inc., electronic-total-station surveying instrument (Model No. 140). For reference, the benchmark network was tied into U.S. Coast and Geodetic Survey benchmarks located 0.75 km from the injection well. Instrument precision and survey technique allowed leveling measurements to be made within +1.0 mm. To measure surface deformation associated with slurry injection, three leveling surveys of the benchmark network were made. A preinjection base-line survey was made approximately 5 to 10 days before an injection. Subsequently, two postinjection surveys were made, one at 5 to 10 days after the injection and another at 30 days after the injection.

4.2 Tiltmeter Measurements

Tiltmeters measure the rotational component of the deformation field induced by the inflation and growth of a hydraulic fracture. The first use of tiltmeters for this purpose was at ORNL in 1960 (Riley, 1961). A review of the tiltmeter method of fracture mapping is given in Evans (1983) and Evans and Holzhausen (1983). In this project, eight biaxial borehole tiltmeters were deployed in an array designed to resolve the general form of the tilt field produced by each slurry injection and to detect radial growth of the grout-filled hydraulic fractures. The tiltmeters were positioned on two concentric rings with radii of 120 and 183 m from the subsurface injection point (Figure 1). Because maximum tilts for horizontal and vertical fractures occur at a radial distance from the injection point equal to about 40 percent of the depth to the center of the fracture (Evans, 1983), the tiltmeters on the inner ring were expected to record the greatest tilts during the injections. Applied Geomechanics Inc. Model AGI-500 tiltmeters were used. These instruments have a resolution of about 5 nrad.

Tilt measurements were recorded digitally to 16 bits of precision on a microcomputer housed in an instrumentation trailer on site. Data were collected every 30 seconds during periods of slurry injection. During the period between injections (October 27-November 27, 1983), data were collected every 10 minutes.

5 DESCRIPTION OF SLURRY INJECTIONS, OCTOBER - DECEMBER 1983

The first injection monitored with tiltmeters took place on October 25 and 26, 1983. Slurry was injected for approximately 10 hours on both of these days. Approximately 475,000 L was injected each day. During most of the pumping time, injection rates remained quite constant between 815 and 850 L of slurry per minute. At the beginning and end of each day's pumping, 1,500 to 2,000 L of water was injected as part of breakdown and cleanup procedures.

The injection scheduled for November 29 began with the pumping of 2,300 L of water to break down the formation. The following day over 40,000 L of liquid waste had been injected when the transmission on the main pump failed. Approximately 387,000 L of slurry were injected on December 1, followed by flushing of the well with roughly 3,200 L of water. On December 2 pumping began with the injection of about 3,000 L of water, followed by the injection of 317,000 L of slurry. This injection was followed by a 3,200 L flush of water. Wellhead pressures during both the October and the November-December injections were about 20 to 25 MPa (3,000 to 3,500 psi).

6 RESULTS OF LEVELING AND TILTMETER MEASUREMENTS

6.1 Leveling

Leveling measurements were made in 1983-1984 for seven hydrofracture injections. Typically, net uplifts, determined by the leveling survey 5 days after the injection, ranged from 20 to 25 mm for a region within 75 m of the injection well. At 75 to 300 m of the well, net uplifts ranged from 5 to 10 mm. At greater distances, uplift values were 5 mm or less. Uplifts determined by the second leveling survey showed that 40 to 60 percent of the original net uplift decayed within 30 days of the injection. Thus, 30 days after an injection, maximum net uplifts within 75 m of the injection well were 8 to 14 mm. Similarly, between 75 and 300 m of the well, net uplifts were 0 to 5 mm. The shape of net uplift patterns varied substantially from injection to injection. However, most patterns were elliptical in shape and asymmetric with respect to the injection well. In several cases, the degree of asymmetry decreased substantially within the 30-

day postinjection period so that the uplift determined by the second leveling survey was nearly symmetrical with respect to the injection well. Contours of uplift 5 days and 30 days after the October 25-26, 1983, injection are shown in Figures 2 and 3.

6.2 Tiltmeter Measurements

Unlike leveling measurements, which provide a "snapshot" of the surface uplift several days after slurry injection, tiltmeters produce a continuous record of the changing pattern of surface deformation during an injection. The difference between the vector tilts measured at the beginning and at the end of an injection also provide an image of the net surface deformation that has occurred during this period.

Surface tilt changes at ORNL resulting from the injection of slurry or water, or from stopping such injection, were large and "instantaneous." That is, they were easily resolvable above background noise and occurred within 30 seconds, which was the sampling interval used during the main injections. A test of the sensitivity of the tiltmeter array to small injections was provided on the evening of November 29 when 2,300 L of water was injected over 4 minutes to break down the formation prior to slurry injection the following day. Every instrument in the array responded to this small injection, defining a clear pattern of surface uplift surrounding the injection well (Figure 4).

There was a great deal of similarity in the surface tilt patterns produced on each of the 5 days of slurry injection monitored with the tiltmeters. In general, each instrument recorded steady tilting in one direction (Figure 5), although when the data were examined in detail, it was found that the pattern of surface deformation and the center of uplift shifted continuously throughout the day. The tilt changes resulting from pumping on October 26 were fairly representative of the general pattern observed on each day of slurry injection. The tilt vectors indicated that the center of uplift was to the northwest of the subsurface injection point and slightly elongated in a northeast-southwest direction (Figure 6).

Tilt changes on a normal day of pumping at ORNL were large with respect to the resolution of the instruments. Average tilts for the entire array were 10 μrad or greater on each full day of pumping. It was also observed that the mean rate of tilt, measured in microradians per liter pumped, increased during the course of each injection. The tilt rate was greater on the second day of a 2-day injection, and the rate increased throughout the day on any single day of pumping. Table 1 gives volumes pumped, mean tilts, and tilt rates for each of the 5 days of slurry injection.

Tiltmeter data were recorded continuously during the month between the October and the November-December injections. They revealed partial subsidence along an east-west zone centered slightly north of the subsurface injection point. We infer that this subsidence caused a shift of the resultant center of uplift from a point slightly north of the injection well to a point slightly south of the well, where it was detected by the leveling surveys (Figures 2 and 3).

7 INTERPRETATION OF RESULTS

The orientation and position of a hydraulic fracture can be estimated from ground displacements and tilts by comparing these measurements with those of elastic models of ground deformation resulting from fracture dilation in a homogeneous medium (Davis, 1983). This procedure was used to make an initial interpretation of the tilt patterns measured at ORNL. Evidence of grout sheet positions from gamma ray logs of observation wells was then used to refine this interpretation and to draw several conclusions about the mechanical behavior of the rocks at the hydrofracture facility during slurry injection.

Dilation of a horizontal hydraulic fracture produces uplift of the ground that is greatest at a point above the center of the fracture (Evans, 1983). For a gently dipping fracture, uplift of the ground surface is greatest at a point where a line perpendicular to the fracture center intersects the surface (Figure 7). The fact that the tilt measurements indicated that uplift centered to the north of the injection well (Figure 6) suggested that the grout sheets dipped to the north. This conclusion was not supported, however, by logs of the cased observation wells surrounding the injection well. These logs indicated that the grout sheets dipped 6° to 9° to the southeast (Table 2). Apparently, some process besides fracture dilation was contributing to the measured tilt pattern.

The observation from well logs (Table 2) that the hydraulic fractures at ORNL have a southerly dip suggests that there may be a component of shear in the fracture plane. In general, near-surface trajectories of principal stresses in the crust are considered to be orthogonal to the ground surface. Thus, horizontal crustal compression at ORNL should induce shears along the inclined hydraulic-fracture planes. The magnitude of this shear stress is difficult to estimate because no measurements of in situ crustal compression have been made in the Oak Ridge area. However, horizontal compressive stresses of 10 to 40 MPa have been measured at shallow depths elsewhere in the Appalachian province (Hooker and Johnson, 1969), and these stress magnitudes might also be expected at Oak Ridge.

Horizontal compressions of 10 to 40 MPa will give rise to shear stresses of about 0.5 to 4.5 MPa in the planes of fractures dipping at 6° to 9°, after subtracting shear stresses of opposite sense induced by the weight of the overburden. The pattern of ground deformation resulting solely from shear in the fracture plane would be one of uplift to the north of the injection well and relative subsidence to the south (Figure 8). Adding this effect to the ground displacements produced by fracture dilation can explain the deformation field measured by the tiltmeters at the end of each day of slurry injection.

Additional evidence supporting the hypothesis that shears parallel to the grout sheets contributed to surface deformations is based on the magnitudes of tilts that were measured. In general, measured tilts were 20 to 100 percent greater than those predicted theoretically using an isotropic elastic model (Davis, 1983) of purely dilatational fractures with volumes equivalent to the volumes injected at ORNL. Again, a simple explanation may be that surface uplift produced by fracture dilation was augmented by uplift induced by shear in the fracture plane.

As described in Section 2 of this paper, the southeastern (down-dip) end of the grout sheet produced in the first injection at ORNL cut upward across bedding. Bedding-parallel shear stresses would have induced tensions in this area (Pollard and Holzhausen, 1979), which might explain the observed behavior.

A further test of the shear hypothesis was provided by computing surface tilts caused by fracture dilation in a transversely isotropic half space (Gazonas, 1985). The thought was that mechanical anisotropy of the sedimentary rocks at the hydrofracture site may have been responsible for the differences between tilts measured and those predicted assuming elastic isotropy of the overburden (Davis, 1983). The transversely isotropic model was run using a variety of hydrofracture and layering orientations and elastic constants approximating conditions at ORNL. These computations revealed numerous minor changes in the predicted pattern of surface deformation, but all showed maximum uplift to the south of the injection point. These results provide further evidence that fracture opening at ORNL is not purely dilational.

Subsidence of the ground surface following the completion of slurry injection (Figures 2 and 3) is thought to result from redistribution of grout in the vicinity of the fracture plane, possibly by flow into small joints and cracks, and mechanical readjustment of the overburden rock. The relative contribution of these two effects and the physical processes at work are not currently known. The reason for the measured shifts in the position of maximum surface uplift following an injection is also not understood.

The observation that the rate of surface tilt increased as each injection progressed may hold important clues to the mechanical behavior of the overburden during hydrofracturing at ORNL. A possible explanation is that cracks and joints in the rock close up as the fracture opens. The overburden thus becomes progressively less compressible, and more of the deformation associated with fracture opening is transmitted to the ground surface.

8 CONCLUSIONS

1. Leveling and tiltmeter surveys during periods of slurry injection at ORNL measured ground surface uplifts as great as 25 mm and surface tilts of tens of microradians. These results were consistent with stable widening and extension of hydraulic fractures with subhorizontal orientations. The surveys detected no evidence of large-sc~~ale vertical fracture growth.~~

2. Tilt patterns measured during each injection suggest that shear displacement in the dipping fracture planes contributed to the total surface deformation field.

3. Evidence for time-dependent, apparently nonlinear processes was provided by the surface deformation measurements. This evidence includes tilt rates that increased over time while pumping rates

remained constant, and nonuniform subsidence of the ground surface following each injection.

4. Tiltmeter measurements and leveling surveys are both effective methods for estimating fracture orientation if an appropriate model for overburden deformation is chosen. Tiltmeter measurements have the advantage of providing a real-time indication of hydraulic-fracture behavior during growth. Leveling provides an absolute measure of net overburden uplift at different points in time following an injection.

5. It should be possible to "calibrate" existing surface deformation models to reflect conditions specific to the ORNL hydrofracture site (e.g., transversely isotropic, gently dipping strata; both dilation and shear in hydrofracture planes). Such models can then be used to interpret tiltmeter measurements on a continuous basis during pumping, providing instantaneous feedback to ensure that geologic containment of the injected wastes is maintained.

9 ACKNOWLEDGEMENTS

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Fig. 1. Topography of ORNL hydrofracture facility (contours in feet) and geometry of tiltmeter array.

Fig. 2. Uplift pattern approximately 5 days after the October, 1983 injection.

Fig. 3. Uplift pattern approximatly 30 days after the October, 1983 injection.

Fig. 4. Tiltmeter response to 2,300-L water injection (tiltmeter channel 3x). Vertical axis is tiltmeter response and the horizontal axis is clock time, in hours.

Fig. 5. Tiltmeter response to slurry injections on October 25 and October 26, 1983 (tiltmeter channel 4x).

Fig. 6. Vector tilts for the period 1526 to 2017 during the October 26, 1983 injection.

Fig. 7. Normalized ground surface tilt response to dilation of a fracture dipping at 10° in an isotropic elastic half space. Greatest uplift occurs where tilt=0 at x/d=0.1. Fracture center is at x/d=0; d/a=2.0. Tilts have been normalized by dividing by internal pressure P and by Q, a function of shear modulus of the material. Plane strain solution.

Fig. 8. Normalized ground surface tilt response to shear T of a fracture dipping at 10° in an isotropic elastic half space. Fracture center is at x/d=0; d/a=2.0. Maximum uplift occurs at x/d=-0.5. Least uplift occurs at x/d=0.8. Plane strain solution.

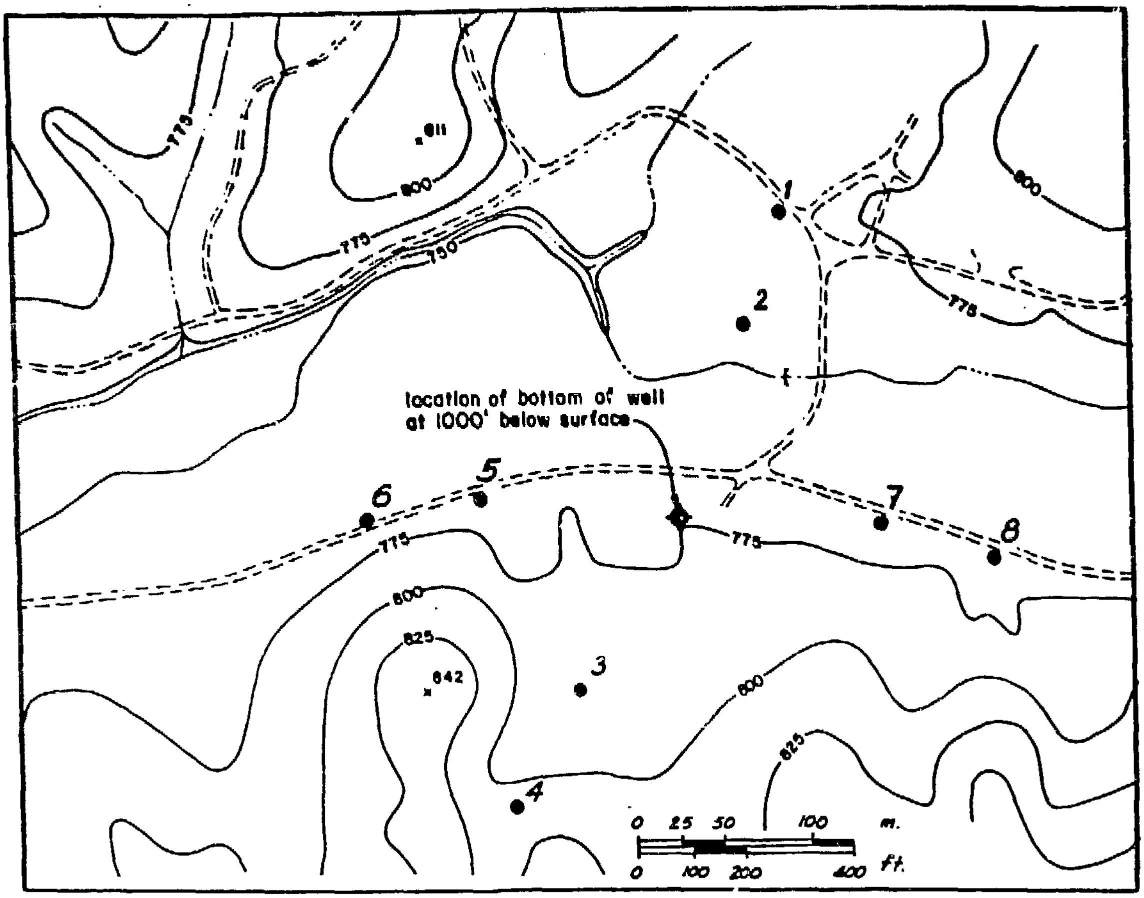
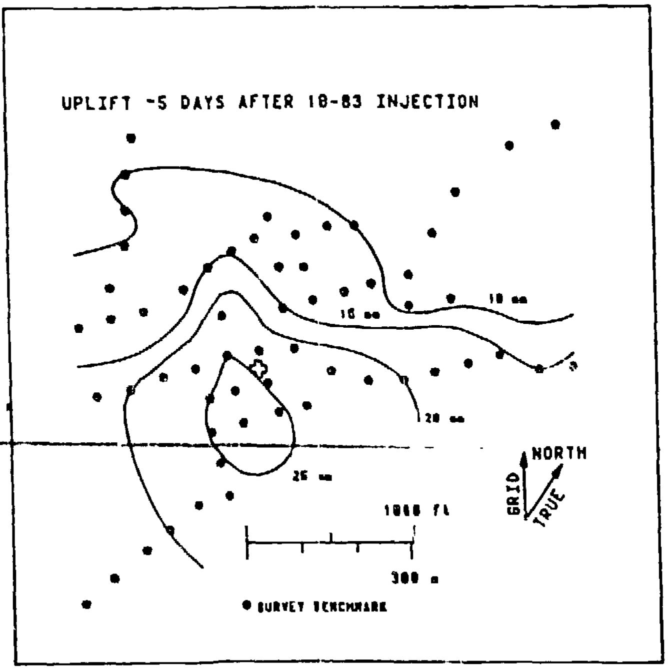

775
811
800
775
750
1
2
800
775
location of bottom of well
at 1000' below surface
5
6
7
8
775
775
800
825
842
3
800
825
4
0 25 50 100 m.
0 100 200 400 ft.

Fig. 1


UPLIFT ~5 DAYS AFTER 10-83 INJECTION
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20 mm
25 mm
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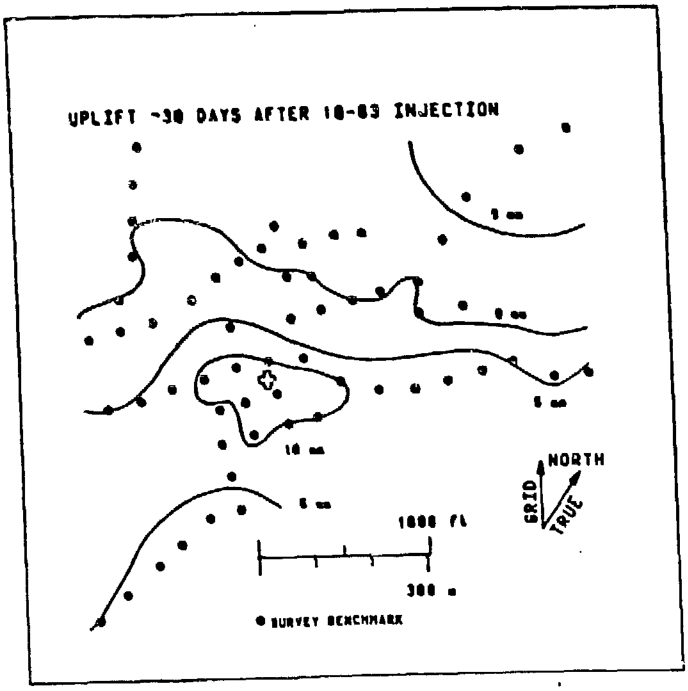
1000 ft
300 m
● SURVEY BENCHMARK

Fig. 2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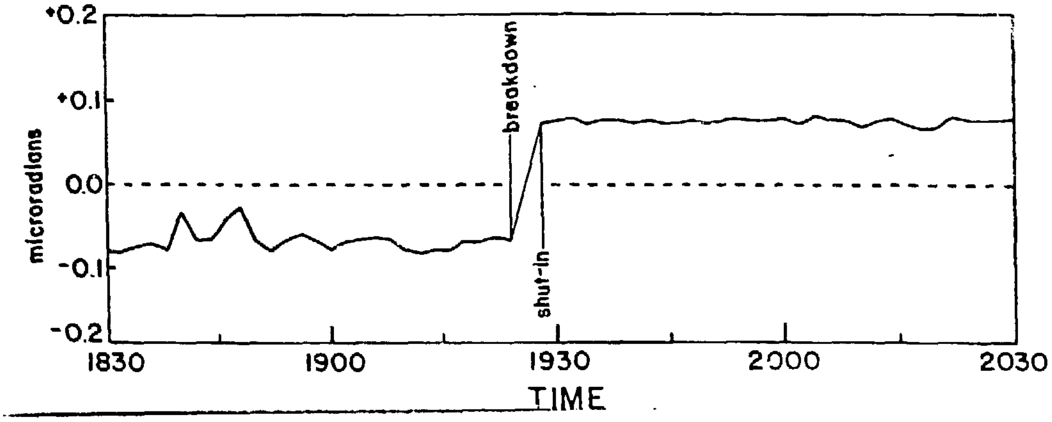
SURVEY BENCHMARK

Fig. 3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-0.2
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breakdown
shut-in
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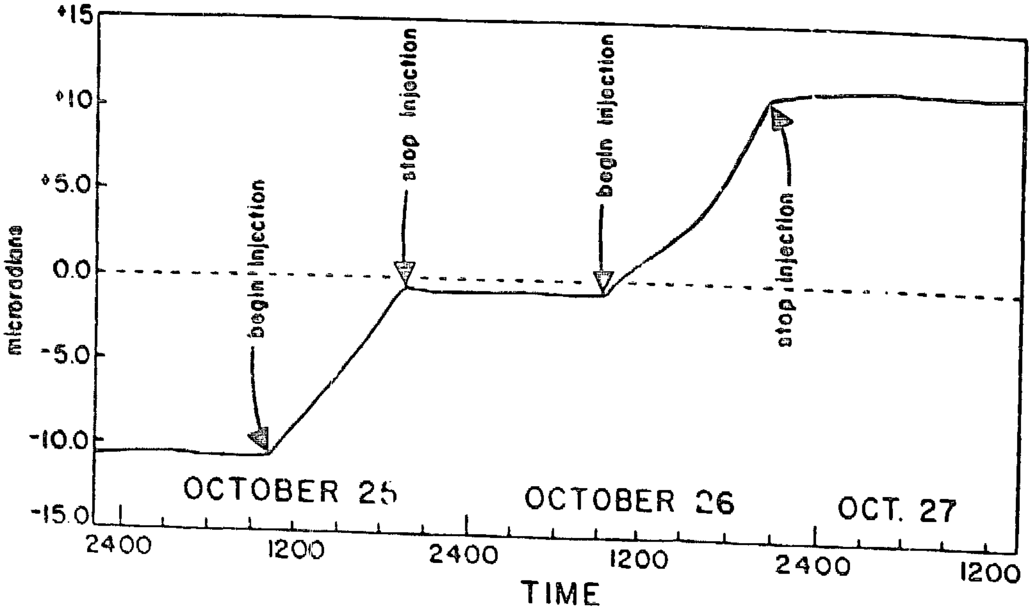
1930
2000
2030
TIME

Fig. 4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+10
+5.0
0.0
-5.0
-10.0
-15.0
microradians
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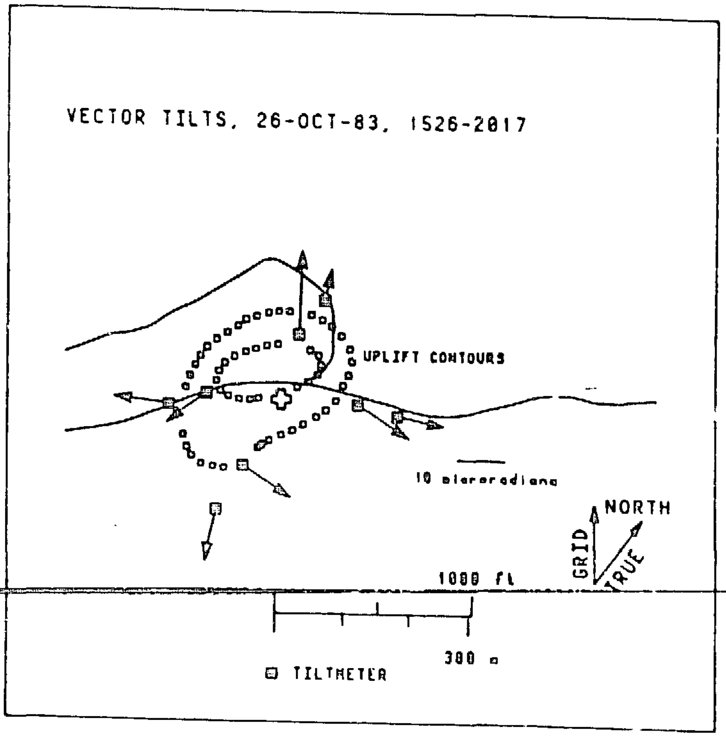
stop injection
begin injection
stop injection
OCTOBER 25
OCTOBER 26
OCT. 27
2400
1200
2400
1200
2400
1200
TIME

Fig. 5


VECTOR TILTS, 26-OCT-83, 1526-2017
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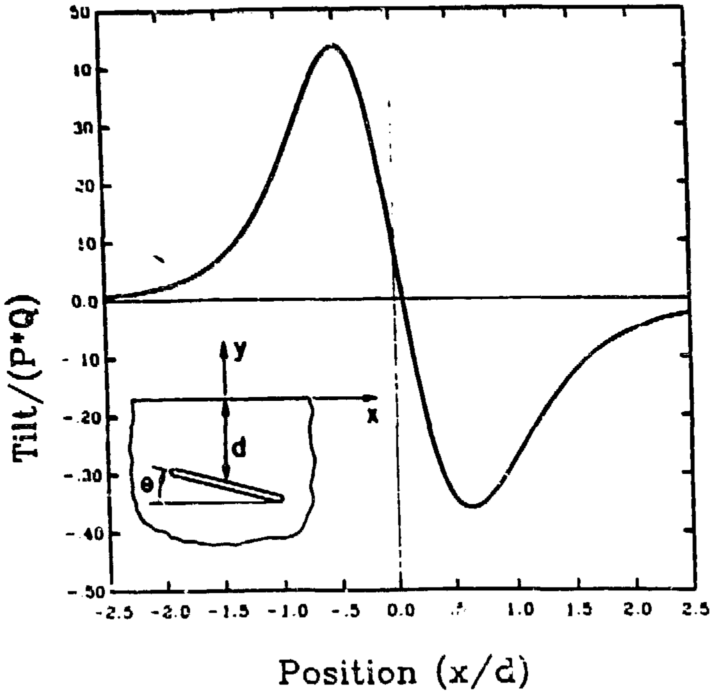
GRID
TRUE
1000 ft
300 m
⊡ TILTMETER

Fig. 6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Tilt/(P*Q)
Position (x/d)
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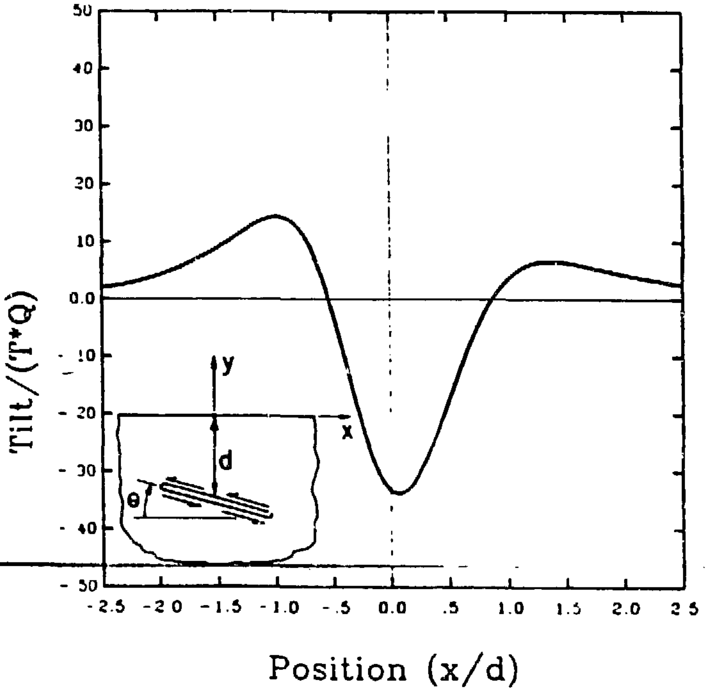
d
θ

Fig. 7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-50
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-2.0
-1.5
-1.0
-.5
0.0
.5
1.0
1.5
2.0
2.5
Tilt/(T*Q)
Position (x/d)
y
x
d
θ

Fig. 8

Table 1. Mean Tilt Magnitudes for Different Periods of Grout Injection

Date	Time	Mean Tilt Magnitude For Total Array (μradians)	Approx. Volume Pumped (liters)	Mean Tilt Rate (μradian/ltr.)
Oct. 25	1004-1924*	9.70	456,200	2.13x10^{-5}
Oct. 26	0916-1526	8.53	286,400	2.99x10^{-5}
	1526-2017	8.84	217,900	4.07x10^{-5}
	0916-2017*	17.27	504,300	3.43x10^{-5}
Nov. 30	1031-1120	1.40	45,400	3.09x10^{-5}
Dec. 01	0823-1100	3.50	147,600	2.37x10^{-5}
	1100-1535	6.80	259,300	2.62x10^{-5}
	1535-1845	6.48	177,900	3.65x10^{-5}
	0823-1845*	16.78	584,700	2.87x10^{-5}
Dec. 02	0852-1545*	14.44	321,700	4.49x10^{-5}

* Full Day

Table 2. Strike and Dip of Grout Sheets from Solution of 3-Point Problem for Observation Wells W200, S200 and E200.

	October Injection	November-December Injection
Strike	N67E-N79E*	N74E
Dip	6°-9° SE*	6°SE
Depth at Injection Well	297m	297m
Minimum East-West Dimension (Horizontal Distance Between Intersection Points in W200 and E200 Wells)	141m	141m
Minimum North-South Dimension (Horizontal Distance Between Intersection Points in S200 and Injection Well)	46m	46m

* Referenced to ORNL grid north