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ENVIRONMENTAL SCIENCES DIVISION

PRECISE LEVELING DETERMINATION OF SURFACE UPLIFT PATTERNS AT THE NEW HYDRAULIC FRACTURING FACILITY, OAK RIDGE NATIONAL LABORATORY

C. Stephen Haase
Stephen H. Stow

Environmental Sciences Division
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ACKNOWLEDGMENTS

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ABSTRACT

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Surface uplift patterns were determined for five grout injections at the New Hydrofracture Facility (NHF) during the period July 1983 through January 1984. The uplift patterns are complex. In plan view, they are elliptical to almost circular and exhibit varying degrees of cross-sectional asymmetry with one side steeper than the other. The long axis of the ellipse is more or less parallel to geological strike. The uplift patterns vary in size, shape, and asymmetry from injection to injection. The region of maximum uplift is typically offset with respect to the injection point, suggesting that most hydrofracture injections dip to the south-southeast. Approximately 40 to 60% of the uplift measured 5 days after an injection subsided within 30 to 45 days. In one case, all of the uplift subsided within 70 days of injection. Modeling of the uplift patterns by simple models, based on homogeneous, isotropic subsurface conditions, suggests that hydofractures produced by the injections are either horizontal or have shallow dips to the south-southeast. Such orientations are consistent with the hydrofracture orientations determined by gamma-ray logging in observation wells surrounding the NHF site.

1. INTRODUCTION

1.1 THE HYDROFRACTURE PROCESS

Oak Ridge National Laboratory (ORNL) has disposed of low-level liquid radioactive wastes for over 20 years by a unique technology called hydrofracturing. The disposal process consists of subsurface injection of radioactive-waste-bearing cementitious grouts into hydraulically fractured intervals of a selected host formation. This formation, the Pumpkin Valley Shale, occurs at depths between 225 and 300 m (740 to 1000 ft) at the ORNL hydrofracture facility. The waste-bearing grout is injected through a slot cut in the bottom of a steel-cased well, and several injections may be made through one slot. Subsequent slots are cut at shallower depths so that over the lifetime of the hydrofracture facility, grout will be injected from the bottom to the top of the Pumpkin Valley Shale. Prior to waste injection, the well is pressurized with water to initiate a hydraulic fracture within the Pumpkin Valley Shale. After fracturing is initiated, waste-bearing cementitious grout is pumped down the well, which further propagates the hydraulic fracture. During subsequent pumping, the grout spreads out to form irregularly shaped sheets, which are typically <1 mm to several millimeters thick and extend outward from the injection well for distances of approximately 90 to 210 m (300 to 700 ft). Further details of the process are presented in deLaguna et al. (1968), IAEA (1983), Haase et al. (1985), Weeren et al. (1985), Stow et al. (1985), Stow and Haase (1986), and Haase and Stow (1987).

1.2 SURFACE DEFORMATION ASSOCIATED WITH HYDROFRACTURE

Hydraulic fracturing, even at depths of several hundreds of meters, causes slight, but measurable, deformation of the ground surface immediately over the fracture (Pollard and Holzhausen 1979; Davis 1983; Evans 1983). The shape and location of this ground deformation may reflect the orientation and extent of the hydraulic fracture (Davis 1983). By accurately measuring the surface deformation during a hydraulic fracturing event and comparing it to elastic models, the geometry and orientation of the subsurface hydraulic fracture may be estimated (Fig. 1).

Hydraulic fracturing technology is used to increase petroleum production by increasing the permeability of producing horizons. In such applications, the material injected during a hydraulic fracturing event is largely fluid with only a small amount of solids to serve as proping agents to help keep fractures partially open after the process is completed. Because much of the injected fluid leaves the vicinity of the fracture within hours to days of completion, the permanent surface deformation associated with a typical "oil field" hydraulic fracturing event is small, even though the surface deformation during the event may be much larger (Evans 1983; Evans and Holzhausen 1983).

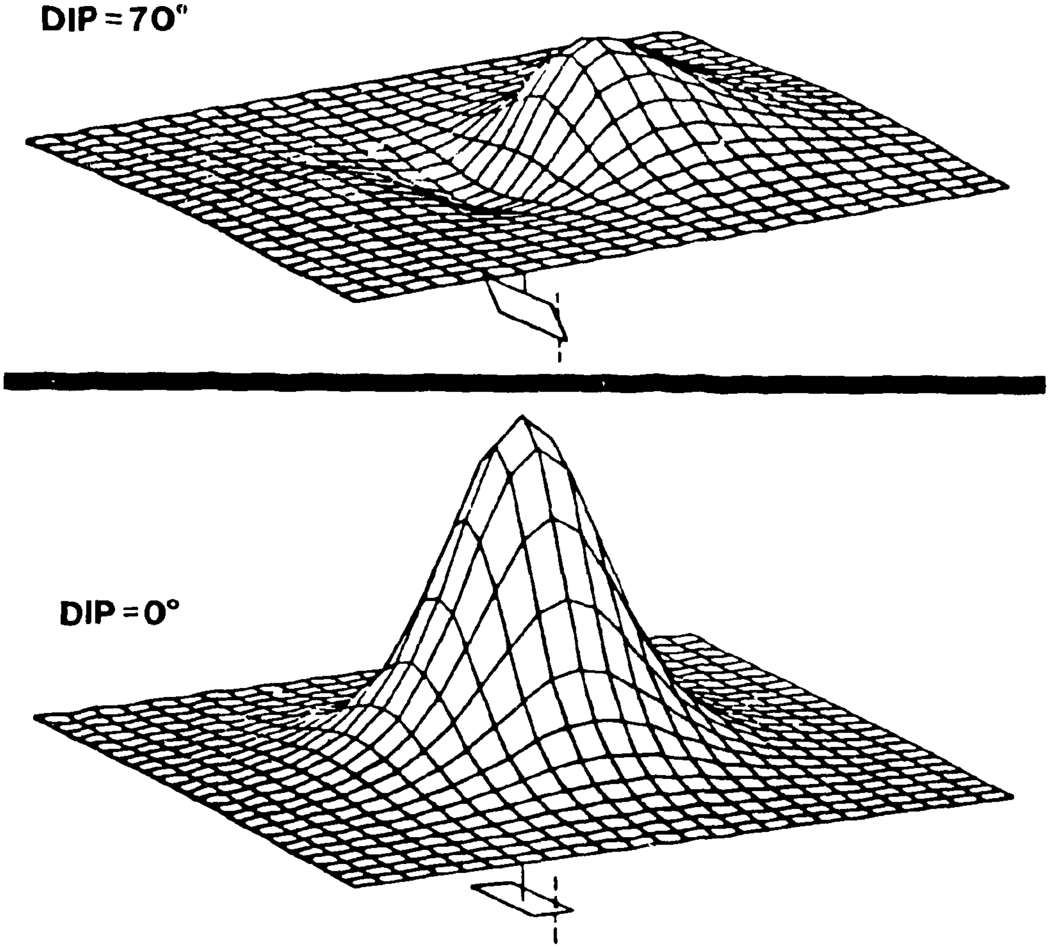

Fig. 1. Hypothetical surface deformation associated with subsurface hydraulic fractures (adapted from Pollard and Holzhausen 1979).

When waste-bearing grouts were injected at depths of approximately 305 m (1000 ft) at the ORNL hydrofracture facility, slight, but measurable, ground deformation occurred (deLaguna et al. 1968; Stow et al. 1985). In contrast to "oil field" hydraulic fracturing operations, however, the grout injected at the ORNL hydrofracture facilities solidified within the fractures, occupying some of the hydraulic fracture volume. Consequently, there are significant long-term surface deformations (deLaguna et al. 1968; Stow et al. 1985; Stow and Haase 1986).

Surface deformation associated with hydraulic fracturing can be measured by tiltmeters and by precise leveling. Tiltmeters give accurate data about the rate and direction of surface uplift during an injection, whereas precise leveling gives data about the extent and shape of the surface deformation pattern.

Recent research at the New Hydrofracture Facility (NHF) at ORNL has focused on measurement of surface deformation by both techniques (Stow et al. 1985; Stow and Haase 1986) in an attempt to initiate development of techniques for monitoring the orientation and extent of the grout sheets.

1.3 APPLICATION OF SURFACE DEFOR ATION TO MONITORING OF HYDROFRACTURE INJECTIONS

To verify that the injected waste-bearing grout sheets do not extend beyond the Pumpkin Valley Shale, it is necessary to determine both the orientation and the size of the grout sheets produced by hydrofracture injections. Because the ground deformation associated with hydraulic fracturing is related to the orientation of the fracture, measurement of ground deformation patterns at the ORNL hydrofracture facilities offers the potential for determining one of the key pieces of information needed to verify that the grout sheets have remained within the Pumpkin Valley Shale.

This report presents the results of precise leveling measurements made during a series of injections from July 1983 through January 1984 at the NHF. The precise leveling measurements were conducted in conjunction with tiltmeter measurements in an attempt to determine the nature of ground deformation associated with waste-bearing grout injections. Preliminary results from leveling measurements at the NHF are presented in Stow et al. (1985), Holzhausen et al. (1985), and Stow and Haase (1986). Details of the tiltmeter measurements and preliminary interpretation of the results are presented in Holzhausen (1984).

2. PREVIOUS LEVELING STUDIES

Prior to the initiation of routine waste disposal operations at the Old Hydrofracture Facility (OHF) in 1965, two hydrofracturing experiments were conducted to evaluate the technology. Precise leveling measurements of the surface uplift associated with test injections at the two experimental sites were obtained. Leveling measurements of surface uplift at the OHF were also obtained throughout the life of that facility.

2.1 FIRST AND SECOND EXPERIMENTAL SITES

The details and results from the first and second hydrofracture experiments are summarized in deLaguna (1961) and deLaguna et al. (1968). In both experiments, the surface deformation patterns associated with grout injection were measured by precise leveling. The leveling measurements were made using a series of benchmarks installed in four radial arms, centered on the injection point for each experiment and extending outward to distances of between 150 to 305 m (500 and 1000 ft).

2.1.1 First Experimental Site

One test injection was conducted at the first experimental site. Approximately 100,000 L (27,000 gal) of grout were injected at a depth of 90 m (290 ft) below ground level. Surface uplifts were determined by leveling measurements after the injection, using a series of benchmarks installed in four radial arms, centered on the injection well and extending outward to distances of 150 m (500 ft). A test drilling program involving 18 boreholes was conducted to determine the extent and orientation of the grout sheet.

Surface uplift values ranged from 3.0 mm (0.12 in.) immediately over the injection point to 1.5 mm (0.06 in) at distances within 60 m (200 ft) of the injection point (Fig. 2); measurable uplift was noted up to 90 m (300 ft) from the injection well (deLaguna 1961; deLaguna et al. 1968). Although the arrangement of the benchmarks did not allow an accurate three-dimensional measurement of the surface uplift pattern to be obtained, the shape of the uplift pattern appeared to be symmetrical, approximately circular, and centered over, or slightly offset to the north of the injection point (deLaguna 1961). Drilling results indicated, however, that the sheet is asymmetrically oriented with respect to the injection well, with the majority of the sheet extending to the north and northeast of the injection point (deLaguna et al. 1968). Thus, the leveling data indicate that a significant amount of surface uplift was associated with the injection, especially within 30 m (100 ft) of the injection well, and that significant surface uplift occurred to the west of the injection well, in areas where the grout sheet was absent (deLaguna 1961; deLaguna et al. 1968).

Detailed interpretation of the shape and location of the surface uplift associated with the grout sheet is difficult because of the poor quality of the data. Application of the theoretical results of Pollard and Holzhausen (1979), Davis (1983), and Evans (1983) to the uplift pattern suggests that the grout sheet should be more or less symmetrically distributed with respect to the injection point and that its orientation is approximately horizontal. Information obtained from the core drilling, however, indicated that the grout sheet dips approximately 15 to 20° to the southeast and is distributed asymmetrically with respect to the injection point. The regional dip of the Pumpkin Valley Shale at the site varies from 10 to 20° to the southeast. Observations from drill core suggest that the grout sheet is oriented essentially parallel to bedding features within the Pumpkin Valley Shale (deLaguna 1961; deLaguna et al. 1968)

2.1.2 Second Experimental Site

Two injections were made at the second experimental site, which is approximately 1.8 km (6000 ft) east of the first site. The first injection was made at a depth of 280 m (934 ft) on September 3, 1960, and consisted of approximately 340,000 L (90,000 gal) of grout slurry. The second injection was

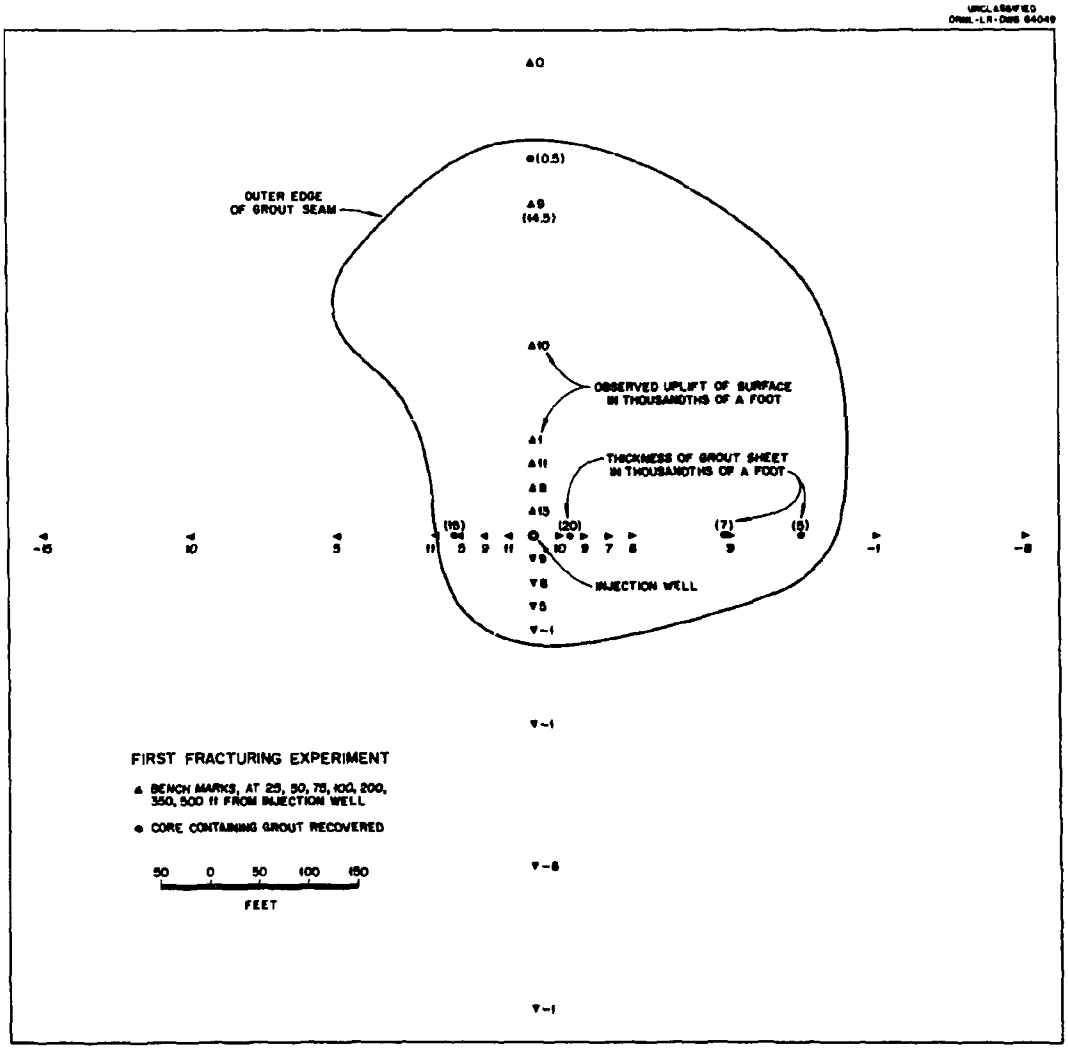

Fig. 2. Surface uplift pattern and extent of grout sheet at the first experimental site, October 1959 (from deLaguna 1961). Outer edge of grout sheet illustrated is inferred from core drilling. (1 ft=0.3048 m)

made at a depth of 210 m (694 ft) on September 10, 1960 and consisted of approximately 500,000 L (133,000 gal) of grout. As with the first experiment, surface deformation was measured with a series of benchmarks installed in six radial arms, centered on the injection point and extending outward to distances of 360 m (1200 ft). Approximately 40 core holes were drilled at the site of the second experiment to determine the extent and orientation of the two grout sheets.

Surface uplifts were measured by precise leveling after both injections. Values obtained ranged from 12.7 mm (0.50 in.) immediately over the injection point to 1.5 mm (0.06 in.) at distances within 150 m (500 ft) of the injection point (Fig. 3); measurable surface uplift extended as far as 210 m (700 ft) from the injection well (deLaguna 1961; deLaguna et al. 1968). As with the first experiment, the

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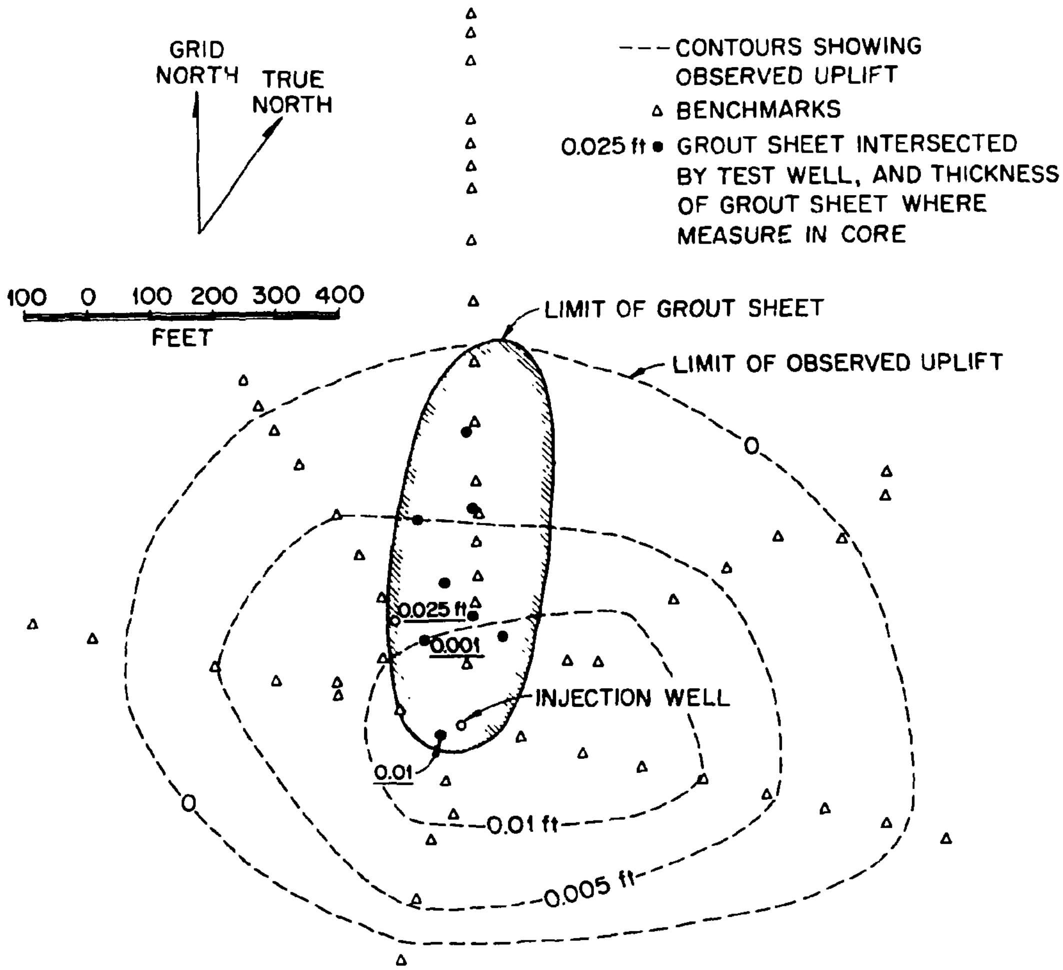

Fig. 3. Surface uplift pattern and extent of grout sheet for the first test injection at the second experimental site, September 1960 (from deLaguna et al. 1968). Grout sheet resulting from this injection is referred to as the lower grout sheet. Limit of grout sheet inferred from core drilling. (1 ft=0.3048 m)

nature of the benchmark array limited the ability of the leveling techniques to determine the three-dimensional shape of the uplift pattern. The general character of the leveling data indicated, however, that each injection was associated with a significant amount of surface uplift that extended well beyond the extent of the grout sheet, as determined by subsequent core drilling. In the first injection, the central portion of the uplift pattern is circular to slightly elliptical and approximately centered on the injection point (Fig. 3). The outer portions of the uplift pattern exhibit a pronounced east-to-west ellipticity but are still centered on the injection point. Core drilling data indicate, however, that the grout sheet associated with this injection is highly elongate in the north-south direction and extends mainly to the north of the injection well (deLaguna 1961; deLaguna et al. 1968).

In the second injection, the amount of surface uplift was significantly greater than that noted in the first injection, which correlates with the larger volume of grout injected. The central portion of the surface uplift pattern is elliptical and offset to the east-northeast from the injection well (Fig. 4). The outer portions of the uplift pattern are more nearly circular, but are also offset to the northeast of the injection well (deLaguna 1961; deLaguna et al. 1968). Core drilling data

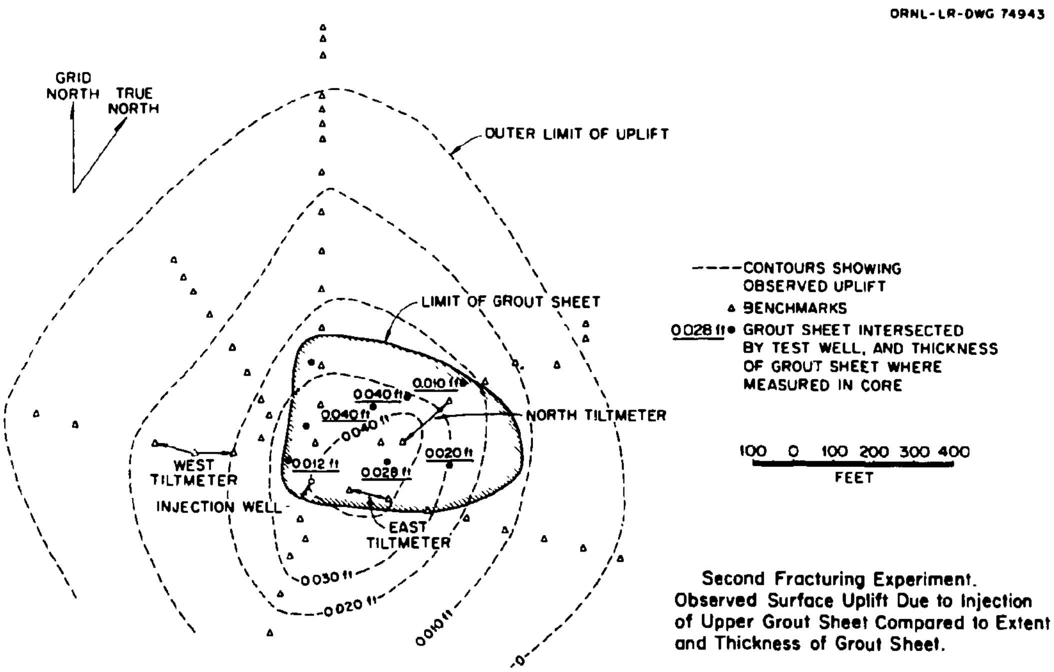

Fig. 4. Surface uplift pattern and extent of grout sheet for the second test injection at the second experimental site, September 1960 (from deLaguna et al. 1968). Grout sheet resulting from this injection is referred to as the upper grout sheet. Limit of grout sheet inferred from core drilling. (1 ft=0.3048 m)

indicate that the grout sheet associated with this injection is circular to slightly elliptical and extends mainly to the northeast of the injection well. Therefore, in contrast to the first injection at the second experimental site, the area of maximum surface uplift associated with the second injection corresponds with the extent and location of the grout sheet (deLaguna 1961; deLaguna et al. 1968).

The benchmark array at the second experimental site was resurveyed in 1964. Results of that resurvey indicated that essentially all of the surface uplift observed in the initial leveling studies had disappeared within a 4-year period after the injections (deLaguna et al. 1968).

Qualitative interpretation of the uplift pattern for the first injection at the second experimental site using the theoretical results of Pollard and Holzhausen (1979), Davis (1983), and Evans (1983) suggests that the grout sheet should be more or less symmetrically distributed with respect to the injection point and that the orientation of the grout sheet should be approximately horizontal. Neither conclusion was verified by subsequent core drilling, although the dip of the grout sheet is relatively shallow (10 to 15°). Interpretation of the surface uplift pattern associated with the second injection also suggests that the grout sheet should be more or less symmetrically oriented about the injection well and that the sheet should have a slight southwestward dip. Again, core drilling results did not substantiate these conclusions: the grout sheet is asymmetrically distributed to the northeast of the injection well and has a shallow dip to the southeast, which appears to be parallel to bedding features within the Pumpkin Valley Shale at the site.

2.2 OLD HYDROFRACTURE FACILITY

During the period 1965 through 1979, 7 experimental and 18 operational hydrofracture injections were made at the OHF (deLaguna et al. 1968; Weeren 1974, 1976, 1980). The volume of grout slurry injected in any one injection during this period ranged from 150,000 to 870,000 L (40,000 and 230,000 gal), with the volumes of the operational injections typically ≥380,000 L (≥100,000 gal). Injection depths ranged from 280 m (945 ft) for the early experimental injections to 240 m (792 ft) for the last operational injections. Surface uplift at the OHF was measured by precise leveling techniques similar to those that had been used at the experimental sites. A benchmark network consisting of four radial arms extending outward from the injection point was installed. The four arms of the network were approximately 60 degrees from each other and extended outward to distances ranging from 335 to 730 m (1100 to 2400 ft) (deLaguna et al. 1968). Surface uplift data and an analysis of uplift patterns for the seven experimental injections are presented in deLaguna et al. (1968), and uplift data for several operational injections are presented in Weeren (1974).

Results from the precise leveling of surface deformation patterns for the seven experimental injections are illustrated in Figs. 5 and 6. The data illustrated represent leveling surveys obtained within (1) 6 days after experimental injection 2 (February 24-26, 1964); (2) 150 days after experimental injection 5

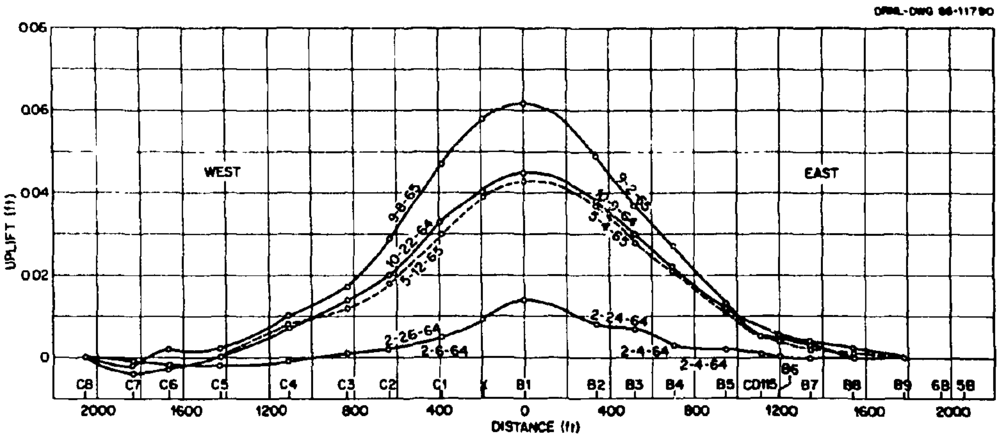

Fig. 5. East-to-west surface uplift profile for the first seven experimental injections at the Old Hydrofracture Facility (from deLaguna et al. 1968). Dates illustrated refer to the time of a particular survey. (1 ft=0.3048 m)

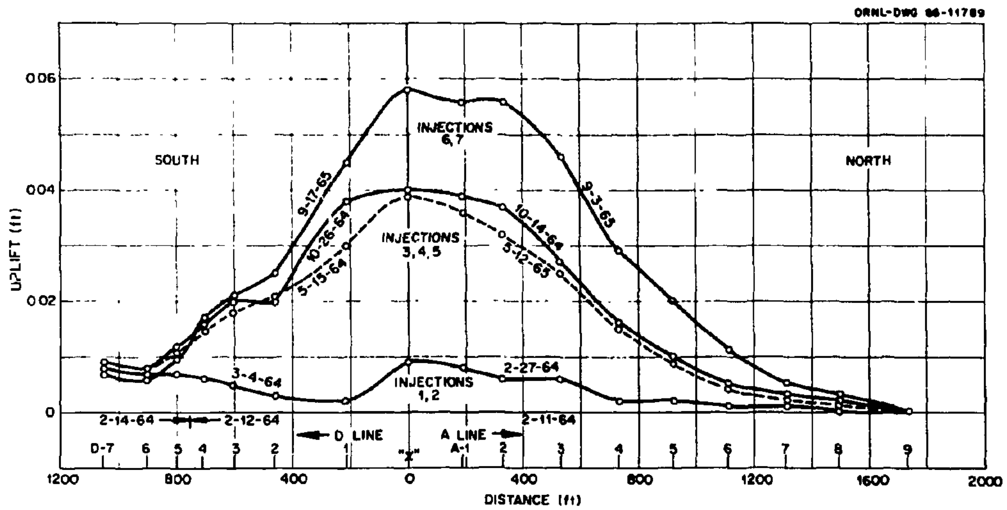

Fig. 6. North-to-south surface uplift profile for the first seven experimental injections at the Old Hydrofracture Facility (from deLaguna et al. 1968). Dates illustrated refer to the time of a particular survey. (1 ft=0.3048 m)

(October 9-22, 1964); (3) 1 year after experimental injection 5 (May 4-12, 1964); and (4) 21 days after experimental injection 7 (September 3-17, 1965). Surface uplifts for the seven experimental injections are cumulative and extend outward approximately 365 to 469 m (1200 to 1500 ft). Uplifts within 60 m (200 ft) of the injection well after the first two injections are approximately 3.0 mm (0.12 in.). After five injections, uplifts near the injection well are approximately 12.7 mm (0.5 in), and after seven injections, they are approximately 18.3 mm (0.72 in). The two surveys at different times following experimental injection 5 suggest a slight decrease in surface uplift with increasing time after an injection. Such a trend was also noted at the second experimental site. Leveling data obtained after operational injection 11 (Weeren 1974) indicate that a similar cumulative surface uplift pattern was continuing and that an uplift of approximately 61.0 mm (2.4 in) had occurred within 60 m (200 ft) of the injection well.

The shapes of the surface uplifts associated with the experimental and operational injections are approximately symmetrical with respect to the injection well. The east-west uplift profile for the seven experimental injections (Fig. 5) exhibits nearly perfect symmetry with respect to the injection well. This symmetrical pattern is also noted in uplift data for operational injections 7 and 11 (Weeren 1974). The north-south surface uplift profile (Fig. 6) for the seven experimental injections are also approximately symmetrical. The region of maximum surface uplift, however, is consistently offset to the north of the injection well.

Qualitative interpretation of the uplift pattern for the seven experimental injections, based on the analysis of Pollard and Holzhausen (1979), Davis (1983), and Evans (1983) suggests that the grout sheet should be more or less symmetrically distributed with respect to the injection point and that its orientation should be approximately horizontal or dipping slightly to the north. Gamma-ray logging of observation wells at the OHF, however, indicates that the grout sheets have a slight (10 to 15°) southeastern dip, which is similar to the dip of bedding within the Pumpkin Valley Shale at the OHF site.

3. LEVELING STUDIES AT THE NEW HYDROFRACTURE FACILITY

3.1 SCOPE AND OBJECTIVES

Hydrofracture injection of waste-bearing grout slurries at the NHF was initiated in 1981. Surface deformation patterns were not measured during the initial nine injections at the facility. During the spring of 1983, a program to study and evaluate various techniques to determine and to monitor grout sheet orientation was initiated (Stow et al. 1985; Stow and Haase 1986). A network of benchmarks was located and installed as part of that program and measurement by precise leveling of the surface deformation associated with five injections at the facility was begun in July 1983. The objectives of the leveling measurements were (1) to accurately determine the extent, location, and shape of surface uplift associated with ORNL hydrofracture injections and (2) to compare and contrast information about grout sheet orientation obtained by precise leveling with information obtained by other measurement techniques.

3.2 METHODS

3.2.1 Benchmarks

A network of 75 benchmarks was installed surrounding the NHF (Fig. 7). The benchmarks were arranged around the facility in as close an approximation to a grid pattern as was permitted by site geography, topography, and road access.

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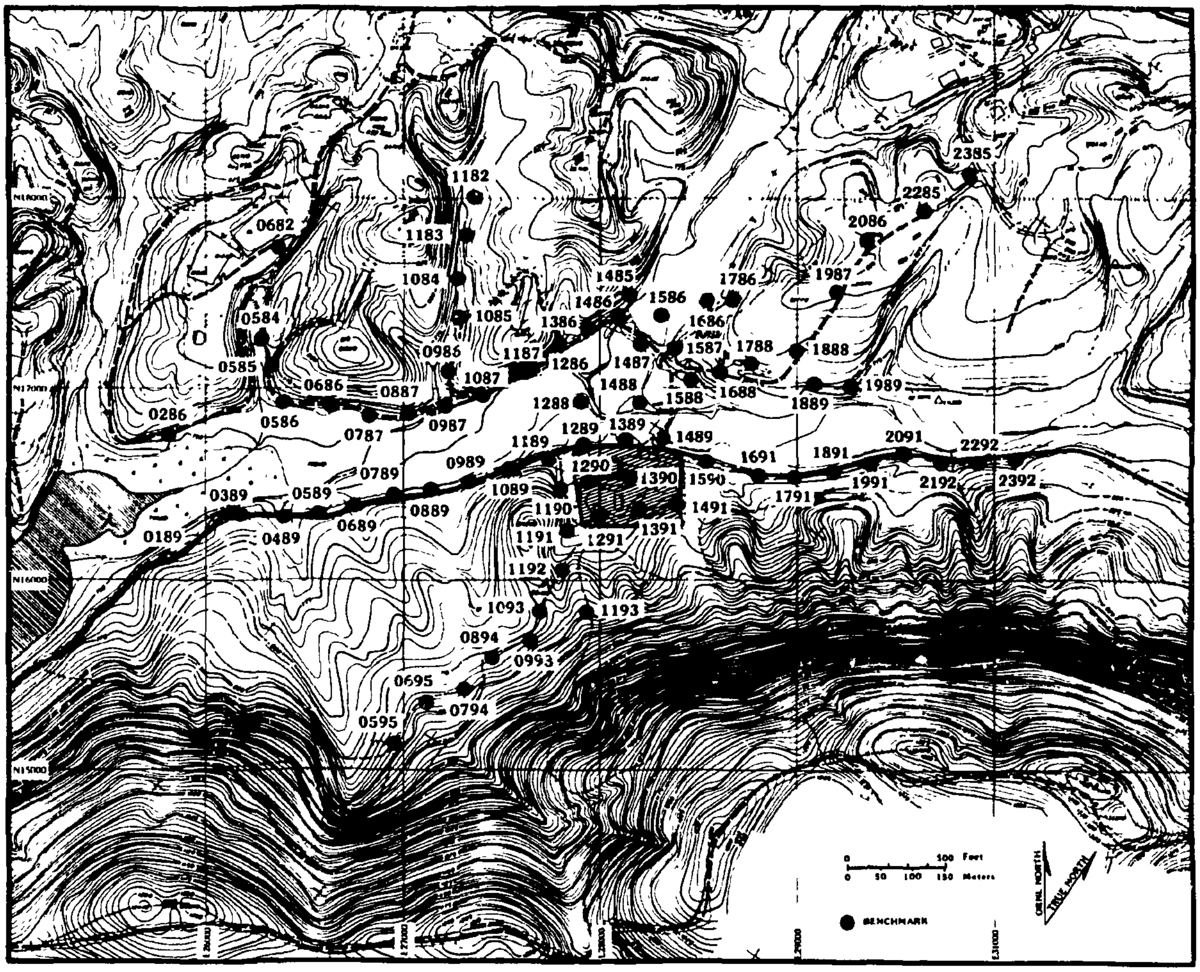

Fig. 7. Site map illustrating location of benchmarks at the New Hydrofracture Facility. Numbers illustrated are benchmark identifiers.

The resulting network extends outward from the injection well approximately 700 m (2300 ft) in the east, west, and north directions. Because of site topography, placement of benchmarks south of the NHF is limited to one string that extends approximately 450 m (1500 ft) south of the injection well.

The benchmarks were constructed by drilling a 30.5-cm- (12-in.-) diameter borehole through soil and overburden to a depth of approximately 3 m (10 ft) into the top of bedrock. Boreholes for benchmarks ranged in depth from 4.5 to 20 m (15 to 65 ft). A piece of 12.7-mm- (0.5-in.-) diameter steel reinforcing bar, extending to the bottom, was centered in the borehole, and a stainless steel bolt was attached to the top of the reinforcing bar to serve as the measuring point in the completed benchmark. High-strength cement was tremied or poured into the borehole to complete the benchmark.

3.2.2 Leveling Surveys

Elevations of the benchmark network were determined by precise leveling immediately before and after each hydrofracture injection. Precise leveling was conducted by surveyors from the Engineering Division of Union Carbide Nuclear Corporation, using a Geodimeter model 140 electronic total station surveying instrument (AGA Geodimeter, Inc), which had a precision of ±2 arc seconds. Individual survey shots during the leveling were kept to distances of 45 m (150 ft) or less which, combined with the precision of the survey instrument, yielded a maximum theoretical accuracy of ±0.5 mm (±0.02 in.) for the benchmark elevations. The benchmark network was referenced to two U. S. Geological Survey benchmarks located approximately 1.2 and 1.5 km (4000 and 5000 ft) from the injection point at the NHF. Surveys of the benchmark network took 3 to 5 days to complete. Surveys that were made before injections were completed within 10 days prior to the injection and surveys that were made after injections were completed within 10 days after the injections.

4.0 RESULTS FOR THE NEW HYDROFRACTURE FACILITY

Precise leveling measurements of surface deformation were made for a total of five injections at the NHF. All the injections were made through the same slot at a nominal depth of 300 m (990 ft). Operational details of the injections are presented elsewhere (Weeren 1984). Key injection parameters and surface uplift characteristics for the five injections are summarized in Table 1. Surface uplift patterns have been calculated for two times after an injection. A 5-days-after-injection uplift pattern is based on the difference in elevation of benchmarks of the network between the before-injection survey and the after-injection survey. A long-term, after-injection surface uplift pattern is based on the elevation differences between the before-injection survey of the injection of interest and the before-injection survey of the subsequent injection. The 5-days-after-injection uplift pattern represents surface uplift as soon after the injection as is possible to obtain survey data, which is approximately 5 days.

Table 1. Summary of injection parameters and uplift pattern characteristics

		Short-Term Uplift Pattern[a]			Long-Term Uplift Pattern[b]			Dip of Grout Sheet	
Injection	Vol. (L)[c]	Max. (mm)	Shape	Location[d]	Max. (mm)	Shape	Location[d]	Inferred[e]	Measured[f]
July 83[g]	850,000	≥25 to <30	Elliptical	South	≥15 to <20	Circular	Centered	Flat	Southeast
Aug. 83[h]	720,500	≥15 to <20	Elliptical	South	0	na[i]	na[i]	Southeast[j]	Southeast
Oct. 83[k]	920,100	≥25 to <30	Elliptical	Southeast	≥10 to <15	Elliptical	Centered	Flat	Southeast
Dec. 83[l]	900,000	≥10 to <15	Elliptical	Southeast	≥10 to <15	Circular	Southeast	Southeast	Southeast
Jan. 84[m]	1,500,000	≥25 to <30	Elliptical	Centered	nd[n]	nd[n]	nd[n]	Flat[o]	Southeast

a Uplift pattern based on leveling survey completed nominally 5 days after an injection.
b Uplift pattern based on leveling survey completed 30 to 70 days after an injection (see text for discussion).
c Total volume of injected grout (from Weeren 1984).
d *Location of area of maximum uplift with respect to the injection well, referenced to ORNL grid directions.*
e Dip of grout sheet inferred from shape and location of long-term uplift pattern.
f Dip of grout sheet determined by gamma ray logging in observation wells (from Weeren 1984).
g Injection SI-6.
h Injection SI-7.
i Not applicable. No uplift measurable 70 days after the injection.
j Dip of grout sheet inferred from shape and location of short-term uplift pattern.
k Injection SI-8.
l Injection SI-9.
m Injections SI-10 and ILW-21.
n No data.
o Dip of grout sheet inferred from shape and location of short-term uplift pattern.

Typically, the long-term uplift pattern represents surface uplift 30 days after a given injection, although in one example, the August injection, the time represented is approximately 70 days.

4.1 INJECTION SI-6 (JULY 1983)

Injection SI-6 occurred on July 12-14, 1983, and consisted of 850,000 L (224,000 gal) of grout slurry (Table 1). Surface uplift patterns approximately 5 days after the July injection are illustrated in Fig. 8. The data define an area of

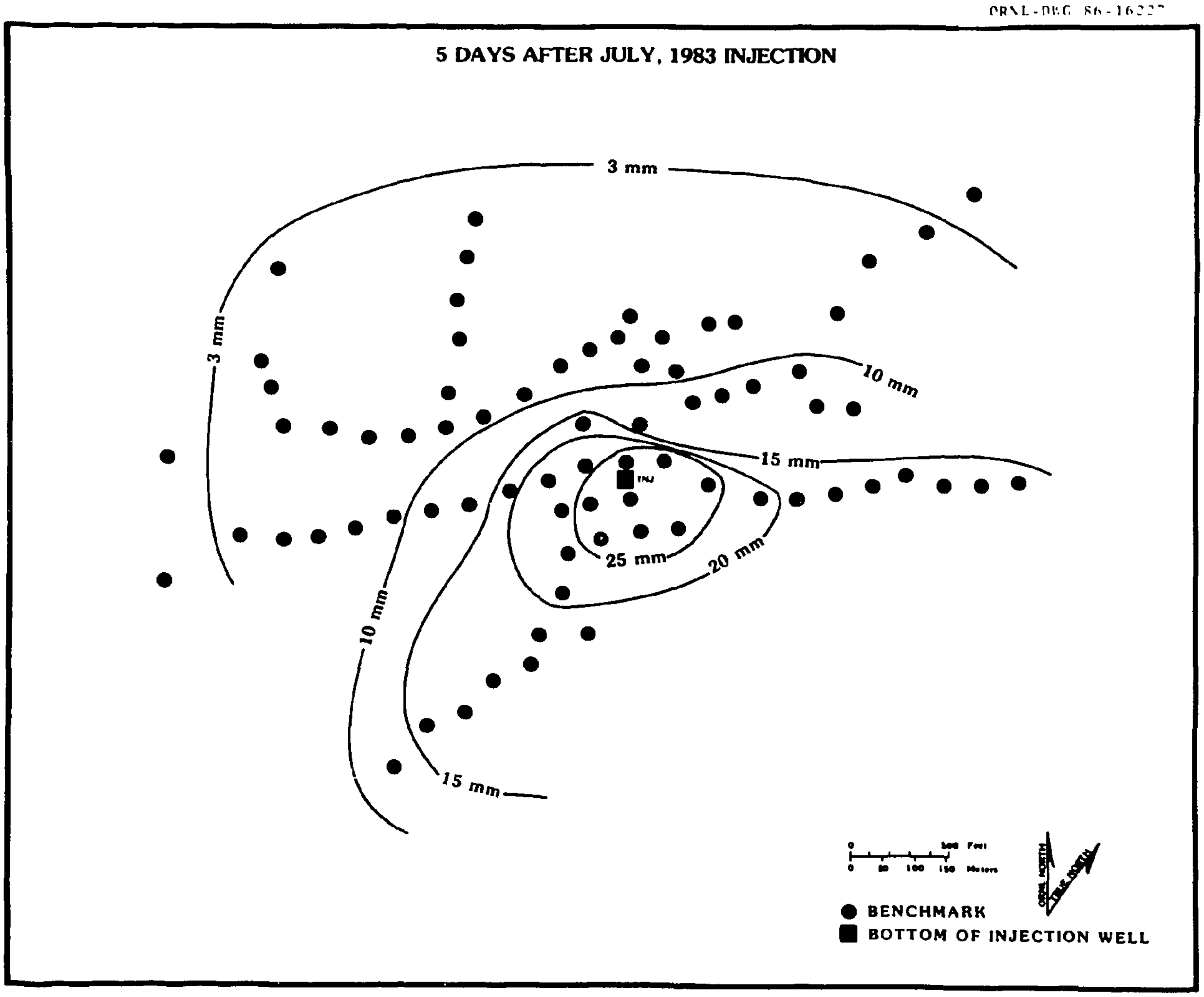

Fig. 8. Surface uplift pattern at the New Hydrofracture Facility 5 days after injection SI-6 (July 1983).

maximum uplift exceeding 25 mm that is centered approximately on the injection point. The 25- and 20-mm uplift contours form approximately concentric circles centered slightly to the southeast of the injection point. The 15- and 10-mm uplift contours are elliptical and appear to be centered well to the south of the injection point. Furthermore, the close spacing of the uplift contours north of the injection point and the wide space to the south indicate that the uplift pattern is strongly asymmetrical and does not have a simple, circular dome shape.

The long-term surface uplift pattern for the July injection is illustrated in Fig. 9.

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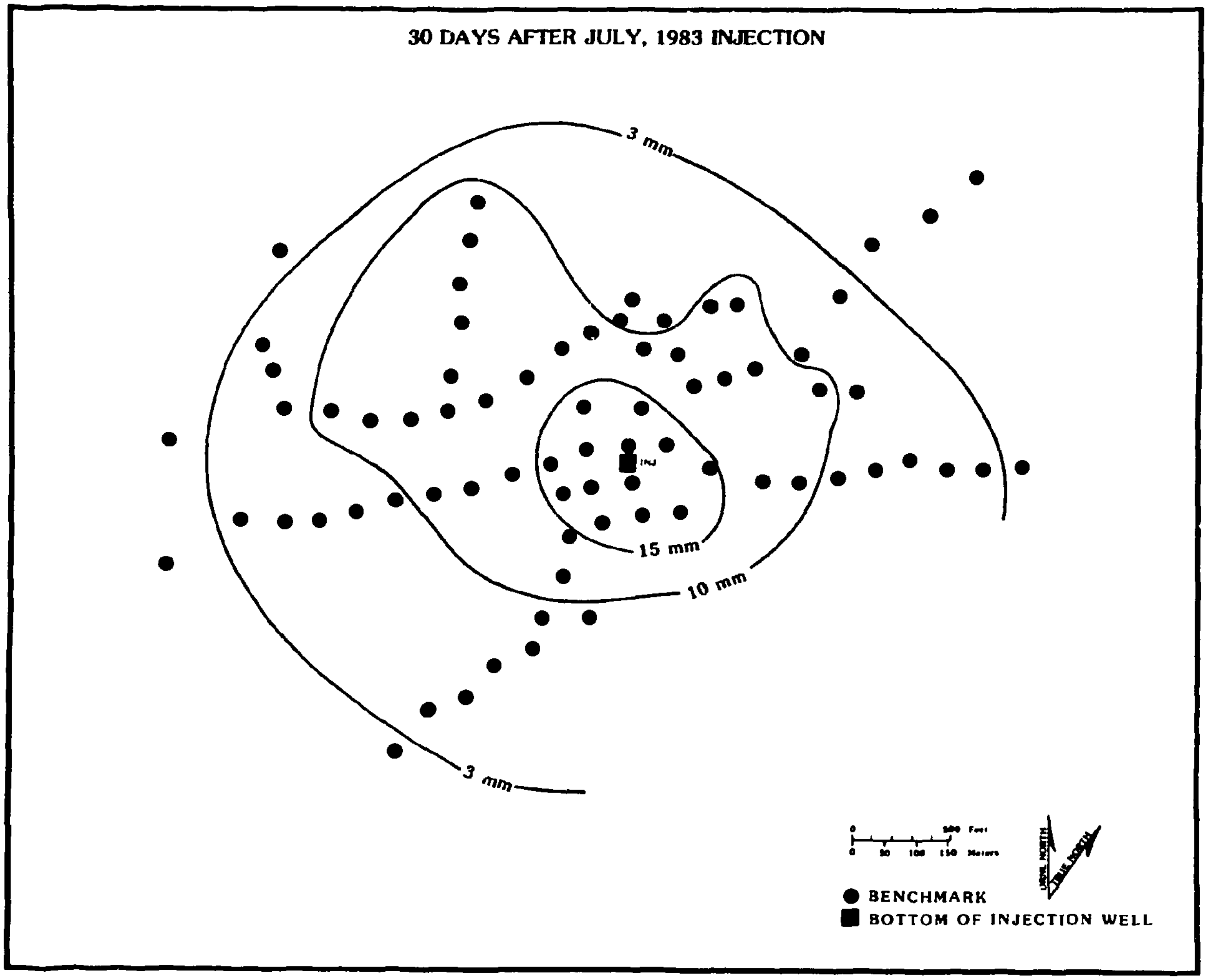

Fig. 9. Surface uplift pattern at the New Hydrofracture Facility 30 days after injection SI-6 (July 1983).

The amount of maximum uplift has decreased to between 15 to 20 mm and the size of the area within the 10-mm contour has decreased compared to that in the 5-days-after survey. The shape and position of the uplift contours have also changed. The 15-mm contour is nearly circular and is centered on the injection point. The 10-mm contour is more circular in shape, although it is still quite irregular. The 10-mm contour is now offset to the north of the injection point as opposed to being offset to the south in the 5-days-after-injection survey.

4.2 INJECTION SI-7 (AUGUST 1983)

Injection SI-7 occurred August 9-10, 1983, and consisted of 720,000 L (190,000 gal) of grout slurry (Table 1). Surface uplift patterns determined in the 5-days-after-injection survey are illustrated in Fig.10. The 15-mm contour

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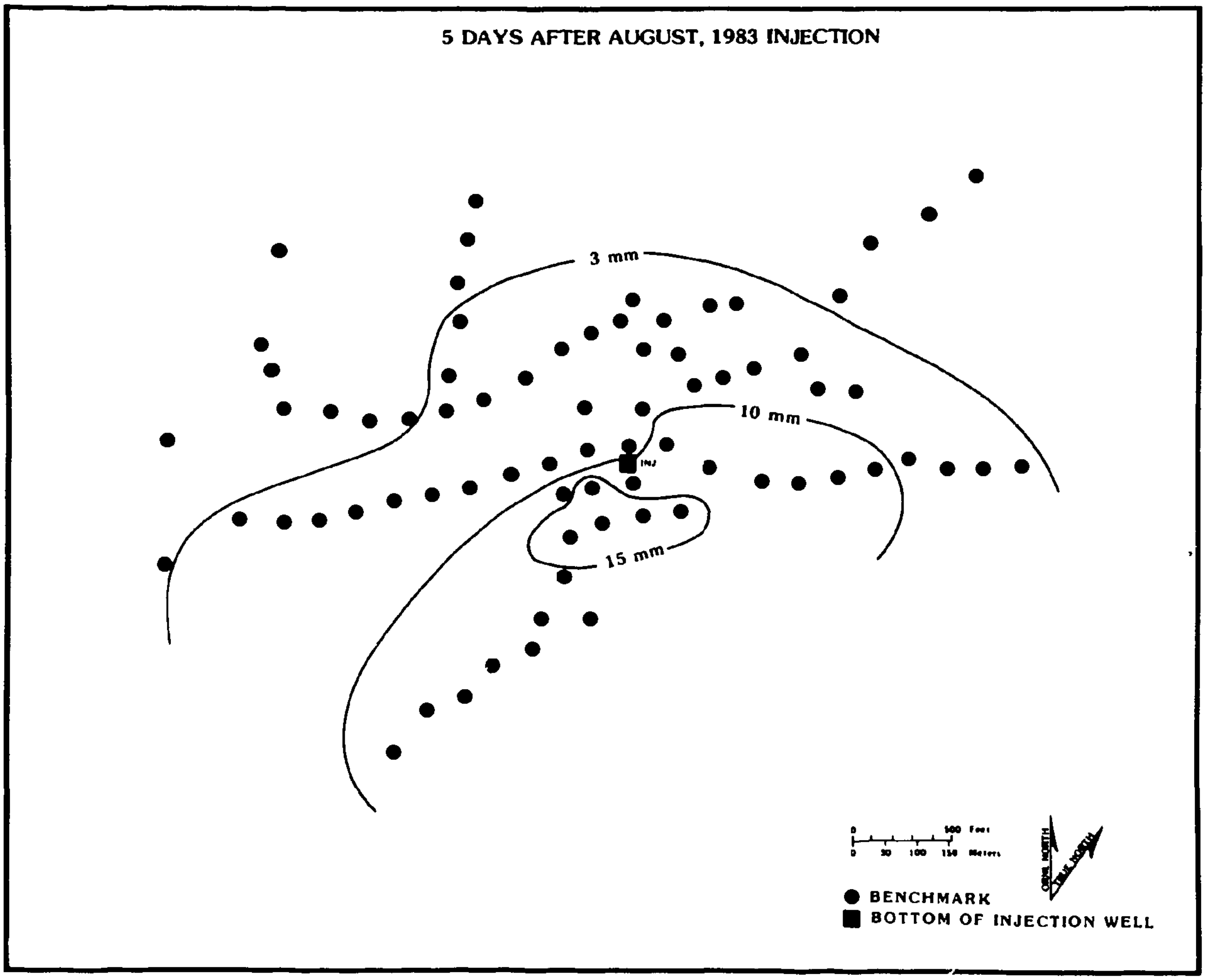

Fig. 10. Surface uplift pattern at the New Hydrofracture Facility 5 days after injection SI-7 (August 1983).

defines the area of maximum uplift. This area is elliptical and is displaced to the southwest of the injection point. The 10-mm contour also appears to be elliptical, but the degree of ellipticity cannot be determined because of the lack of benchmarks south of the NHF. The area enclosed by the 10-mm contour is also displaced to the southwest of the injection well. Compared with the July injection, however, the surface uplift associated with the August injection is more asymmetrical and smaller in magnitude and areal extent.

The long-term surface uplift for the August injection is illustrated in Fig. 11. The

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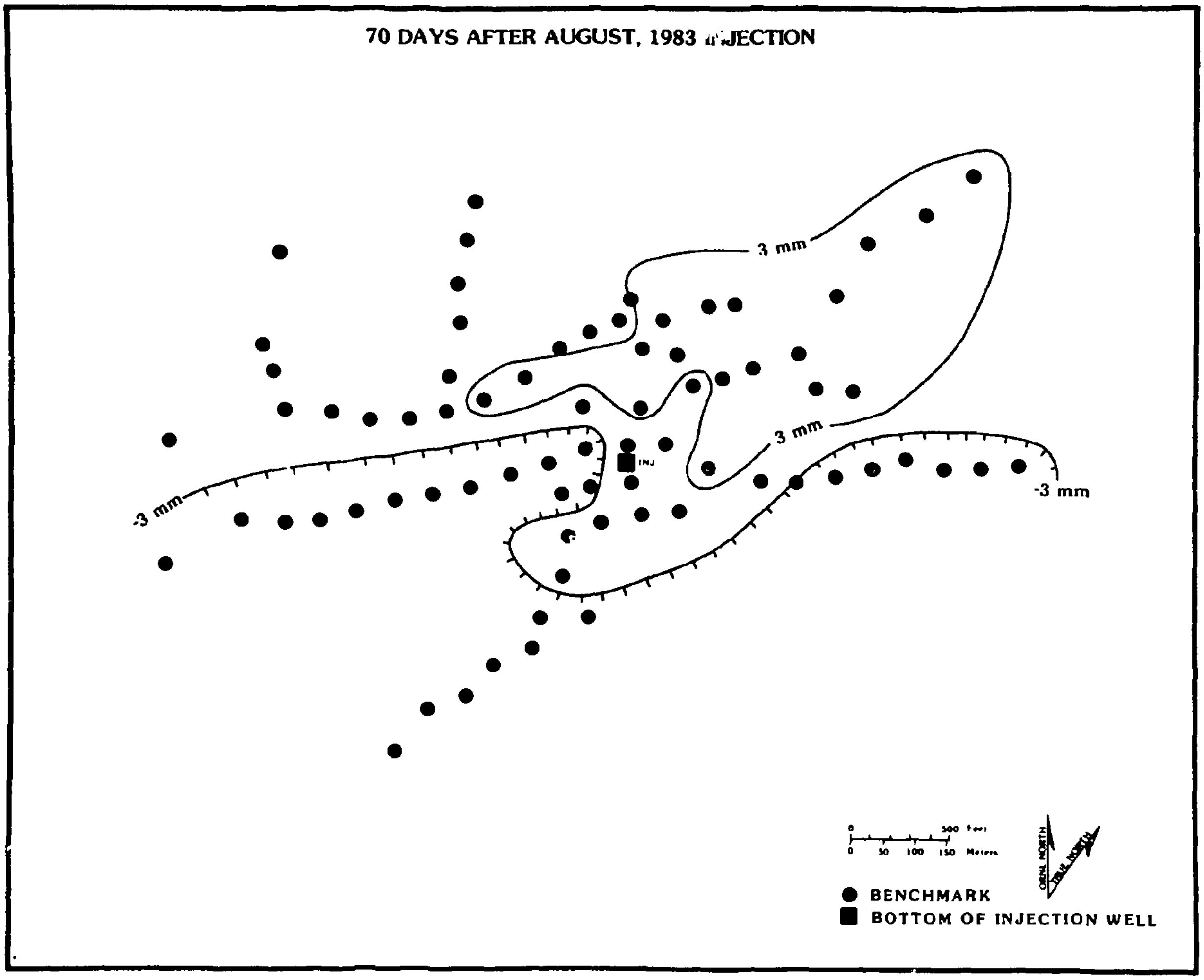

Fig. 11. Surface uplift pattern at the New Hydrofracture Facility 70 days after injection SI-7 (August 1983).

plot depicts the net surface deformation approximately 70 days after the August injection. Most surface uplift has disappeared, but an elliptical region remains to the northeast of the injection point with uplift greater than 3 mm but less than 10 mm. The area immediately around the injection point exhibits no surface uplift, and regions to the south exhibit apparent slight decreases in surface elevation with respect to values prior to the August injection.

4.3 INJECTION SI-8 (OCTOBER 1983)

Injection SI-8 occurred during October 25-26, 1983, and consisted of 920,000 L (240,000 gal) of grout slurry (Table 1). Five-days-after-injection surface uplift patterns are illustrated in Fig. 12. The 25-mm contour defines the area of

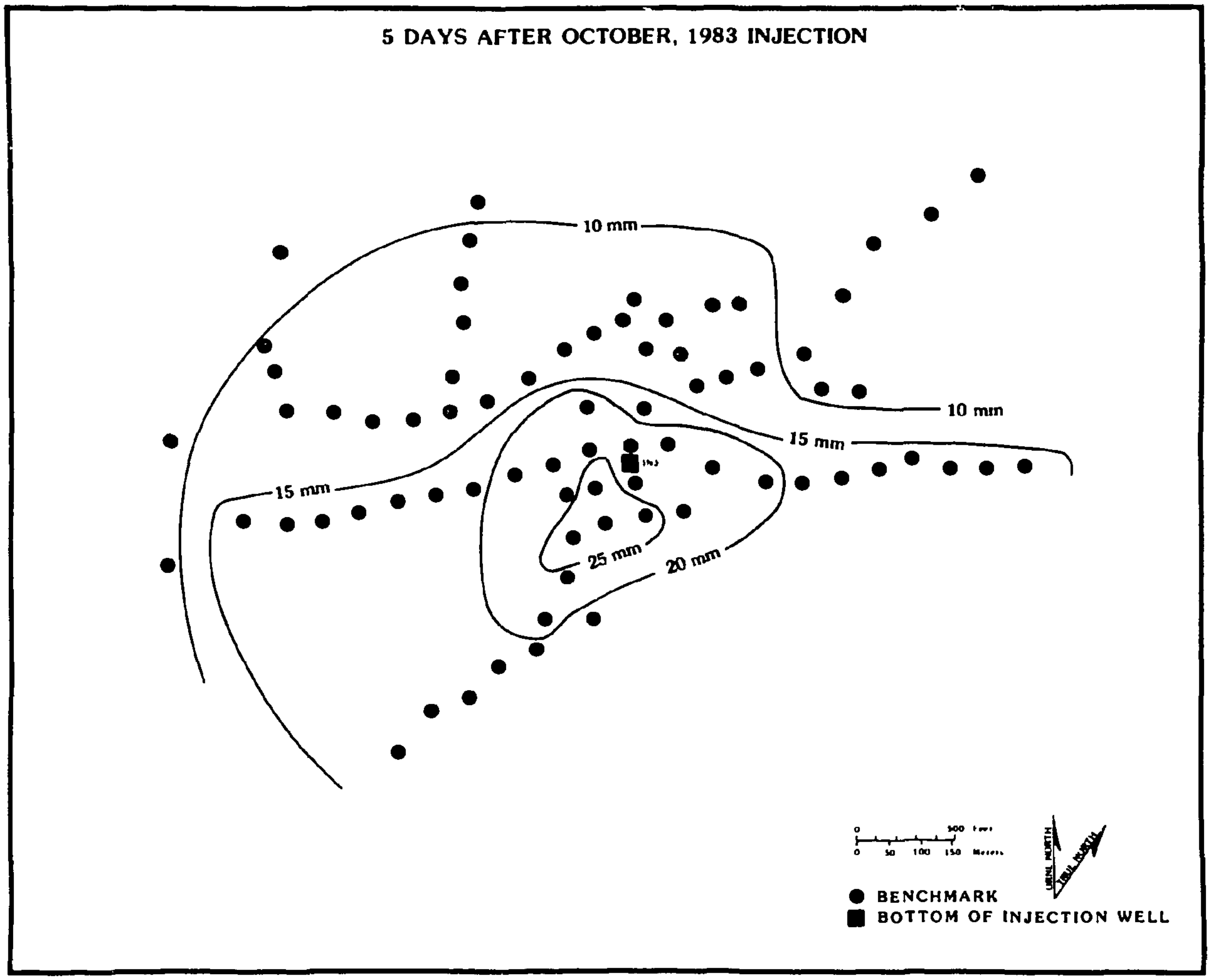

Fig. 12. Surface uplift pattern at the New Hydrofracture Facility 5 days after injection SI-8 (October 1983).

maximum uplift. The 20- and 25-mm contours form irregular to slightly elliptical, approximately concentric circles that are centered to the southwest of the injection point. The areas outlined by the 10- and 15-mm contours are elliptical and extensive, covering virtually the entire benchmark network. Because all benchmarks in the network experienced an uplift greater than 3 mm, a 3-mm contour could not be plotted in Fig. 12. Although it is not centered on the injection point, the region of maximum uplift is more radially symmetrical than the maximum uplift areas associated with the July and August injections.

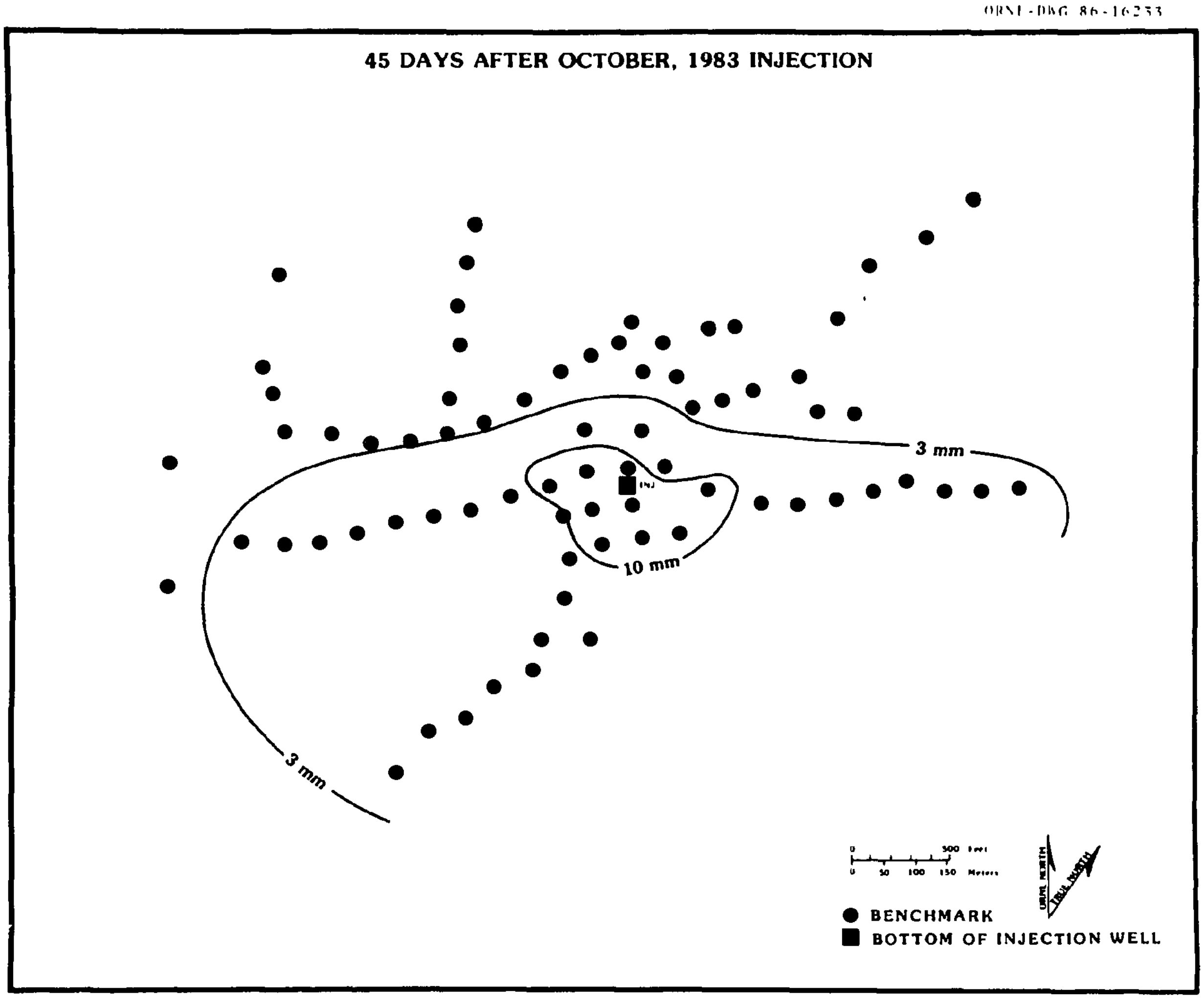

Fig. 13. Surface uplift pattern at the New Hydrofracture Facility 45 days after injection SI- 8 (October 1983).

The long-term (45-day) surface uplift patterns for the October injection are illustrated in Fig. 13. The amount and extent of surface uplift has decreased significantly with respect to the 5-days-after-injection survey. The area of maximum uplift is defined by the 10-mm contour. This region is elliptical in shape but is now centered approximately over the injection point. An extensive region of minor uplift, defined by the 3-mm contour, remains largely to the south of the injection point.

4.4 INJECTION SI-9 (DECEMBER 1983)

Injection SI-9 occurred on December 1-2, 1983, and consisted of 900,000 L (240,000 gal) of grout slurry (Table 1). The 5-days-after-injection surface uplift patterns are illustrated in Fig. 14. The areal extent and the amount of surface

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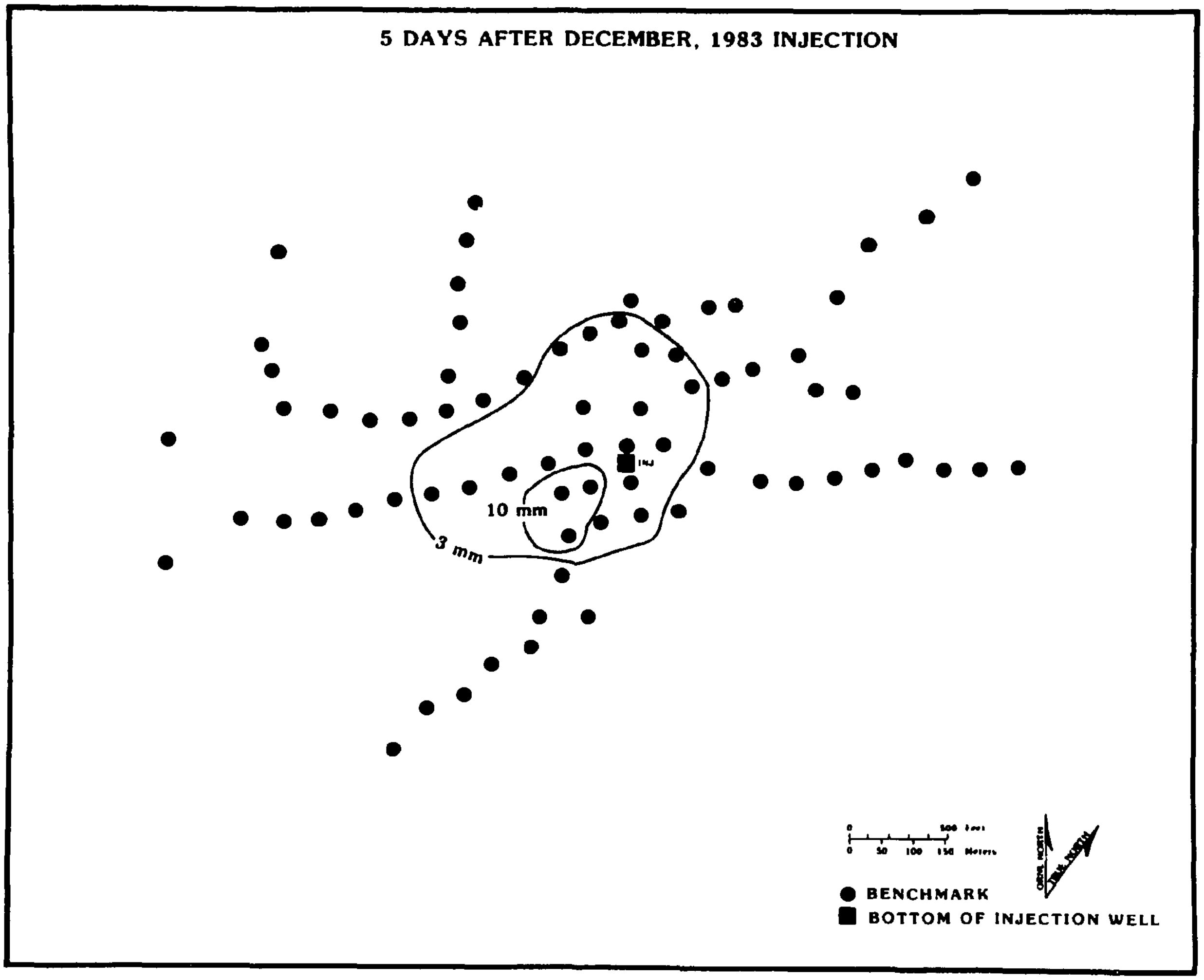

Fig. 14. Surface uplift pattern at the New Hydrofracture Facility 5 days after injection SI-9 (December 1983).

uplift for this injection are significantly less than those observed for the October injection (compare Fig. 14 with Fig. 12) even though the amounts of grout slurry injected in both cases were essentially identical. The region of maximum uplift is defined by the 10-mm contour. This region is nearly circular and is not centered on the injection point, being located to the southwest. The limit of uplifted area is approximately defined by the 3-mm contour. The area of steepest uplift gradient is toward the south of the uplifted region, and the area with the shallowest uplift gradient is located to the north of the uplifted region. This trend is the opposite of the trends noted for the the July, August, and October injections.

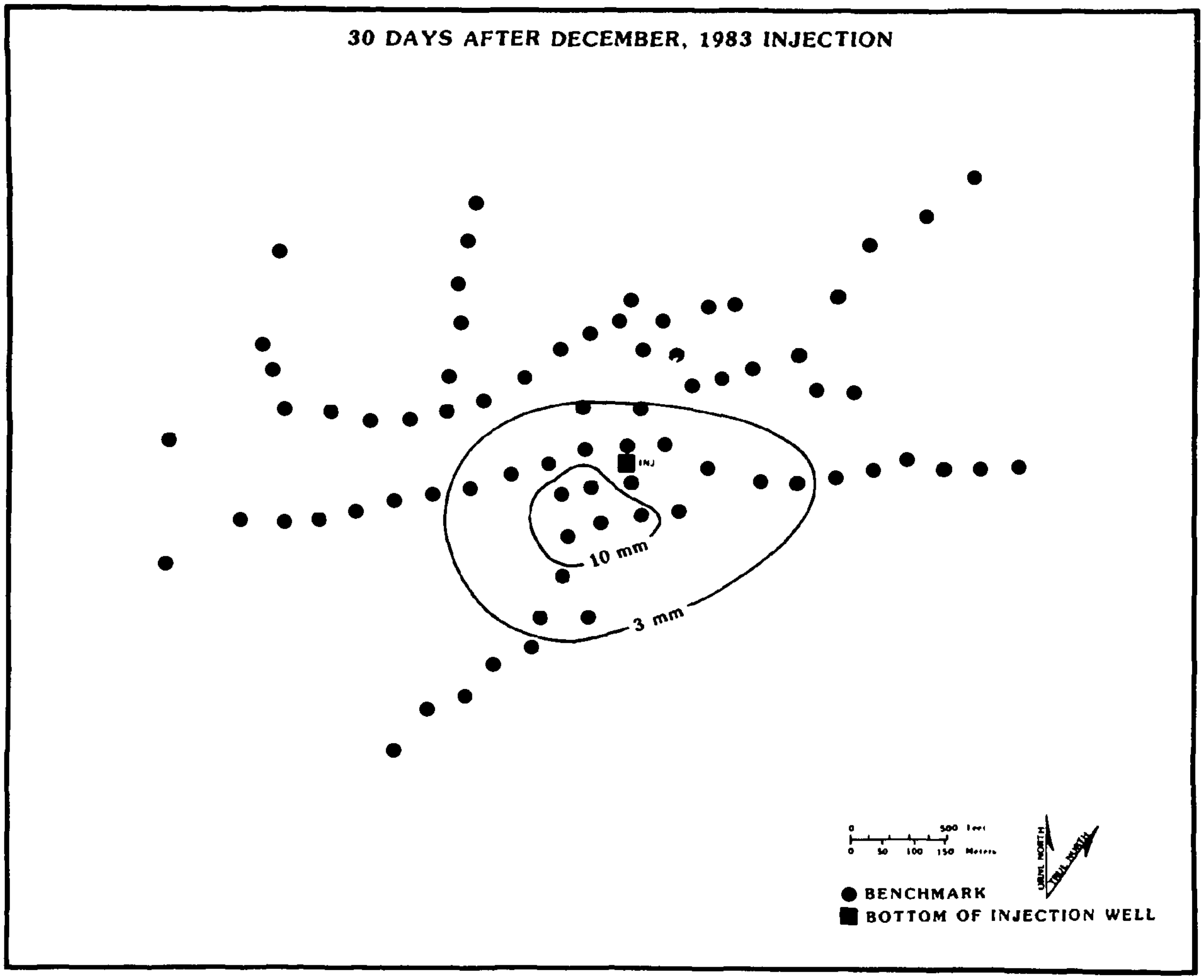

Fig. 15. Surface uplift pattern at the New Hydrofracture Facility 30 days after injection SI-9 (December 1983).

The long-term surface uplift pattern for the December injection is illustrated in Fig. 15. Unlike the previous injections, there is not a significant difference in the amount of long-term surface uplift compared to that determined in the 5-days-after-injection survey. Although the amounts of short- and long-term surface uplift are quite similar, the shape and extent of the long-term uplift have changed somewhat. The long-term surface uplift is more radially symmetrical than the short-term uplift, and the area of maximum uplift has increased slightly. The long-term uplift pattern also appears to be more centered on the injection point.

4.5 INJECTIONS SI-10 AND ILW-21 (JANUARY 1984)

Injections SI-10 and ILW-21 occurred in the period January 25-28, 1984, and consisted of 1,500,000 L (410,000 gal) of grout slurry (Table 1). Because the two injections occurred back to back, they are treated as one event. The 5-days-after-injection surface uplift patterns associated with these injections are illustrated in Fig. 16. The amount of uplift is similar to that exhibited by other large injections (October, for example), but is much more areally extensive than previously observed. The region of maximum uplift is essentially circular and is centered on the injection point. The 20- and 25-mm contours define concentric, nearly circular regions centered on the injection point. The 15-mm contour defines an elliptical region extending eastward from the injection point. The rest of the benchmark network is within a region exhibiting at least 10 mm of uplift.

Survey data for the 30-days-after-injection survey, representing the long-term uplift resulting from the January injection are not available. Operational and weather-related problems resulted in ambiguous and substandard data for the final survey of the project.

5.0 DISCUSSION

5.1 SHAPE AND LOCATION OF UPLIFT PATTERNS

Because of the limitations of survey precision, the 3-mm uplift contour is taken as the limit of significant surface uplift associated with injections at the NHF. The shapes of the uplift patterns determined using the 10-mm and larger contour intervals are typically elliptical and variable from injection to injection and change with time for any given injection. The shapes of the patterns determined shortly after injections are typically somewhat more elliptical than the shapes of the patterns observed several weeks after an injection. The long axis of the uplift ellipse trends north-northeast and is approximately parallel to geological strike at the site. In a north-south profile, the short-term uplift pattern is typically asymmetrical, with one side being significantly steeper than the other. The asymmetry is most noticeable during the July and August injections, with the steep gradient side occurring to the north of the injection point for both

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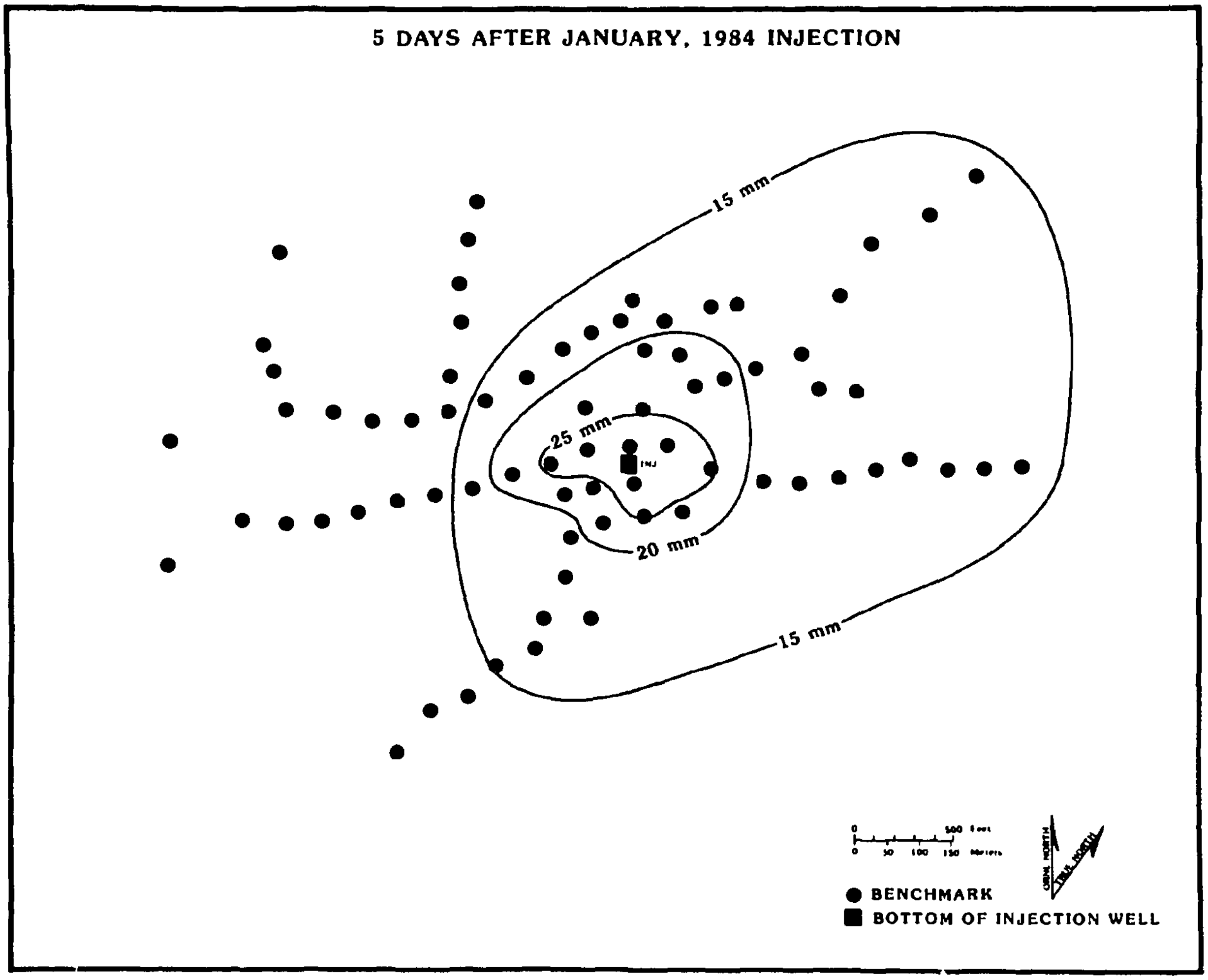

Fig. 16. Surface uplift pattern at the New Hydrofracture Facility 5 days after injections SI-10 and ILW-21 (January 1984).

injections. For the December injection, the steep gradient side of the uplift pattern occurs southwest of the injection point. Short-term surface uplift patterns for the October and January injections exhibit less asymmetry than do patterns for other NHF injections monitored. The long-term surface uplift patterns for all injections except August were significantly more symmetrical than the short-term uplift patterns. In particular, the long-term uplift patterns for the July and December injections are nearly symmetrical and resemble a bull's eye target pattern.

In addition to the asymmetry in the shape of the uplift patterns, most of the uplifts are offset from the injection point. Typically, the area of maximum uplift is offset to the south-southeast of the injection point, as would be expected based on the theoretical analysis of Pollard and Holzhausen (1979). As with the variations in the shape of the uplift pattern, the direction and amount of offset of the region of maximum uplift changes from injection to injection and with the time of the leveling survey for any given injection. Among the short-term surface uplift patterns, the patterns for the July and January injections exhibit the greatest degree of coincidence of the uplift pattern with the injection point and the December injection exhibits the least. Among the long-term uplift patterns, however, only the pattern for the August injection does not exhibit good correlation between the area of maximum uplift and the injection point.

The degree of asymmetry of the surface uplift associated with hydrofracture injections had not been observed on previous leveling experiments conducted at the OHF. This is largely due to the simple arrangement of the benchmark network installed at that site and to the assumption, based in part from core drilling data obtained at experimental facilities (deLaguna et al. 1968), that the grout sheets were largely horizontal. Because of the apparently simple uplift pattern associated with previous injections, analysis of data from those leveling experiments was based on simple models appropriate for homogeneous, isotropic subsurface conditions.

Modeling of surface uplift for homogeneous, isotropic subsurface conditions indicates that asymmetrical uplift patterns that are not coincident with the injection point are associated with nonhorizontal, dipping hydraulic fractures (Pollard and Holzhausen 1979; Evans 1983). The direction of offset from the injection point of the region of uplift is the same as the direction of the dip of the hydraulic fracture. Also, the greater the dip of the fracture, the greater the degree of asymmetry of the associated uplift pattern. Because of the subsurface heterogeneity of the site, application of model calculations to the analysis of uplift patterns at the NHF is qualitative at best (Pollard and Holzhausen 1979; Holzhausen 1984; Holzhausen and Gazonas 1985; Holzhausen et al. 1985). None-the-less, several general conclusions about the orientation of the hydrofracture grout sheets can be reached by application of Holzhausen and Pollard's results to the surface uplift patterns observed at the NHF. The short-term uplift patterns for the July and January injections suggest that the hydrofractures associated with those injections are essentially horizontal. Short-term uplift patterns for the August, October, and December injections suggest that the hydrofractures associated with those injections have southern or southeastern dips. Long-term uplift patterns for the July and October injections suggest that the hydrofractures for those injections are essentially horizontal. Such a conclusion agrees with the orientation determined from the short-term uplift pattern for the July injection but not for the October injection, where a southeastern dip is suggested by the short-term pattern. The long-term uplift pattern for the December injection suggests that the hydrofracture for this injection has a southeastern dip; such a dip is also inferred from the short-term uplift pattern. For all injections, the dip of hydrofractures determined by gamma-ray logging in observation wells surrounding the NHF is to the southeast (Weeren 1984).

5.2 AMOUNT OF UPLIFT AND ITS SUBSIDENCE WITH TIME

For all but one of the injections (December), there was a significant decrease in the amount of uplift with time. Surface uplift observed in the long-term survey, taken 30 to 70 days after the injection, was typically 40 to 60% less than that observed in the 5-days-after-injection survey. The amount of surface uplift recorded by the long-term surveys is more appropriate for the amount of grout injected. Data for the August injection indicated that after 70 days there was no net surface uplift associated with the grout injection. Because the long-term survey for this injection was made much later than those for other injections, it is not known whether this complete subsidence is typical of injections at the NHF or whether it is associated with just this one injection.

The cumulative surface uplift for the July through December injections is illustrated in Fig. 17. The cumulative uplift pattern indicates that there was no net surface uplift due to these five injections measurable approximately 3 months after the last of these five injections. Such a conclusion is consistent with data obtained for the August injection, which also indicates that there was no net surface uplift due to that single injection approximately 70 days after the injection date. The apparent lack of cumulative uplift at the NHF indicates that this site had a significantly different response to hydrofracture injections than did the OHF site, where suface uplift due to hydrofracture injections was cumulative.

5.3 RELATED STUDIES

Real-time measurement of surface deformation caused by the October and December injections was undertaken with tiltmeters (Holzhausen 1984; Stow et al. 1985; Stow and Haase 1986). Eight tiltmeters were installed in September 1983 in shallow wells at radii of 120 and 180 m (400 and 600 ft) from the injection well at the NHF. Continuous measurement of surface tilts was begun several days prior to the October injection to establish background conditions. Surface tilts associated with the October injection were on the order of several microradians to several tens of microradians and varied in rate, magnitude, and direction throughout the duration of the injection, suggesting a nonlinear response of the strata over the injection zone. The data indicate that the area of maximum uplift during the actual injection was slightly to the north of the injection point, which suggests a northward-dipping fracture. This finding contrasts with gamma-ray logging data from observation wells ,which indicated that the hydrofracture had a southeastern dip. The results also contrast with the leveling data obtained after the injection had ceased, which indicated that the area of maximum surface uplift was to the south and southwest of the injection point.

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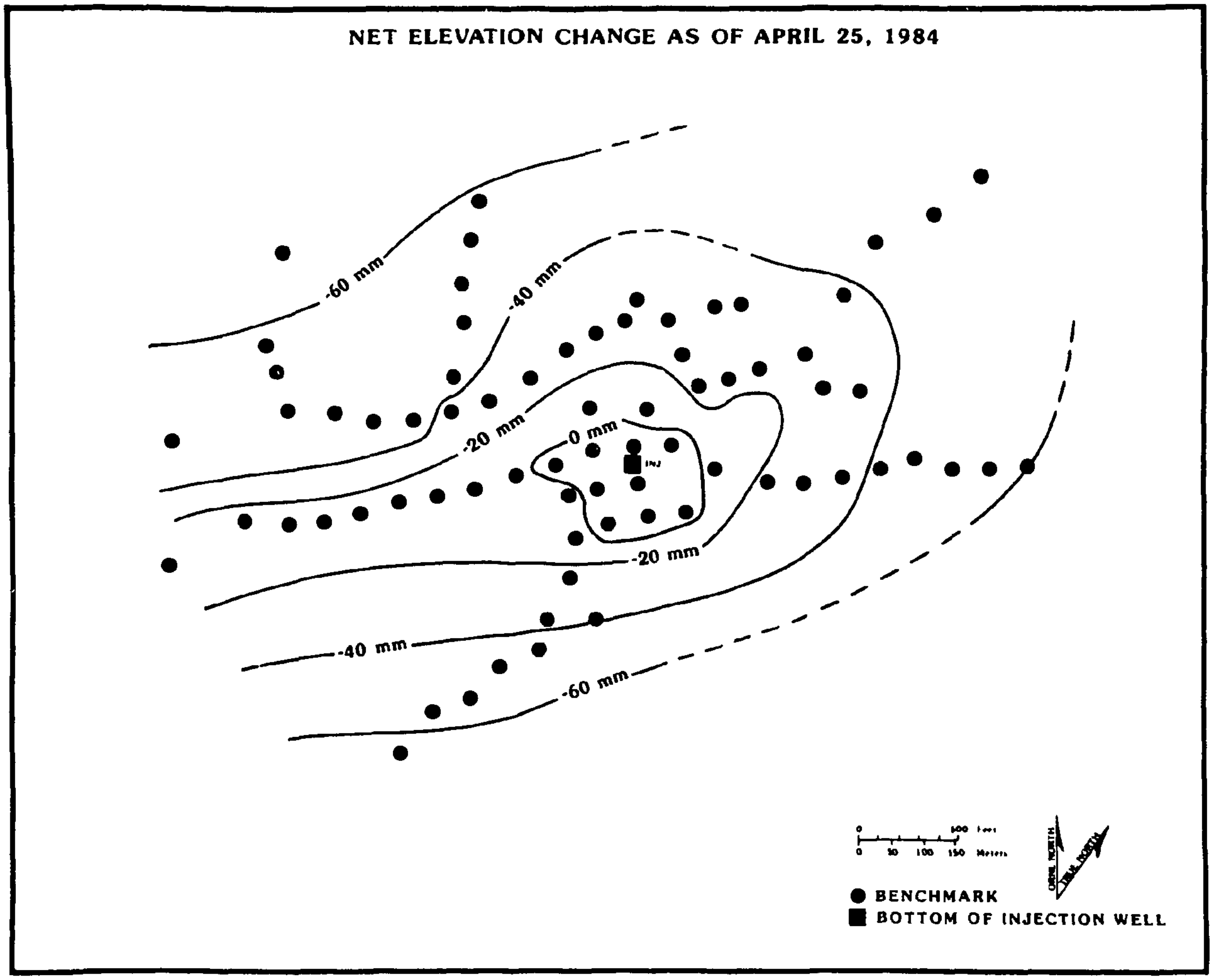

Fig. 17. Net surface elevation change at the New Hydrofracture Facility for the period July 1983 to April 1984.

Elastic modeling of a purely dilational fracture suggests that the tilt pattern observed for the October injection corresponds to a hydrofracture that dips to the north (Holzhausen 1984). This result is obtained using both an elastic isotropic model and a transversely isotropic model in which rock stiffness parallel to bedding is 5 times greater than that perpendicular to bedding (Davis 1983; Holzhausen 1984). Much of the apparent discrepancy in hydrofracture orientation inferred using data obtained by tiltmeter measurements and those obtained using precise leveling techniques can be resolved by more careful modeling of the uplift pattern expected for sites with the complex subsurface geology of the NHF (Holzhausen and Gazonas 1985; Holzhausen et al. 1985). Results indicate that shear stress across gently dipping fractures, such as those produced at the facility, can produce the type of surface uplift patterns observed in the real-time tiltmeter measurements (Holzhausen and Gazonas 1985).

Measurement of surface tilts between the October and December injections indicated a gradual deflation of the surface uplift caused by the October injection. This finding is in agreement with results of the leveling surveys after the October injection, which indicate that approximately 40 to 60% of the initial surface uplift subsided within a 45-day period following the October injection.

6.0 SUMMARY

The surface uplift patterns determined for five grout injections at the NHF are complex. In plan view, they are elliptical to almost circular and exhibit varying degrees of cross-sectional asymmetry, with one side steeper than the other. The long axis of the ellipse is more or less parallel to geological strike. The uplift patterns vary in shape and asymmetry from injection to injection. The region of maximum uplift in the short-term survey is typically offset to the south or southwest of the injection point. Approximately 40 to 60% of the uplift measured 5 days after an injection subsides within 30 to 45 days. In one case, all of the uplift subsided within 70 days of injection. The region of maximum uplift in the long-term typically coincides with the injection point. Modeling of the uplift patterns by simple models, based on homogeneous, isotropic subsurface conditions, suggests that hydrofractures produced by the injections are either horizontal or have shallow dips to the south-southeast. Such orientations are consistent with hydrofracture orientations determined by gamma-ray logging in observation wells surrounding the NHF site.

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