Transient Head Data from Multilevel Samplers: A Promising New Approach for Subsurface Characterization

James J. Butler, Jr., Carl D. McElwee and
Geoffrey C. Bohling
Kansas Geological Survey
1930 Constant Avenue, Campus West
University of Kansas
Lawrence, KS 66047

Kansas Geological Survey
Open-file Report

Disclaimer

ABSTRACT

Site-specific features of the hydraulic conductivity distribution must be quantified for reliable prediction of contaminant movement/remediation in units composed of complex mixtures of lithologies. In particular, knowledge of the existence of laterally contiguous zones of relatively high conductivity is often critical for successful remediation designs. The identification of such zones, however, has proven to be a rather difficult task, as many conventional field techniques provide information either of a highly averaged nature or restricted to the immediate vicinity of a test well. We have begun work on a new field method for the characterization of spatial variations in hydraulic conductivity between wells. This method is based on the use of pressure sensors in the tubing of multilevel samplers, which allows very detailed information about vertical variations in pumping-induced head changes to be obtained. These data can then be employed to estimate large-scale conductivity variations between wells. Laboratory and preliminary field experiments have demonstrated that two types of pressure sensors hold considerable promise for this application. An extensive series of experiments are underway at a heavily instrumented field site to more fully assess the ultimate potential of the proposed methodology.

INTRODUCTION

Over the last two decades, a considerable amount of theoretical, laboratory, and field research on the mechanisms of large-scale solute transport has identified the spatial distribution of hydraulic conductivity (K) as a significant factor in determining how a plume of a conservative tracer will move in the subsurface (Dagan, 1986; Gelhar, 1986; Hess et al., 1992; Jensen et al., 1993). The estimation of K on a scale of relevance of contaminant transport investigations, however, has proven to be a rather difficult task. Conventional pumping tests in heterogeneous formations will provide large-scale volumetric averages (Butler and Liu, 1993), which may be of rather limited use in transport investigations where identification of continuous zones of relatively high K is of critical importance. Although multiwell tracer tests can provide information about conditions between wells, they are very expensive in terms of time, money, and effort. Other techniques are needed to allow information on K variations and, specifically, the existence of preferential flow paths to be incorporated into models at sites of suspected groundwater contamination.

A wide variety of experimental methods for obtaining information about spatial variations in K have been reported in the literature. Laboratory analysis of core samples is probably the most common approach. However, the time and expense of laboratory analyses can be high and there are many questions concerning the relation of core-scale information to scales of interest in most field investigations. Single well tests, such as the slug test (Butler et al., 1996), borehole flowmeter surveys (Boman et al., 1997), the dipole well test (Kabala, 1993), and

short-term tracer tests of various types (Taylor et al., 1990), are the second most common class of experimental methods. However, the estimated parameters obtained with these techniques only represent conditions in the immediate vicinity of the test well. An area of considerable current interest is the use of various parameters derived from geophysical surveys, such as seismic velocities, to estimate K variations (Copty et al., 1993). However, the lack of a unique correlation between the geophysical parameters and K (e.g., Figure 2 of Hubbard et al., 1997) has limited the effectiveness of these approaches up to now.

We have begun work on a new field method for the estimation of interwell variations in hydraulic conductivity. This approach is a combination of a recently proposed method for hydraulic tomography (Bohling, 1993), multilevel sampling wells (Pickens et al, 1978; Boggs et al., 1988), and a sensing device for measuring head changes in the small-diameter tubing of a multilevel sampling well. The focus of this presentation is on the potential for measuring pumping-induced drawdown in the tubing of a multilevel sampling well. Two different options for transient head measurements will be described and the results of preliminary field experiments will be presented.

HEAD MEASUREMENT IN MULTILEVEL SAMPLING WELLS

Multilevel sampling wells (henceforth designated as MLSs) are commonly employed in large-scale tracer tests for the collection of vertically isolated water samples (Pickens et al., 1978; Boggs et al., 1988). These wells usually consist of bundles of small-diameter (often 0.18" ID) polyethylene tubing, with each tube terminating at a different depth below land surface. Although some work has been reported on measuring head differences between tubes in a MLS (Pickens et al., 1978), we are unaware of any previous work on the collection of transient head data in such wells. Multilevel sampling wells present an excellent vehicle for the collection of pumping-induced drawdown data at a much finer vertical spacing than has previously been possible. However, the collection of such data is not routine because of the small diameter of the tubing. Two approaches for the collection of head data in MLS tubing are described in this section.

Fiber Optic Pressure Sensors

The submersible pressure transducers commonly employed in hydrogeologic investigations are much too large for use in the small-diameter tubing of a MLS. However, fiber optic pressure sensors offer a very small diameter alternative to the standard transducers used in hydrogeology. These sensors essentially consist of a Fabry-Perot interferometer on a microchip that is attached to the end of a fiber optic cable (Wolthuis et al., 1991;

Photonetics, 1996). The interferometer consists of a cavity that has been etched in glass. The bottom of the cavity is at a fixed position while the top is a pressure sensitive diaphragm. The depth of the cavity thus changes as a function of pressure. Both top and bottom of the cavity are partially reflective surfaces, so the light reflected from the interferometer has maxima and minima as a result of constructive and destructive combination of reflections from the two surfaces. A mini spectrometer is used to detect the minimum in a certain spectral range. Within that range, the position of the minimum is a unique function of cavity depth and thus pressure.

We are currently working with sensors that are 3.2 mm (0.126") in outer diameter and are attached to a 2 mm (0.079") diameter fiber optic cable (Photonetics, 1996). Although preliminary laboratory and field assessments of these sensors have indicated that they hold considerable promise, manufacturing delays have prevented us from having a sufficient number of sensors to perform a detailed field evaluation of their utility for this application.

Air Pressure Sensors

One of the major advantages of working with fiber optic sensors is that the probes can be placed right above the port at the lower end of the MLS tubing. Measured changes in water pressure should thus be reflective of conditions in the formation immediately adjacent to the port. However, the cost and effort required to get such measurements can be considerable. A simpler and cheaper approach is to measure air pressure changes

in sealed MLS tubing and then relate the air pressure changes in the airtight tubing to water pressure changes in the formation. This approach is illustrated in Figure 1, which displays two hypothetical cross sections showing a single tube from a MLS. Figure 1A displays conditions prior to the onset of pumping. The air pressure in the sealed tube is P_1 and the air column has length l_1. After a period of pumping, the head in the formation has changed by an amount Δh ($= h_2 - h_1$), while air pressure in the tubing has changed by an amount ΔP ($= P_2 - P_1$). Unfortunately, the relationship between Δh and ΔP is not unique, as it is dependent on l_1 and P_1. However, use of the Ideal Gas Law and a series of first order approximations allows the following linear relationship between Δh and ΔP to be obtained:

$$\Delta h \approx \frac{\Delta P}{\gamma}\left(1 + \frac{l_1 \gamma}{P_1}\right) \qquad (1)$$

where γ is the weight density of water $[M/L^2 T^2]$. Although equation (1) is approximate in nature, the approximations upon which it is based are very appropriate for the range of pressure changes expected in shallow ground-water applications. Figure 2A is a plot of $\Delta P/\gamma$ versus Δh from a laboratory calibration in an apparatus similar to that depicted in Figure 1. The major departures from the best-fit straight line in Figure 2A are primarily a product of air leaks, measurement error, and a small degree of nonlinearity.

The linearity of the relationship depicted in Figure 2A

7

indicates that inexpensive pressure transducers can be used to measure air pressure changes in the tubing, which then can be related to water pressure changes in the formation. Figure 2B presents the results of the laboratory calibration of an air pressure transducer expressed as voltage versus Δh. The calibration data presented in Figure 2B are for a l_1 of 18.4 ft. Given the dependence of equation (1) on l_1, a series of calibrations must be performed in the laboratory over the range of l_1 expected in the field.

All the laboratory calibrations/experiments that we have performed indicate that changes in air pressure in the MLS tubing can be used to determine changes in water pressure in the formation. The remainder of this presentation consists of the description of a series of experiments that were recently performed to assess the potential of this approach in a field setting.

FIELD SITE

The Kansas Geological Survey (KGS) has developed a research site, the Geohydrologic Experimental and Monitoring Site (GEMS), in the Kansas River valley just north of Lawrence, Kansas. The shallow subsurface at GEMS consists of an alluvial facies assemblage of approximately 70 ft in thickness. The upper half is primarily clay and silt, while the lower half is composed of coarse sand and gravel. The stratigraphy is a complex system of stream-channel sand and overbank deposits. Analyses of sampled cores (McElwee et al., 1991) and a multiwell tracer test (Bohling et al., 1995) indicate that a considerable degree of lateral and vertical heterogeneity in hydraulic conductivity exists in this alluvial sequence. The multiwell tracer test was performed in an extensive network of MLSs, an areal view of which is presented in Figure 3. The field experiments described in this presentation were performed in this MLS network. The well labelled DW (discharge well) was pumped and pressure responses were monitored in MLSs TMC-1 and TMC-3, and observation well TMO-1. In all cases, a constant rate of approximately 70 gpm was maintained for the duration of pumping. Pumped water was discharged at a considerable distance off site to prevent infiltration of discharged water from impacting measured responses.

FIELD TEST OF THE AIR PRESSURE TRANSDUCER

The laboratory calibrations described earlier indicate that air pressure changes in the MLS tubing are reflective of head changes in the formation under steady-state conditions. One of the first questions addressed in the field was whether this relationship is also viable for the measurement of transient pumping-induced drawdown. In order to assess performance under transient conditions, a length of MLS tubing was attached to a standard submersible pressure transducer as shown in Figure 4A. The submersible transducer and attached tubing were then placed below the static water level in observation well TMO-1 near the center of the MLS network shown in Figure 3. Figure 4B shows how the air pressure transducers, which are housed four to a box, are attached to the MLS tubing. A short length of tubing runs from the box housing the sensors to the MLS. This extension tubing, as well as that in the MLS, has a relatively low gas permeability to minimize air loss. Vacuum grease is used to minimize loss at the tubing connections.

Well DW was pumped for approximately 25 minutes. Measurements from the air and water pressure transducers were acquired at a sampling rate of 1 Hz. In addition, two readings of the water level in TMO-1 were obtained using an electric tape. Figure 5A compares the drawdown calculated from the air pressure transducer using the relationship of Figure 2B with that measured with the electric tape. Note the sensitivity of the air pressure transducer to the disturbance created by the electric tape. Figure 5B is a similar plot comparing drawdown calculated from the air pressure transducer with that from the

submersible water pressure transducer. Except for the divergences at points B and C, the air pressure transducer closely tracks the water pressure transducer. For example, both display the abrupt break in slope shown at point A. Divergences between the two records are primarily a product of the disturbances associated with the electric tape readings.

The conclusion that can be drawn from these data is that the air pressure transducers can provide very accurate measurements of transient head changes in the formation. However, these sensors do appear to be quite sensitive to external disturbances such as the jostling of the tube during measurement with the electric tape. Further evidence of this sensitivity will be presented in a later section.

CONVENTIONAL PUMPING TEST ANALYSIS OF MLS DRAWDOWN DATA

Research on pumping tests in heterogeneous formations has shown that changes in drawdown at early times are sensitive to the properties of the material lying between the pumping well and the observation point, while changes in drawdown at later times will be reflective of large volumetric averages of formation properties (Javandel and Witherspoon, 1969; Butler, 1990; Butler and Liu, 1993). Thus, regardless of whether the pumping and observation wells fully or partially penetrate the aquifer or of the radial location at which drawdown measurements are obtained, plots of the logarithm of time versus drawdown should be parallel at large dimensionless times of pumping. Figure 6 is a comparison of drawdown measured with a submersible pressure transducer in TMO-1 with that calculated from air pressure readings from Port 5 of MLS TMC-1. If slopes are calculated for the time interval between 30 and 300 seconds (interval designated as "Interval of Analysis" in Figure 6), the slope of the data from the air pressure transducer is within 5% of that calculated from the transducer in TMO-1. The close agreement between the slopes estimated from field data, which is what would be predicted from theory, is a further demonstration that pressure measurements from MLS tubing are reflective of pressure changes in the aquifer. Analysis of late-time drawdown data (Cooper-Jacob semilog method) from a number of pumping tests in which MLSs were used as observation wells yielded an average hydraulic conductivity of 421 ft/day, a value that is quite reasonable for the sand and gravel sequence at GEMS.

LATERAL AND VERTICAL VARIATIONS IN K

Although late-time drawdown data from MLSs can be analyzed with conventional methods to obtain estimates of the average hydraulic properties of an aquifer, the real promise of transient head data from MLS tubing lies in the characterization of lateral and vertical variations in hydraulic properties. In this section, results of preliminary field experiments are presented to illustrate the potential of such data.

A series of short-term pumping tests were performed in the MLS network using the field setup shown in Figure 7. Figure 8A displays the first 1000 seconds of drawdown at TMC-1 for ports 1, 3, 5, and 7 (spaced 4 ft apart in the vertical). Port 5 is opposite a layer of relatively high diffusivity, while port 7 appears to be screened in material of relatively low diffusivity. The disturbances recorded by all four sensors at A are due to an external surface disturbance and are not related to pressure changes in the aquifer. Figure 8B displays drawdown from the same period for ports 1, 3, 5, and 7 at TMC-3, which is approximately ten feet radially outward from TMC-1 (see Figure 3). A comparison of Figures 8A and 8B indicates that there is no longer a dramatic diffusivity contrast between the material opposite ports 1, 3, and 5. However, the low diffusivity layer at Port 7 appears continuous between TMC-1 and TMC-3. Although this comparison is highly qualitative in nature, it does reveal the significant potential for use of transient pumping-induced head data from MLSs for the characterization of interwell variations in hydraulic conductivity. Such information may be very difficult to obtain using other means.

CONCLUSIONS

A large body of research has shown that information about the spatial distribution of hydraulic conductivity is of considerable value at sites of suspected groundwater contamination. Knowledge of the existence of continuous zones of relatively high K, which can serve as preferential flow paths, is particularly useful. In this presentation, a new field method for the characterization of spatial variations in K between wells is described. This method is based on the use of transient drawdown data from the small diameter tubing of multilevel sampling wells. Two approaches for acquiring such data were presented. One approach uses fiber optic pressure sensors to obtain direct measurement of water pressure changes in the tubing, while a second approach uses the relationship between changes in air pressure and water pressure in airtight MLS tubing. Preliminary laboratory and field experiments have demonstrated the potential utility of the information that can be obtained with these approaches. Although additional issues must be addressed before high-quality drawdown data can be obtained from MLS tubing on a consistent basis, the approach does appear to have considerable potential for providing valuable additional information about spatial variations in hydraulic properties.

REFERENCES

Boggs, J.M., S.C. Young, H.F. Hemond, L. Richardson, and M.E. Schaefer, 1988, Evaluation of tracer sampling devices for the macrodispersion experiment, Electric Power Research Institute (EPRI), Research Project 2485-5, Interim Report.

Bohling, G. C., 1993, Hydraulic tomography in two-dimensional, steady-state groundwater flow [abstr.], Eos, 74(16), p. 141 [also: KGS Open-File Report 93-17, 15 pp.].

Bohling, G. C., C. D. McElwee, J. J. Butler, Jr., M. Orcutt, and G. L. Macpherson, 1995, GEMSTRAC1 - an induced gradient tracer test in an alluvial sand and gravel aquifer [abstr.], Abstracts. Week A, IUGG XXI General Assembly: Geophysics and the Environment, p. A231.

Boman, G.K., F.J. Molz, and K.D. Boone, 1997, Borehole flowmeter application in fluvial sediments: Methodology, results and assessment, Ground Water, 35(3), 443-450.

Butler, J.J., Jr., 1990, The role of pumping tests in site characterization: Some theoretical considerations, Ground Water, 28(3), 394-402.

Butler, J.J., Jr. and W.Z. Liu, 1993, Pumping tests in nonuniform aquifers: The radially asymmetric case, Water Resour. Res., 29(2), 259-269.

Butler, J.J., Jr., C.D. McElwee, and W.Z. Liu, 1996, Improving the quality of parameter estimates obtained from slug tests, Ground Water, 34(3), 480-490.

Copty, N., Y. Rubin, and G. Mavko, 1993, Geophysical-hydrological identification of field permeabilities through Bayesian updating, Water Resour. Res., 29(8), 2813-2825.

Dagan, G., 1986, Statistical theory of groundwater flow and transport: Pore to laboratory, laboratory to formation, and formation to regional scale, Water Resour. Res., 22(9), 120S-134S.

Gelhar, L.W., 1986, Stochastic subsurface hydrology from theory to applications, Water Resour. Res., 22(9), 135S-145S.

Hess, K.M., S.H. Wolf, and M.A. Celia, 1992, Large-scale natural gradient tracer test in sand and gravel, Cape Cod, Massachusetts, 3. Hydraulic conductivity variability and calculated macrodispersivities, Water Resour. Res., 28(8), 2011-2027.

Hubbard, S.S., Y. Rubin, and E. Majer, 1997, Ground-penetrating-radar-assisted saturation and permeability estimation in bimodal systems, Water Resour. Res., 33(5), 971-990.

Javandel, I., and P.A. Witherspoon, 1969, A method of analyzing transient fluid flow in multilayered aquifers, Water Resour. Res., 5(4), 856-869.

Jensen, K.H., K. Bitsch, and P.L. Bjerg, 1993, Large-scale dispersion experiments in a sandy aquifer in Denmark: Observed tracer movements and numerical analyses, Water Resour. Res., 29(3), 673-696.

Kabala, Z.J., 1993, The dipole flow test: A new single-borehole test for aquifer characterization, Water Resour. Res., 29(1), 99-107.

McElwee, C.D., J.J. Butler, Jr., and J.M. Healey, 1991, A new sampling system for obtaining relatively undisturbed samples of unconsolidated coarse sand and gravel, Ground Water Monitoring Review, 11(3), 182-191.

Photonetics, 1996, Fiber Optic Probe Guide.

Pickens, J.F., J.A. Cherry, G.E. Grisak, W.F. Merritt, and B.A. Risto, 1978, A multilevel device for ground-water sampling and piezometric monitoring: Ground Water, 16(5), 322-327.

Taylor, K., S. Wheatcraft, J. Hess, F. Molz, 1990, Evaluation of methods for determining the vertical distributions of hydraulic conductivity: Ground Water, 28(1), 88-98.

Wolthuis, R.A., G.L. Mitchell, E. Saaski, J.C. Hartl, and M.A. Afromowitz, 1991, Development of medical pressure and temperature sensors employing optical spectrum modulation, IEEE Trans. on Biomedical Engineering, 38(10), 974-981.
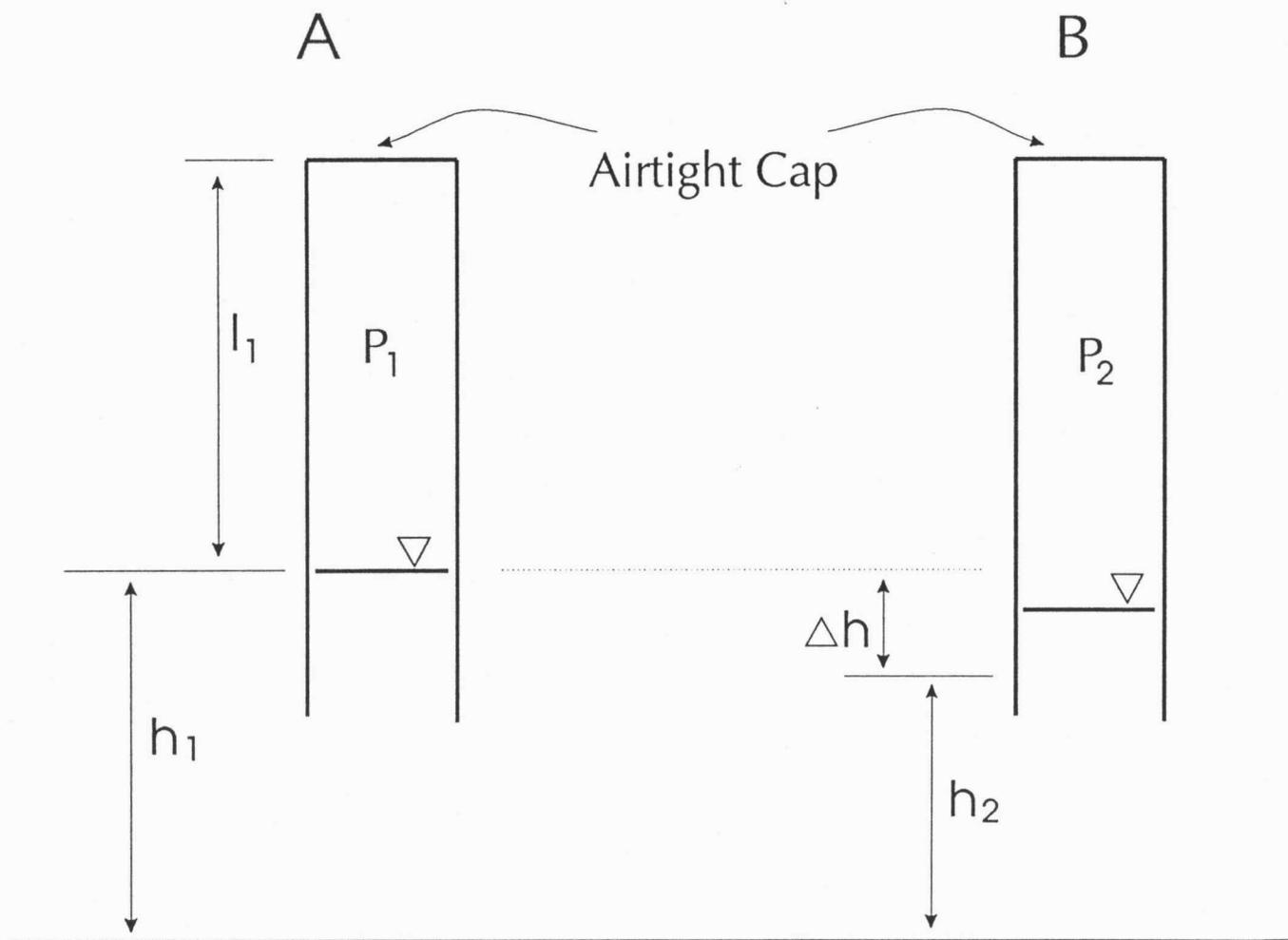
15

FIGURE 1
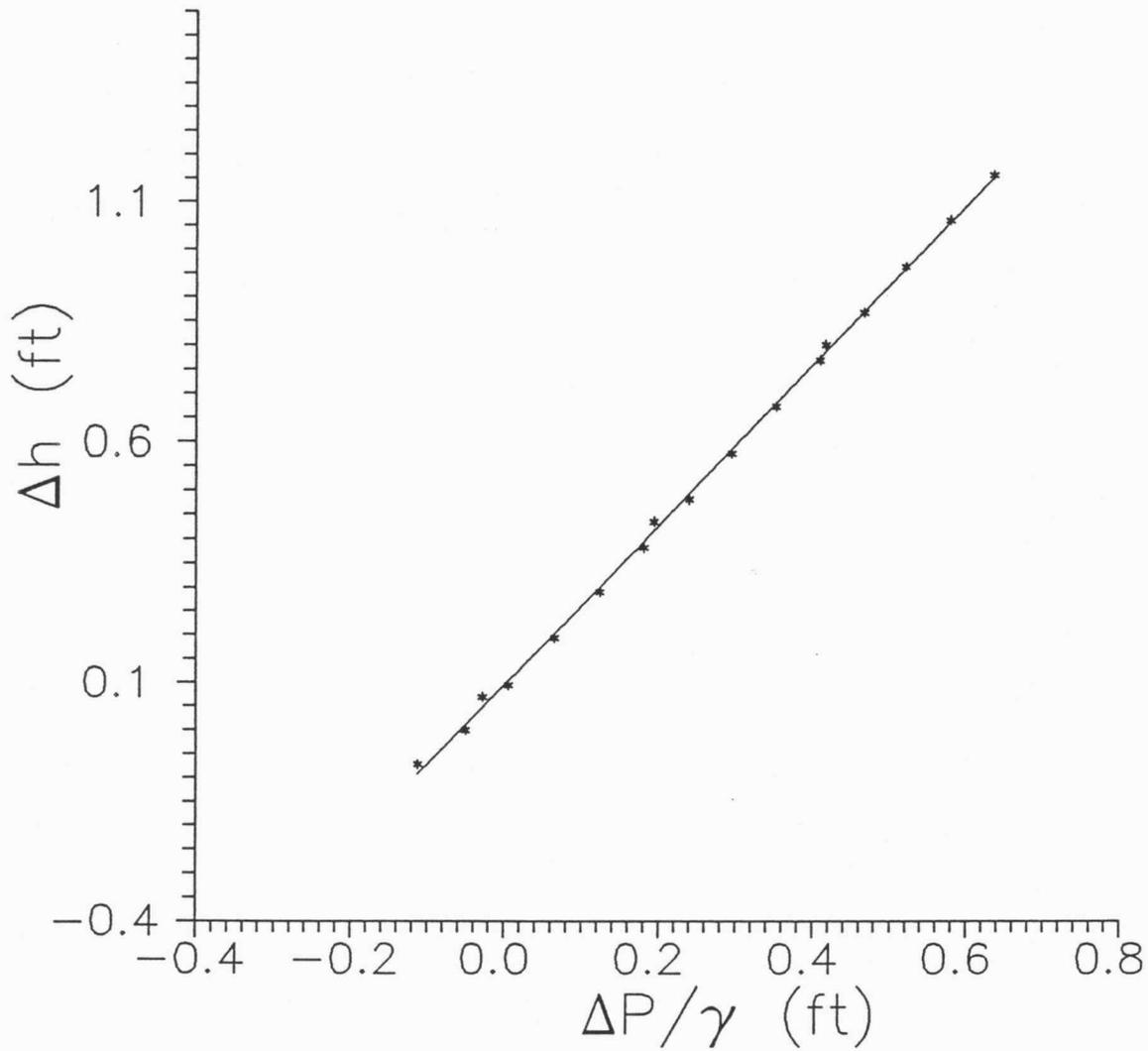
FIGURE 2A
Calibration #2 — 5/13/97

FIGURE 2B
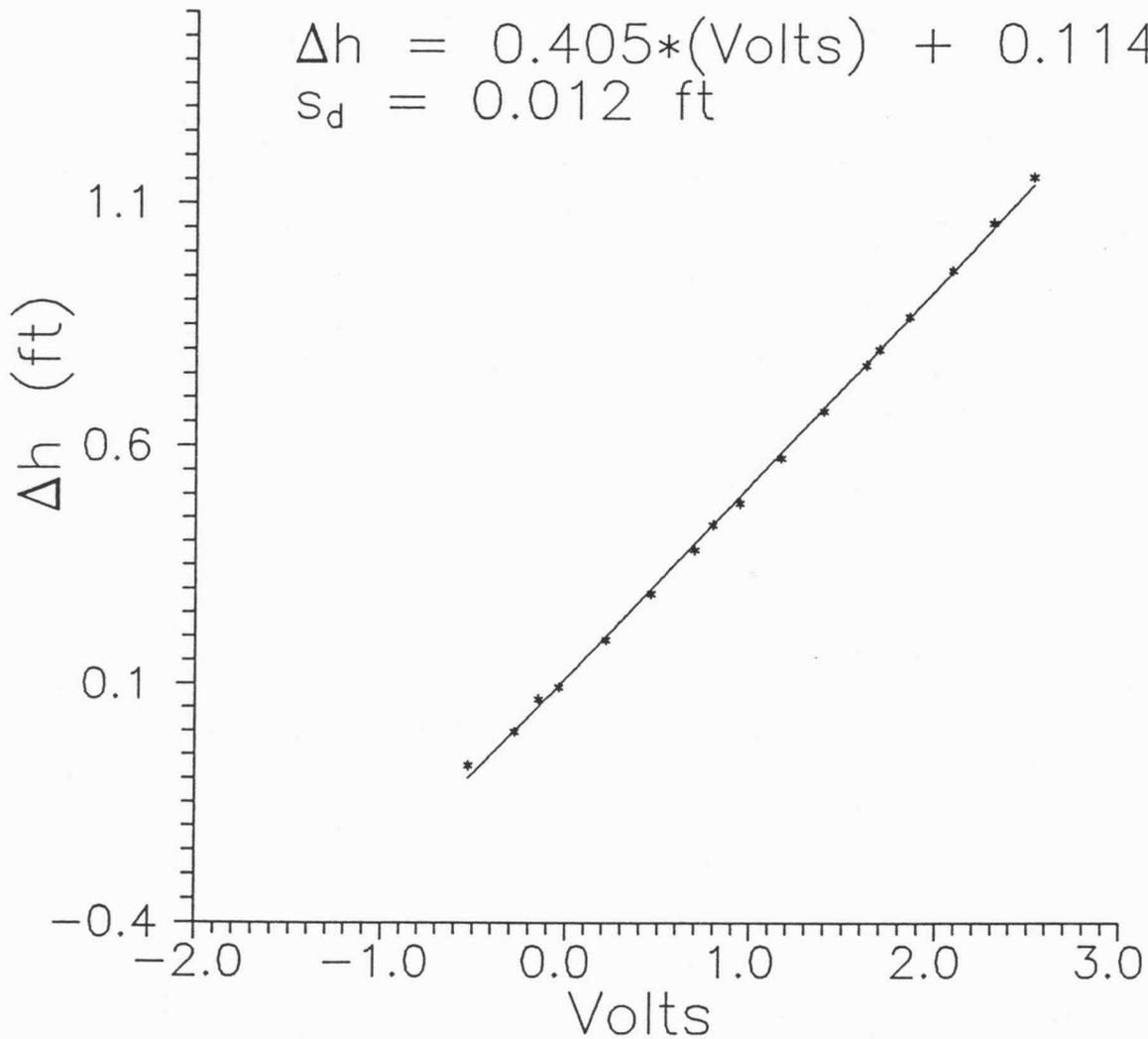Calibration #2 − 5/13/97
Box 1, Channel 1
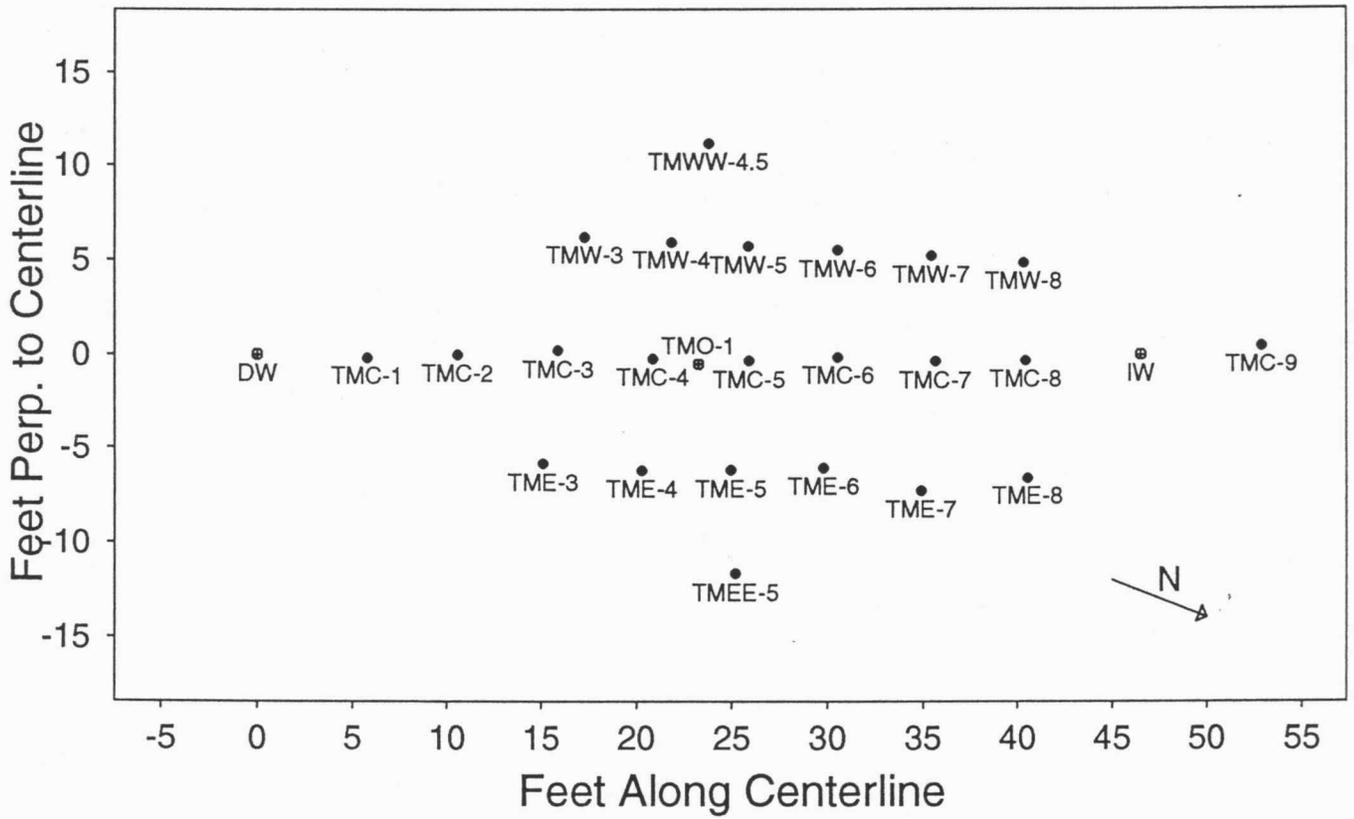
$\Delta h = 0.405*(Volts) + 0.114$
$s_d = 0.012$ ft

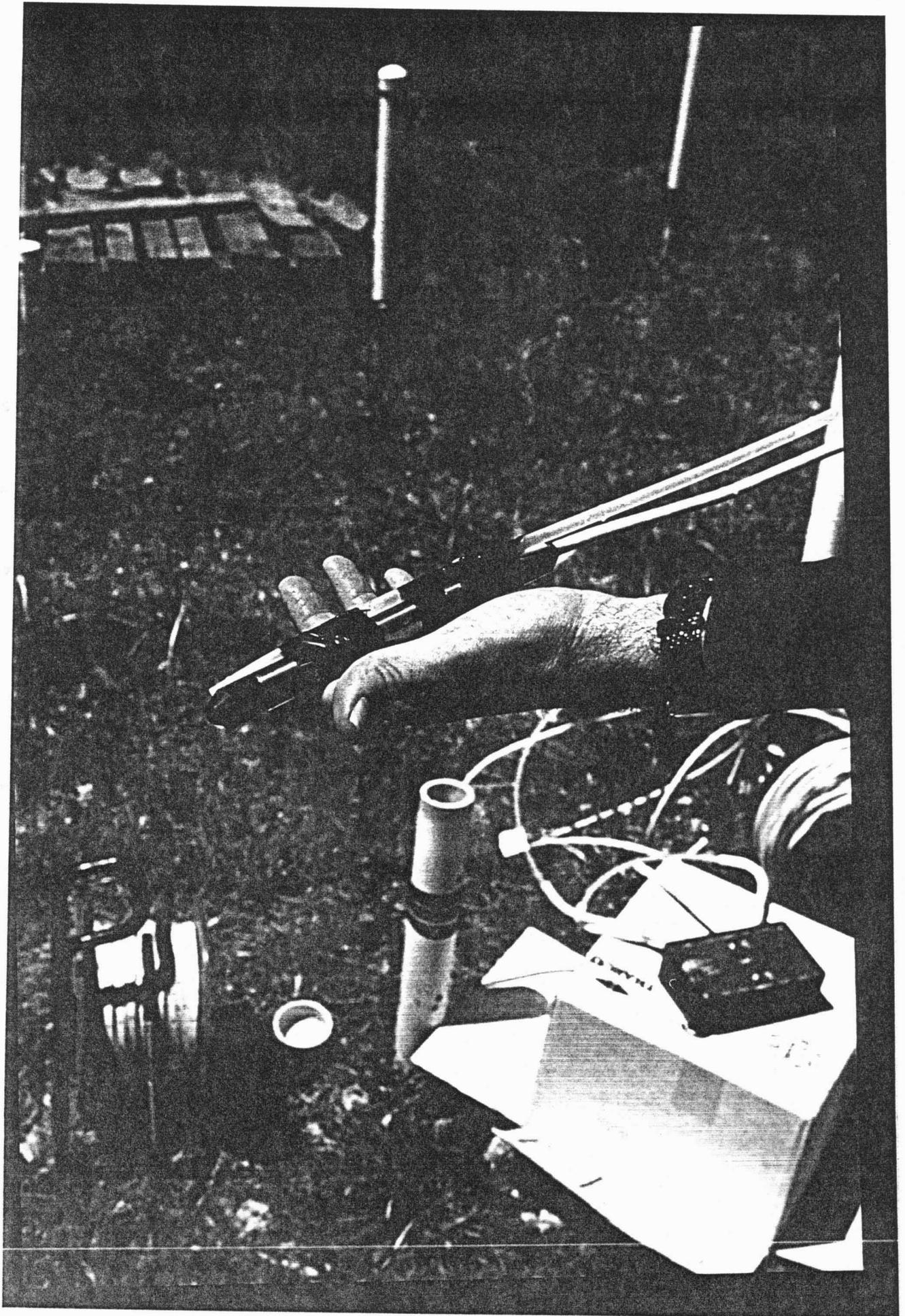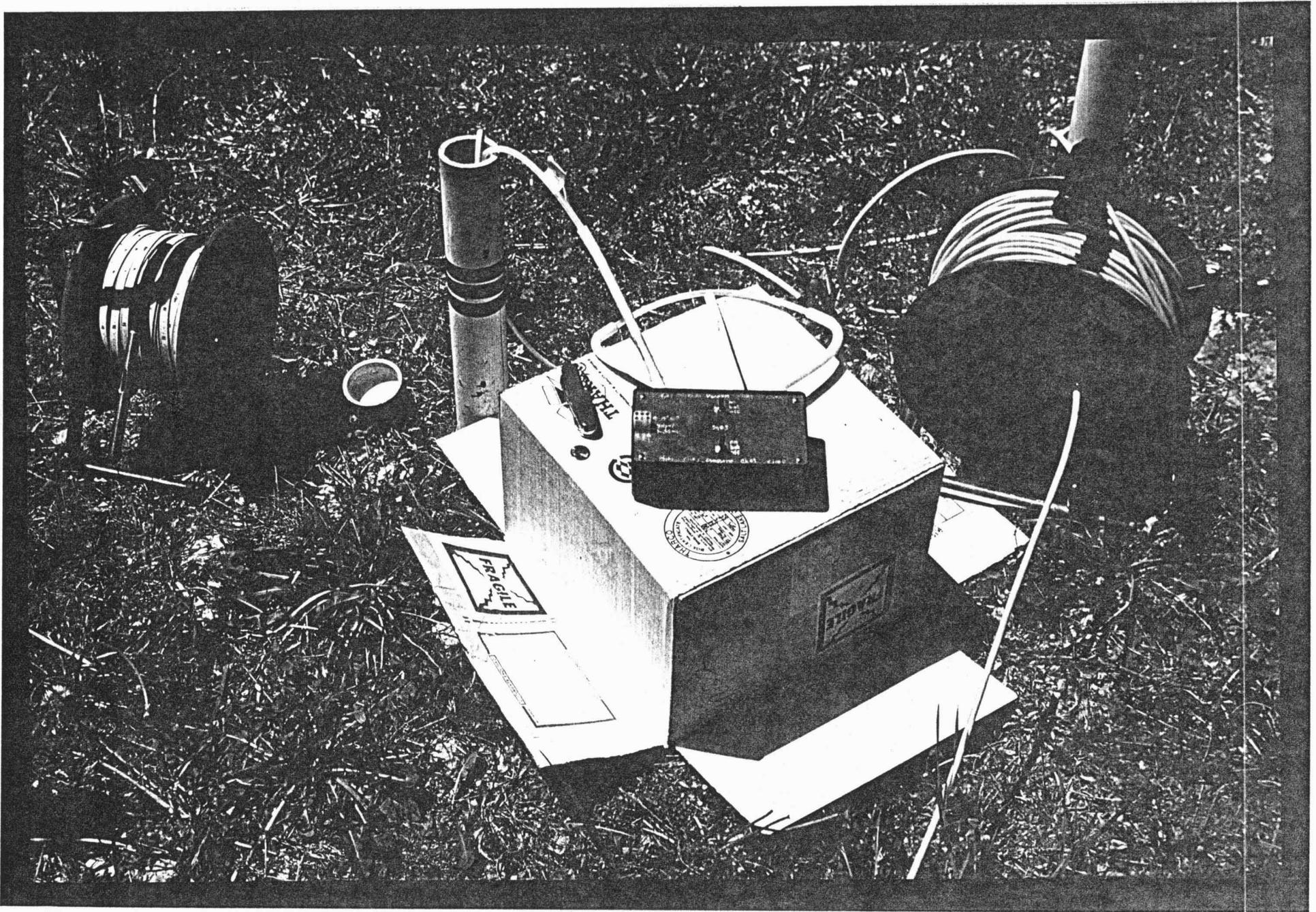Figure 3: Areal View of Sampling Network

Figure 4A

Figure 4B

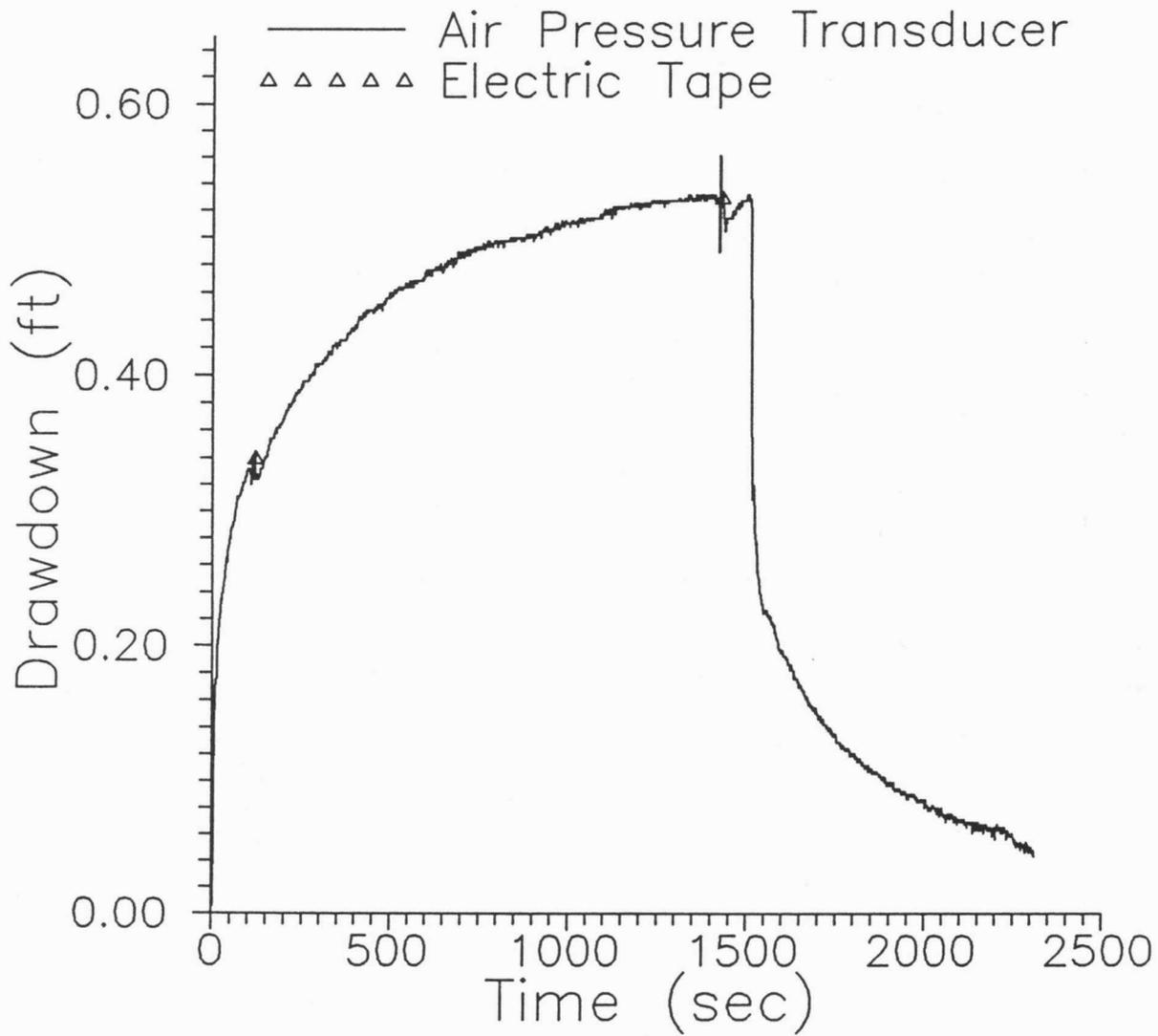FIGURE 5A
GEMS — TMO-1
PUMPING TEST #1 — 5/16/97
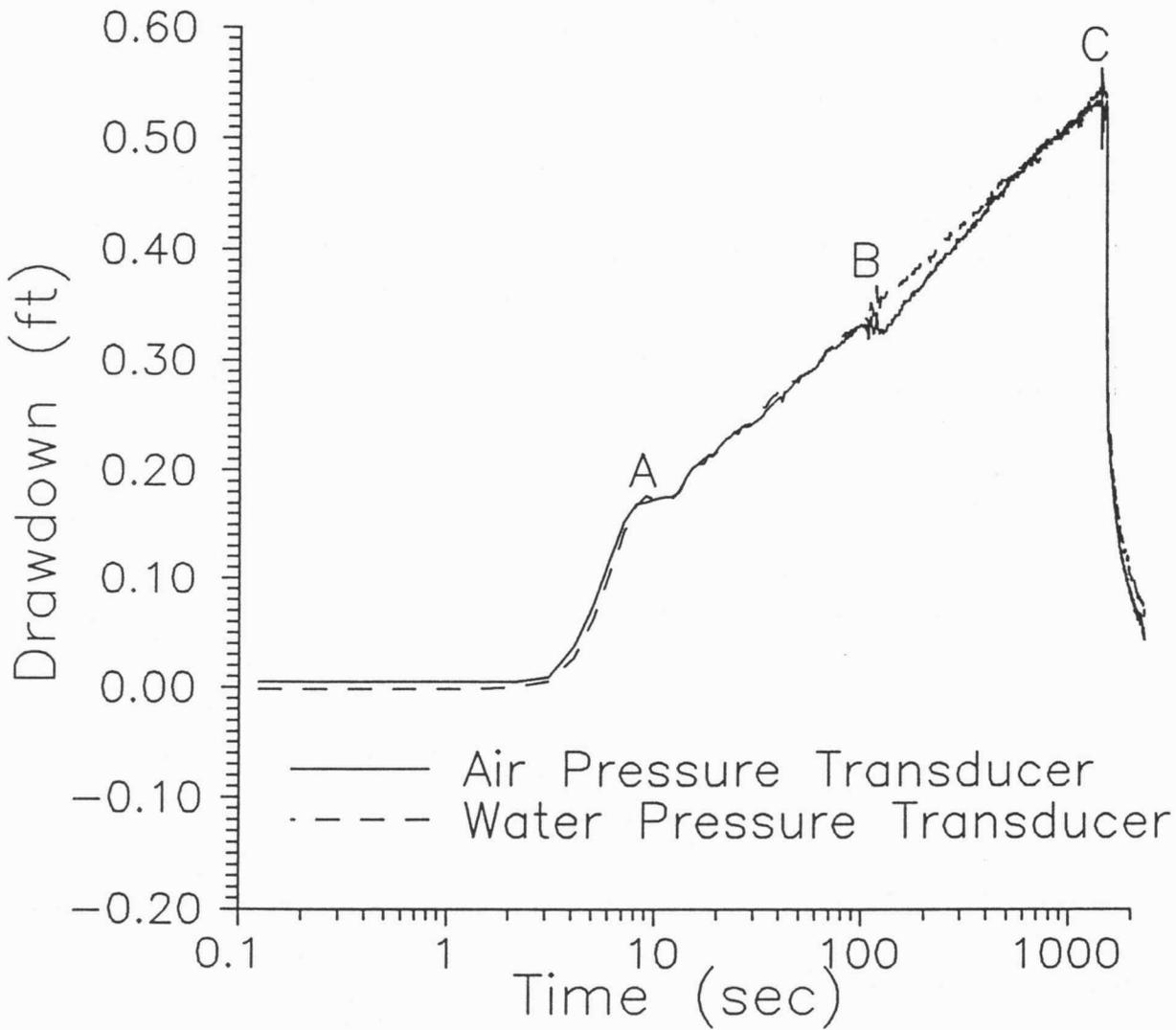
FIGURE 5B
GEMS — TMO-1
PUMPING TEST #1 — 5/16/97

FIGURE 6
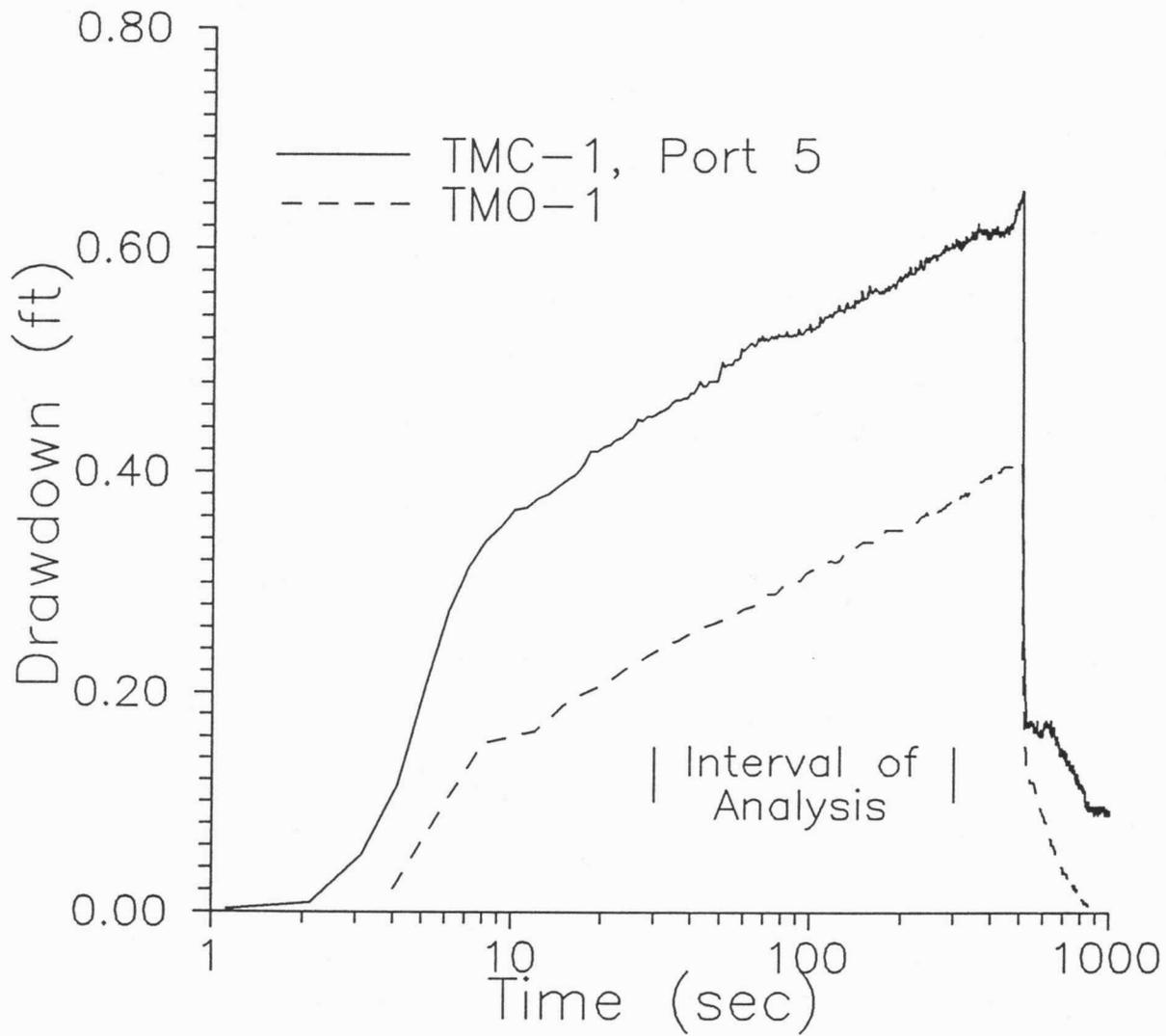GEMS — TMO—1 and TMC—1
Pumping Test #4 — 5/16/97
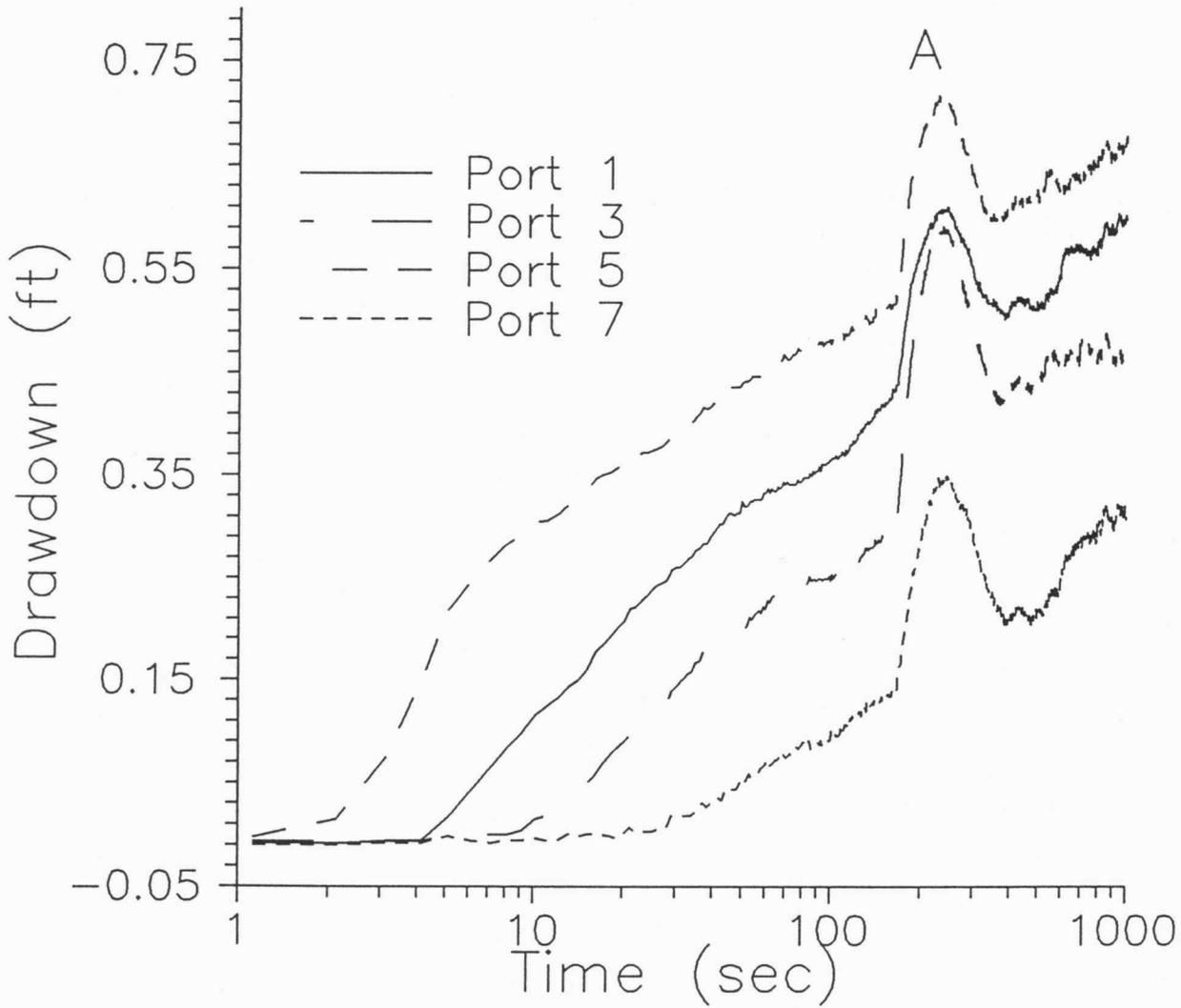
Figure 7

FIGURE 8A
GEMS — TMC—1
Pumping Test #2 — 5/16/97

FIGURE 8B
GEMS — TMC—3
Pumping Test #2 — 5/16/97