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Hydrogeologic Site Assessment of the Engineering Geoscience Well Field at the Richmond Field Station, Contra Costa County, California

Gregory W. Pouch

Engineering Geosciences

Department of Materials Science and Mineral Engineering

Hearst Mining Building

University of California, Berkeley

Berkeley, CA 94720

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ABSTRACT

The Engineering Geoscience group at the University of California at Berkeley has drilled an Injection, an Extraction, and six observation wells at the Engineering Field Station in Richmond (Richmond Field Station). The group plans to trace an injected slug of saltwater using electrical resistivity.

Analysis of driller's logs indicates that the unconsolidated sediments underlying the field station were deposited in a deltaic environment. In the lower alluvial sequence, depositional strike appears to be east-west. In the fluvial parts of the sequence, lenticular bodies of sand and gravel in a clay matrix serve as the main avenues of conduction, although storage in and leakage through the surrounding clays must be taken into account. There appear to be extensive layers which have been deposited under marine or quasi-marine conditions.

Hydraulic head measurements indicate that the wells are set in at least three different aquifer zones. Pump-test data confirm two of the zones and one pump test indicated significant leakage to the pumped aquifer. A third pump test indicated connection between the Sanitation Engineering Well Field 500' to the east and the southern three wells. The northern and southern wells are not in the same aquifer zone.

1. Introduction

The Richmond Field Station is located in the southeastern quarter of the Richmond Quadrangle (1:24 000), at approximately 37° 55′ N, 122° 20′ W. (see Figure 1.) The Engineering Geoscience Well Field is located in the field west of Building 300, the Sanitation Engineering Well Field is about 300 feet east of Building 300. (see Figure 2.) The ground surface at the Engineering Geoscience Well Field is about 17' above mean sea level.

The purpose of this investigation is to delineate the geologic and hydrologic conditions underlying the Engineering Geoscience Well Field, with particular regard to contaminant migration paths. This is of interest as part of a study by the Engineering Geoscience group at the University of California at Berkeley to test the feasibility of using surface and borehole-to-surface geophysics to track groundwater contamination (Morrison and others, 1986). The hope is to use electrical resistivity methods to track the movement of the electrically more conductive saltwater to be injected and recovered in the Engineering Geoscience wells. As leachate from municipal landfills, various holding ponds, and other sources often contains an anomalously high concentration of total dissolved solids, this experiment has the potential of assisting in the assessment and remediation of numerous groundwater contamination sites.

In the 1950's, the Sanitation Engineering group did an experiment at the Richmond Field Station on the migration of contamination; this resulted in at least twenty wells drilled and set in a gravel and sand layer which apparently correlates with the Maria gravel (see section on geology, Figure 11, and Appendix 1). The well casings of the Sanitation Engineering wells are severely rusted and it is unlikely that they are open only at their original perforations. Head measurements made in these wells could be misleading due to contact with other aquifer zones (see Davis and DeWiest, 1966, pp. 51-52). The location of the Sanitation Engineering Well Field is shown in Figure 2 and a map of the wells, the well logs, and other data gathered there is included in Appendix 2.

In August and September of 1986, the Engineering Geoscience group had two six-inch (INJ and EXT) and six four-inch (OBS 1 to 6) wells drilled by Smitty's Drilling of Oakland. (see Figure 3 for locations.) The designations of Extraction and Injection wells were based upon an assumed regional groundwater flow to the south; in reality, all the wells could be used for either purpose. The original names are retained to avoid confusion. The driller's logs are presented as drafted stratigraphic columns in Figures A1-A8 and in Appendix 1, along with the interpreted correlations and inferred environments of deposition. The wells were drilled and constructed under the supervision of Ted Asch, who also took SP, resistance, and gamma-ray logs. (see Appendix 1.) Analysis of some of the geophysical logs confirms the driller's logs, which contain more useful data such as color of some units and occurrence of scattered gravel.

The locations of the wells can be seen in Figure 3, and the surveyed locations are listed in Table 1. Note that "north" refers to grid north determined by the line joining OBS 1, INJ and OBS 4; this closely corresponds to north as determined by Brunton compass. The origin for the coordinate system is the INJ (injection) well. No azimuth markers survive at the Richmond Field Station, so the actual geodetic azimuth is unknown. The horizontal control was obtained with a theodolite with three-wire level for bearings and distances, respectively. Vertical control was obtained by levelling.

Throughout this report, English units are used except where otherwise noted. 34.'20 means thirty-four and twenty hundredths feet. "Gradient to the east" means the east end is lower than the west end (east is downhill).

Table 1. Surveyed locations of wells at Richmond Field Station Engineering Geoscience Well Field.

Distances are in feet. Elevations are relative to mean sea level, as noted in the section on total head measurements.

Well	Northing	Easting	Elevation	Well
INJ	0.00	0.00	18.371	INJ
EXT	-203.40	1.20	18.351	EXT
OBS 1	55.10	0.00	18.314	OBS 1
OBS 2	-45.00	-28.30	18.843	OBS 2
OBS 3	-43.20	31.00	18.462	OBS 3
OBS 4	-124.70	0.00	18.236	OBS 4
OBS 5	-264.10	-0.80	18.236	OBS 5
OBS 6	2.60	99.70	17.784	OBS 6

2. Geology

The Richmond Field Station is located on the alluvial fan/delta built by Wildcat and San Pablo creeks. This is a semi-arid alluvial fan which extends from the Berkeley Hills down to San Pablo Bay (northern part of San Francisco Bay) and is semi-circular in plan view. While the area has been inhabited for some time, so that the contours are influenced by construction, it appears to be a typical fan, with radiating distributary channels and floodplains. The Bay shore is dominated by muds, although occasional gravel beaches and sand beaches occur.

Examination of driller's logs (Appendix 1, Figures A1-A8) indicates that the Richmond Field Station is underlain by deltaic deposits. This is particularly evident from the occurrence of layers which can be correlated across the entire well field and intervening zones in which a variety of clastic deposits cannot be correlated between adjacent wells. In particular, one can recognize a regressive sequence (coarsening upward) in OBS 4 between 90' and 95', where sand and gravel overlie brown clay which overlies gray clay, indicating an increase in energy with time (further onshore).

Evidence of fluvial deposition can be seen in OBS 5 between 82' and 87', where tan clay overlies sand and gravel which overlies coarse gravel (a classic point bar sequence), and at several other such sequences scattered throughout the well field. Gravel clay is also evidence of non-marine deposition: wave action strong enough to move gravel would winnow out clays. A more likely source is that the gravels were deposited in a river channel under high flow conditions during the winter rainy season and the clays were deposited under low flow conditions during the summer dry season. In addition, the numerous sequences where no correlations are seen probably represent fluvial sediments.

Figures 5-7 and 11 are stratigraphic correlation diagrams. Figures 5-9 are overlays for Figure 4a, which is an isometric drawing of the five northern wells (INJ, OBS 1, OBS 2, OBS 3, and OBS 6). Figure 8 shows the positions of the well screens and gravel packs and Figure 9 shows the relative proportions of fine and coarse material encountered in ten-foot vertical intervals. Figure 10 shows the graphic well logs of OBS 1, INJ, OBS 4, EXT, and OBS 5 and the intersection of the OBS 2-OBS 3 section with the north south line plotted in their correct positions along the north-south line; Figure 11 is the corresponding correlation diagram. Figure 12 shows the positions of screens and gravel packs and the relative portions of coarse and fine materials in ten-foot vertical intervals. The symbols used on all correlation diagrams and graphic well logs are standard lithologic symbols, which are also shown on Figure 4b for convenience. In the geologic sections and interpreted well logs, feminine names denote inferred aquifer zones and masculine names denote inferred aquitard zones. Beds were named solely to facilitate discussion.

Correlations were drawn on the basis of maximizing the number and extent of horizontal sand and gravel layers. This is based on the assumption that the unconsolidated sediments have not been significantly deformed or tilted since deposition. Sands and gravels are rare enough that they are considered correlations. Clays were not correlated unless they were sandwiched by sand and gravel layers or appeared to have the same redox state (gray and green reduced clays were correlations, brown and tan oxidized clays were correlations) or some other distinctive feature such as the presence of gravel. Old Bay Mud was also considered grounds for correlation. White areas on the stratigraphic correlation diagrams were left where no correlations were obvious and probably represent fluvial deposits. These sediments are overwhelmingly dominated by clays. (see Figures 9 and 12.) In the fluvial portions of the sequence, sands and gravels occur as lenses set in a clay matrix.

The sequence from 55' to 83' where the sequence of the Tom Old Bay Mud, the Becky sand and gravel, the Ted clay (reduced to the south, oxidized to the north) and the Cindy sand and gravel occurs in all the wells except OBS 1 is almost certainly the result of marine (estuarine) deposition. In addition, sand and gravel layers seem to coalesce to the north while the extensive clay layers seem to pinch out northward. This would indicate that the paleo-shoreline was to the north of the sea, as it is presently.

OBS 6 has an excessive amount of clay. This could be due to simple chance, caving during drilling and logging of the caved debris or perhaps even soft-sediment deformation.

It should be emphasized that all the above geology is based on the driller's logs: cuttings were not saved during drilling, and, of course, visual inspection of the deposits for sedimentary features was impossible. These limitations should be born in mind when viewing the cross-sections and fence diagrams. The continuity of certain deposits and the repetition of the same sequence in different wells, however, lend a fair amount of credence to the geologic interpretation.

Bearing in mind that the data on hand is limited to texture and occasionally color, the following geologic history is proposed. Deposition of the lower alluvial units (Lauren gravel, Mike gravel clay and others) to the north and possibly marine/possibly fluvial units to the south, (Maria gravel and others) began with initial subsidence of the Bay. A later sea level rise (possibly the Sangamon Interglacial highstand) resulted in deposition of the lower marine sequence (Tom, Becky, Ted, Cindy, unnamed clays, Jennifer). A drop in sea level or progradation of the shoreline resulted in deposition of an upper alluvial sequence (roughly between 24' and 56' near OBS 2 and OBS 3) with intertonguing marine (or at least rather extensive) deposits including the Lisa sand and gravel, which could be a beach/nearshore or channel deposit. The uppermost units (Brian to Kathy) could be the result of another era of marine deposition, or they could just be landfill.

This scenario is in general agreement with the ideal stratigraphic column of Atwater and others (1977) in which Holocene estuarine (Qhe) and alluvial deposits (Qha) overlie Pleistocene-Holocene (Wisconsin) alluvial (Qpha), terrestrial (Qpht) and eolian (Qphw) deposits which overlie Pleistocene (Sangamon) estuarine deposits (Qpe) which overlie and intertongue with Pleistocene alluvial deposits (Qpa) which rest on bedrock. The upper marine sequence would correspond to the Holocene estuarine deposits (Qhe), the upper alluvial deposits would correspond to the Pleistocene-Holocene alluvial sediments (Qpha) deposited during the low sea levels of the Wisconsin Glaciation, the lower marine sequence would correspond to the estuarine sediments (Qpe) deposited during world sea-level rise of the Sangamon Interglaciation, and the lower alluvial sequence would correspond to the late Pleistocene deposits (Qpa) of pre-Sangamon age.

The Lauren gravel is thickest in INJ (10') and OBS 6 (14'), thins to a 1' sand layer in OBS 1 to the north and a 1' gravel and sand layer in OBS 2 and OBS 3 at depths of 98', 95', 105', 101' and 103' respectively. This results in an east-west striking diamond shaped bar, which could be a channel deposit or a distributary mouth bar. The great thickness speaks against a subaerial river deposit, whose thicknesses rarely exceed the channels' depth. Although a river channel is possible, an east-west mouth bar better explains the thickness and shape.

The Maria gravel is observed in OBS 5 (5' thick, 100.'5 deep) and EXT (7' thick, 101' deep) and seems to continue as a 1' sand layer at 107' and a 1' sand and gravel at 108.'5 in OBS 4. This was deposited in some high energy environment, possibly marine. It is only seen in the three southern wells, which lie on a north-south line. A connection to the Lauren gravel seems unlikely, although pump test results indicate a connection to the Sanitation Engineering Well Field "aquifer".

Bill Dietrich (pers comm., 1987) has expressed curiousity about the lack of sand in the stratigraphic section. This is a legitimate concern. It is possible that sands were not recognized in the cuttings, although the occasional sand layer/lens speaks against this. I feel it likely that the source regions (the Berkeley Hills) consist of rocks which do not weather to sand-sized fragments. Observations of stream cuts in the East Bay show a colluvium of clay with pebbles in it and no observed sand. Given the local geology, the absence of sand is not surprising.

It should be pointed out that the extensive gravel layers could be due to braided streams or fortuitous intersection of a channel deposit, although in most cases this seems unlikely. A very large area would need to be blanketed by sands and gravels to produce such layers, which, if sloping, would be very vulnerable to landslides and rainwash erosion; such an occurrence would be a very good source for a turbidite.

On the basis of the geologic correlations, it appears that groundwater flow at the Richmond Field Station will be channeled into the former river channels, distributaries and marine beach/nearshore deposits. This piping will result in complicated and tortuous flow paths in the channel and bar finger deposits, although flow in the marine (estuarine) parts of the sequence may approach that of ideal confined aquifers due to the lateral extent and uniformity of these deposits.

3. Hydrology

The hydrology of the Richmond Field Station is complex and is controlled by the geological framework within which flow occurs. The hydrologic data gathered comprises "static" water levels (head measurements), pump tests of the INJ and EXT wells, and continuous records obtained with

Steven's recorders. A series of water level measurements in the Sanitation Engineering Well Field were taken in March.

The water level in B8 (see map in Appendix 2) on 30 March 1987 was 9.'34 while EXT (to the west) was at 7.'80, indicating flow to the west if the water levels in the Sanitation Engineering wells can be trusted.

The continuous records showed drawdown of a few centimeters due to transient pumping once or twice a week, probably from the Sanitation Engineering production well to the east, and little else. The Steven's records were discontinued in early December because they provided little useful information, were unreliable, and required a large effort to obtain. A Steven's gauge record is included as Figure 13.

Flow patterns in individual units are not necessarily the same, and in fact the gradient between INJ and OBS 6 is usually to the west while OBS 2 usually has a higher head than OBS 3 to the east. (Slopes are in opposite directions for the two east-west profiles only 50' apart.) Each aquifer zone is capable of behaving independently, particularly in response to pumping. Heads from wells set in one aquifer zone cannot be projected to another aquifer zone and used to determine flow there. (see Davis and DeWiest, 1966.)

3.1. Water Level Measurements

The depth to water in wells was obtained using the chalked tape method. In this method, a weight (in this case an eight-ounce fishing weight) is attached to the end of a survey tape to keep it taut and the tape is lowered into the well, keeping an even number of feet at the top of the well next to some surveyed point on the casing. When the tape is withdrawn from the well, the reading at the top of the wetted zone is recorded, along with the reading at the top of the well. The difference between the two is the depth to water (DTW). The principle is the same as reading the oil dipstick in a car. This method has an accuracy of 0.'01, although misreads (0.'05, 0.'10, and 1.'00 mistakes should be most likely.) can occur.

Elevations were obtained by levelling with a Leitz level and self-levelling dumpy level. Closure for the loop containing the Engineering Geoscience wells was 0.'017 for five level stations, 0.'013 for five level stations linking the Engineering Geoscience and Sanitation Engineering well fields, and 0.'014 for a four level station loop linking the Sanitation Engineering well field with the police station benchmark labelled "19.02 +/- 0.005 U.S.C.S". This leads to a cumulative accuracy for each well elevation (distributing the closure equally amongst the sights) of 0.'0055.

Total head is the elevation of the water level in the well. Total head is obtained by subtracting the depth to water from the elevation. The resulting heads have an accuracy of about 0.'01. The water levels in the Engineering Geoscience wells are presented as a series of cross-sections in Figures 14 through 18.

Inspection of the water-level sections (Figures 14 through 18) and Table 2 indicates that the wells fall into three logical groups: OBS 6 and INJ; OBS 1, OBS 2, and OBS 3; and OBS 4, OBS 5, and OBS 6. The first two groups are always close to each other in head; the third group is sometimes three or four feet lower, as they were on 5 December 1986 and 18 February 1987.

Table 2. Total Head in Engineering Geoscience Wells.

Values are in feet above mean sea level. See text for methodology.

DATE	INJ	EXT	OBS 1	OBS 2	OBS 3	OBS 4	OBS 5	OBS 6
8 NOVEMBER 1986	5.67	5.46	5.84	6.27	5.89	5.67	5.64	5.87
18 NOVEMBER 1986 16:27 16:53	5.38	5.29	5.61	6.10	5.55	5.34	5.07	5.63
5 DECEMBER 1986 14:52 15:20	5.48	2.69	5.42	5.68	5.04	2.77	2.30	5.32
5 DECEMBER 1986 15:20 15:39	5.47	2.73	5.36	5.63	5.03	2.85	2.32	5.28
30 JANUARY 1987 16:56 17:25	6.81	7.07	6.81	6.98	6.97	7.06	7.17	6.92
3 FEBRUARY 1987 15:45 16:41	6.94	7.17	6.97	7.13	7.13	7.16	7.32	7.06
6 FEBRUARY 1987 11:01 11:26	6.99	7.23	7.01	7.17	7.16	7.21	7.36	7.10
6 FEBRUARY 1987 12:30 12:52	6.99	7.23	7.01	7.17	7.17	7.22	7.37	7.11
6 FEBRUARY 1987 14:35 14:56	7.00	7.23	7.02	7.18	7.17	7.22	7.36	7.11
6 FEBRUARY 1987 17:39 17:52	6.99	7.22	7.02	7.18	7.17	7.21	7.35	7.11
18 FEBRUARY 1987 16:51 17:15	6.80	2.34	7.00	7.32	6.45	2.33	1.26	6.92
23 FEBRUARY 1987 10:44 11:04	7.14	7.27	7.17	7.35	7.27	7.24	7.39	7.28
1 MARCH 1987 13:46 14:07	7.36	7.58	7.39	7.55	7.53	7.56	7.71	7.47
7 MARCH 1987 17:02 17:21	7.52	7.80	7.53	7.69	7.68	7.77	7.93	7.65
9 MARCH 1987 17:50 16:10	7.55	7.83	7.56	7.71	7.71	7.79	8.01	7.66
16 MARCH 1987 18:00 18:20	7.65	7.95	7.66	7.82	7.83	7.91	8.09	7.76
23 MARCH 1987 15:51 16:15	7.60	7.88	7.62	7.80	7.78	7.84	7.93	7.70
30 MARCH 1987 14:23 14:44	7.52	7.80	7.56	7.70	7.62	7.76	7.92	7.64
7 JULY 1987 14:37 15:09	6.03	6.13	6.05	6.17	6.14	6.12	6.23	6.12
DATE	INJ	EXT	OBS 1	OBS 2	OBS 3	OBS 4	OBS 5	OBS 6

OBS 6 and INJ are both set in the Lauren gravel bar. As mentioned earlier, this seems to be an east-west striking distributary mouth bar deposit. All observations but 5 December 1986 indicate flow to the west; on 5 December 1986, the flow was to the east. After 3 February 1987, head in OBS 6 is about 0.'12 higher than that in INJ; before this date, it varies more, up to a difference of 0.'25 on 18 November 1986. The typical gradient is 0.0013 or a grade of 0.13% to the west. Note that this is only the east-west component and there could be a north south-component as well.

OBS 1, OBS 2 and OBS 3 have thick gravel packs (around 60') which bridge the Lauren gravel, the Nathalie gravel, and the Jennifer gravel; OBS 2 and OBS 3 also connect with the Cindy sand and gravel. None of these wells should be thought of as piezometers. (see below.) OBS 2 and OBS 3 are usually equal in head as on 30 January 1987 through 6 February 1987 and 1 March 1987 through 23 March 1987. On 23 February 1987 and 30 March 1987, OBS 2 was 0.'08 higher than OBS 3, giving a "gradient" of 0.0014 or 0.14% to the east. Note that this is the opposite that in INJ and OBS 6. On 8 November 1986, 18 November 1986, and 5 December 1986, and 18 February 1987, OBS 2 had a much higher head than OBS 3 (0.'36, 0.'65, 0.'62 and 0.'87 respectively), resulting in "gradients" of 0.006 to 0.014 (0.6% to 1.4%).

OBS 1 is usually 0.'16 lower than the average of OBS 2 and OBS 3 (the interpolated value at the N-S line between the two wells). This would give a "gradient" of 0.0016 or 0.16% to the north. On 5 December 1986, OBS 1 was 0.'05 higher than the average of OBS 2 and OBS 3. On 8 and 18 November 1986, OBS 1 was 0.'24 and 0.'21 lower than the average of OBS 2 and OBS 3.

The head in OBS 1 is usually equal to or 0.'03 higher than the head in INJ. On 5 December 1986 OBS 1 was 0.'08 lower than INJ, and on 18 February 1987, OBS 1 was 0.'20 higher than INJ. Under normal conditions, there is no flow from INJ to OBS 1 or the "gradient" is 0.0005 or 0.05% to the north. The head in INJ is usually lower than the average of OBS 2 and OBS 3 by varying amounts, with 5 December 1986 and 18 February 1987 being exceptions as usual.

The depth to water measurements in OBS 1, OBS 2, and OBS 3 are NOT measurements of head at a point; rather, they are the result of the interaction of several aquifers' potentials and flow between aquifer zones is likely taking place through their gravel packs. The slope of the water level measured in these wells is not a measure of gradient (which requires two point measurements) in some integrated single aquifer: there is not an integrated aquifer through which flow is taking place but rather a series of individual zones which can easily have flow in different directions and at different velocities. (see Davis and DeWiest, 1966, pp. 51-52.) Vertical gradients of head are observed, as between INJ and OBS 1, OBS 2, and OBS 3. The one conclusion that can be drawn from their DTW measurements is that under normal conditions, the higher zones are under greater head than the Lauren sand and gravel.

The three southern wells -- OBS 4, EXT, and, OBS 5 -- are set in the Maria sand and gravel. On 8 and 18 November 1986, all three had lower heads than INJ. On 5 December 1986, the head in EXT was 2.'74 lower than in INJ; on 18 February 1987, it was 4.'46 lower than in INJ. Similarly low heads were observed in OBS 4 and OBS 5 on these days. Most likely, the Sanitation Engineering production well was pumped; this would explain the anomalous heads and gradients all over the Engineering Geoscience well field which occurred on those dates. On 6 and 7 July 1987, the Sanitation Engineering Production Well was pumped yielding similar results.

After 30 January 1987, OBS 4, OBS 5, and EXT have heads which are higher than in INJ and the other northern wells, except on 18 February 1987 as mentioned before. From 8 November 1986 through 5 December 1986, OBS 4 had a greater head than EXT by amounts ranging from 0.'05 to 0.'23; from 30 January 1987 through 18 February 1987, OBS 4 and EXT had the same head; and from 23 February 1987 through 30 March 1987, EXT had a head greater than OBS 4 by 0.'04. OBS 5 has a higher head than EXT on all dates except 5 December 1986, 18 February 1987, and 18 November 1986, usually by 0.'13, although higher and lower values occur. The typical difference of 0.'013 leads to a gradient of 0.002 or 0.2% to the north. On 18 February 1987, the total head in OBS 5 was only 1.'26 above mean sea level: further pumping could easily induce saltwater intrusion from the Bay.

Temporal variations in head are well behaved. From 8 November through 5 December 1986, heads fell by amounts ranging from 0.'20 to 0.'70 (excluding obvious drawdowns due to the 5 December 1986 pumping). From 8 November 1986 through 30 March 1987 (the wet season), heads rose by amounts from 2.'0 to 3.'0, again excluding effects obviously due to the 5 December 1986 and 18 February 1987 pumpings. Between 30 march 1987 and 7 July 1987, heads fell by 1.'5 in most of the wells, again in keeping with the expected seasonal patterns.

3.2. Pump Tests

A series of pump tests was conducted by Cindy Yates and Ray Solbau under the supervision of Sally Benson, all of Lawrence Berkeley Laboratory's Earth Sciences Division. An unsuccessful attempt at a pump test was made on 22 November 1987. After air-lift development of the wells and jerry-rigging of plumbing to limit the net pumping rate to 10 to 20 gallons per minute, the EXT was pumped at 10 gpm for 23 hours on 8 and 9 December 1986. INJ was pumped at 20 to 18 gpm for 20 hours on 12 and 13 December 1986. Drawdown was measured using pressure transducers in OBS 1, OBS 4, OBS 5, and OBS 6.

The Theis curve is an analytic solution for the transient response of an infinite, homogeneous, isolated aquifer releasing water from storage to a pumped well (see Ch. 8.3 of Freeze and Cherry, 1979). It is traditionally plotted as a master curve and field data fit to the curve determining transmissivity (product of hydraulic conductivity and thickness) and storativity (volume of water released per unit area of the aquifer per unit decrease in head). The Jacob straight line analysis uses a late-time approximation to the Theis solution, in which the data is plotted on semi-logarithmic paper and the slope and intercept determine the aquifer properties.

The pump test data were reduced and plotted by Cindy Yates on log-log and semi-log paper for Theis curve and Jacob straight line analysis. Her analysis and match curves and my analysis and match curves are shown in Figures 19-22 and Table 3.

Table 3. Analysis of pump test data.

Reduction, plotting and original analysis (Theis curve matching and and Jacob straight-line analysis) done by Cindy Yates. Re-interpretation of log-log plots done by Greg Pouch on reduced copies, using Plate 9, Theis curves with image wells from Lohman, (1972) (USGS Prof. Paper 708).

$K = r_{image}/r_{pumping}$, where r_{image} is the distance to the image well and $r_{pumping}$ is the distance to the real pumping well. These curves could also be fit with leaky aquifer curves.

$1.0E-04 = 1.0 \times 10^{-4}$. T is transmissivity in units of square feet per second, S is storativity (dimensionless).

Pumped Well	Method of Analysis	Well	Cindy Yates		Greg Pouch		
			T ($\frac{ft.^2}{sec}$)	S	T ($\frac{ft.^2}{sec}$)	S	K
EXT	log-log (Theis curve matching)	OBS 1	9.54 E-04	7.8 E-04	10.4 E-04	7.06 E-04	0
		OBS 4	3.84 E-04	1.04 E-04	2.85 E-04	1.03 E-04	5
		OBS 5	2.31 E-04	2.75 E-04	1.74 E-04	2.44 E-04	2.5
		OBS 6	9.54 E-04	7.8 E-04	10.4 E-04	7.06 E-04	0
	semi-log (Jacob straight line method)	OBS 1	8.76 E-04	4.92 E-04			
		OBS 4	4.20 E-04	0.77 E-04			
		OBS 5	3.42 E-04	1.85 E-04			
		OBS 6	8.76 E-04	4.92 E-04			
INJ	log-log (Theis curve matching)	OBS 1	5.52 E-04	3.06 E-04	5.43 E-04	3.26 E-04	0
		OBS 4	10.9 E-04	12.0 E-04	12.7 E-04	14.2 E-04	0
		OBS 5	10.2 E-04	6.39 E-04	10.5 E-04	6.72 E-04	0
		OBS 6	3.81 E-04	0.50 E-04	3.90 E-04	0.55 E-04	0
	semi-log (Jacob straight line method)	OBS 1	6.06 E-04	2.32 E-04			
		OBS 4	10.1 E-04	11.9 E-04			
		OBS 5	11.7 E-04	4.77 E-04			
		OBS 6	4.23 E-04	4.29 E-04			

Note that when INJ is pumped, OBS 4 and OBS 5 (furthest of the four observed wells) have the highest transmissivities, while when EXT is pumped, OBS 6 and OBS 1 (furthest of the four pumped wells) have the highest transmissivities. Inspection of Figure 20 indicates that the drawdowns in OBS 4 and OBS 5 flatten out after a time during the EXT pump test. Observe further that for the pumping of INJ, t/r^2 (proportional to $1/u$) ranges from 0.02 to 2 for OBS 1, 0.01 to 7 for OBS 6, 0.13 to 5 for OBS 4, and 0.035 to 1 for OBS 5; when the extraction well is pumped, it ranges from 0.06 to 1.3 for OBS 1, 0.2 to 1.6 for OBS 6, 0.2 to 15 for OBS 4, and 0.15 to 25 for OBS 5: in other words, late-time data is lacking for most of the pump tests. Finally, observe that the data for OBS 4 and OBS 5 during the EXT pump test do not depart from the Theis curve until t/r^2 exceeds 3 or 4.

A reasonable match to the Theis curve for drawdown in an isolated, ideal infinite plane aquifer can be made for all the pump test data; this must not be misconstrued as proving that the wells are pumping from such an aquifer. The problem is that transient drawdown curves for a wide range of boundary conditions look alike, especially at early times. In particular, one can fit the curve for the unpumped aquifer in a leaky aquifer-aquitard-aquifer system onto the Theis curve and even get the resulting transmissivity greater than would have been obtained using a piezometer in the pumped aquifer. (see Fig. 8.9, p. 322 of Freeze & Cherry, 1979.) The basic problem, as pointed out by Freeze and Cherry (1979, p. 349) is that pump tests suffer from non-uniqueness: this is a fundamental result of groundwater flow being a potential field. Just as a layered model can be fit to most resistivity soundings, the Theis curve appears to be equally robust for pump tests. The result is that the actual meaning of the pump test results is unclear.

The flattening out of the drawdown curves at late time in OBS 4 and OBS 5 for pumping of EXT indicates that the "aquifer" was gaining water; this could be from leakage from the surrounding clays, from a constant head boundary such as the Bay (1400' to the south), a marsh, a storage pond, or a stream, or a zone within the aquifer system of virtually infinite transmissivity or storativity (this last being more modelling technique for setting boundary conditions than physical description).

Analysis of the pump data using image theory and Theis type-curve analysis (Lohman, 1972, Plate 9, drawdown curves for Theis aquifer with image constant head or no flux boundaries) would have a recharging image 400' from OBS 4 and 150' from OBS 5; these circles do not intersect, although they come closest near and bracket the cement-lined storage pond near Building 277. More likely, the drawdown curve is dominated by leakage from surrounding clays, although the the possibility of constant head boundaries should be considered. It is likely that the drawdowns observed in the far wells during the pump tests result from transmission of pressure differences across geologic boundaries: the pressure across a surface must be equal, and thus the effects of pumping a well will be felt in all geologic units.

On 6 and 7 July 1987, two pump tests were conducted by Greg Pouch assisted by Jennifer Noon and John Kessler. In these, the Sanitation Engineering Production Well was pumped at about 110 gallons per minute, and water levels in the Engineering Geoscience wells were recorded using the chalked tape method. On 6 July 1987, measurements were made in several wells in the Sanitation Engineering well field (B2, B16, B12, B8, and B17); all but B16 showed 14.' to 18.' of drawdown after 40 minutes of pumping. B16 showed no response. In the Engineering Geoscience well field, at the end of 46 minutes of pumping, INJ, OBS 1, OBS 2, and OBS 6 showed no response, OBS 3 had 0.'09 of drawdown, and OBS 5, OBS 4, and EXT had 0.'24, 0.'44, and 0.'26 of drawdown respectively. (These data are presented in Appendix 3, but are not graphed.) This is in keeping with the predictions made earlier, although more dramatic drawdowns were desirable. This is consistent with the lenticular geology deduced from the driller's logs, water levels, and earlier pump tests.

More dramatic falls in water level were desirable to confirm the hypotheses put forward earlier, so another pump test was conducted on 7 July 1987. (Raw data are given in Appendix 3 and graphed as Figure 23.) Again the Sanitation Engineering Production Well was pumped at 110 gpm and water levels recorded. After 90 minutes of pumping, drawdowns were negligible (<0.'04) in INJ, OBS 1, OBS 6, and OBS 2; 0.'22 in OBS 3; and 3.'41, 2.'07, and 2.'33 in OBS 4, EXT, and OBS 5. After 3 hours of pumping, the drawdowns were 0.'01 in OBS 1, 0.'07 in OBS 2, 0.'50 in

OBS 3, 0.'18 in OBS 6, 0.'25 in INJ, and 4.'16, 3.'92, and 4.'73 in OBS 4, EXT and OBS 5. As can be seen, OBS 4, EXT and OBS 5 (all set in the Maria sand and gravel) show large drawdowns due to pumping of the Sanitation Engineering Production Well 545' away, while INJ and OBS 6, set in the Lauren gravel, show little response (<0.'25) to such pumping. Of the wells set in several layers (OBS 1, OBS 2, and OBS 3) including the marine units (Jennifer, Cindy, Ted, Becky, Tom) OBS 1 and OBS 2 showed virtually no response (0.'01 and 0.'07, respectively) while OBS 3 showed a drawdown a larger drawdown of 0.'50, indicative of some sort of connection to the Maria gravel.

Several conclusions can be reached from this pump test data. First, the anomalous behavior of the water levels on 5 December 1986 and 18 February 1987 was definitely due to pumping of the Sanitation Engineering Production Well. Second, the southern wells are set in the same aquifer zone as at least some of the Sanitation Engineering wells. Third, the northern wells are not set in the same aquifer zone as the southern wells (OBS 4, EXT and OBS 5). Fourth, depositional strike in this area is east-west, at least in the lower alluvial sequence; a corollary conclusion is that the lower marine sequence is marine and not a fortuitous intersection of a channel's longitudinal profile.

4. Conclusions

The geologic sections, static head data, and pump test results indicate the presence of at least three separate aquifer zones penetrated by wells in the Engineering Geoscience Well field: the Maria sand and gravel to the south (OBS 5, EXT, and OBS 4); the Lauren gravel (a distributary mouth bar) to the north (penetrated by OBS 1, OBS 2, and OBS 3, and the only zone penetrated by OBS 6 and INJ); and the Becky, Cindy, Jennifer, and Amanda aquifer zones (penetrated by OBS 1, OBS 2, and OBS 3). EXT and INJ are not set in the same aquifer zone: this is particularly illustrated by the occurrence of 3' to 5' head differences between the two wells.

In the alluvial sections of the sediment column, flow will be piped in ancient channels and bar fingers and contaminant migration will be difficult to predict because of the unknown areal distribution of these deposits. The connection of the southern three wells to the Sanitation Engineering Well Field indicates that the depositional strike in the lower alluvial sequence is probably east-west. If this is so, contamination will travel along east-west lines. The westward regional hydraulic gradient would cause contaminant to move to the west in the absence of pumping.

Flow in the marine portions of the sediment column will be far more predictable due to the comparative uniformity of these deposits. As no head data exists for these aquifer zones, the regional flow patterns are unknown, although regional flow to the west would be most reasonable in view of the flow in the lower marine sequence and regional topography.

The possibility of cross-aquifer contamination is large due to the thick gravel packs in OBS 1, OBS 2, and OBS 3.

There may be a substantial flux past OBS 6 and INJ through the Lauren gravel. Assuming the bar has a cross-sectional area of 46.5 square meters and a hydraulic conductivity of 0.001 meters per second (a typical value for a clean sand, Freeze & Cherry, p.29) and using the observed of hydraulic gradient of 0.0013, the hydraulic flux through the Lauren is

$$(46.5m^2)(0.001\frac{m}{s})(0.0013) = 6.04x10^{-5}\ \frac{m^3}{s}$$

or 0.95 gallons per minute. This is a very conservative estimate of the flux: the hydraulic conductivity of coarse gravel can easily be a thousand times greater. The average liner velocity (contaminant transport velocity) corresponding to the low hydraulic conductivity estimate is about three meters per day.

5. Recommendations

Because the flow will be more regular in the marine/estuarine portions of the sedimentary sequence, perforating the wells in the Becky, Cindy, Lisa, or Jennifer aquifer zones is advised. The bar finger and channel deposits will be subject to piping of contaminants and have more erratic areal distribution.

Saltwater intrusion is a common problem in coastal aquifers. The potential exists for inducing saltwater intrusion through excessive pumping, although too little is presently known of the field site to calculate the threshold pumping rate.

Contaminant that makes it into the Becky, Cindy, Nathalie, and Jennifer aquifer zones may be difficult to recover because they are already losing water to the Lauren aquifer zone. The thick gravel packs bridging several aquifer zones in OBS 1, OBS 2, and OBS 3 should be removed prior to injection of potentially dangerous substances. This would best be done by breaking the bottom plug off the well screen and using a sand bailer to remove the gravel pack; the void could be plugged with clay or cement.

The most favorable setup for an injection test would be to inject the contaminant upstream from a monitoring well. Ideally, the zone into which the contaminant was injected would be isolated from other zones. The first requirement could be met by injecting into OBS 6 and monitoring INJ, although the gravel packs in OBS 1, OBS 2, and OBS 3 might cause cross-zone flow. Injecting contaminant into OBS 4, EXT or OBS 5 would prevent cross-zone flow, but does not allow monitoring of a downstream well.

Because of the geology and setting of the screens, a tracer test should be done before any injection experiments. Jim Hunt (pers. comm., 1987) pointed out that the groundwater in this area lacks fluoride, and that EBMUD water is fluoridated. A specific ion probe (similar to a pH probe) could be put into the water stream from or into a well along with a flowmeter and the total fluorine injected or recovered determined. The experiment could be done with hot water, which has a higher conductivity, and would not be as prone to adversely affect other groundwater users.

Acknowledgements

I wish to express by gratitude for the assistance I have received from my fellow graduate students, Lawrence Berkeley Laboratory employees, Richmond Field Station workers and numerous University of California professors. I give special thanks for many long hours of patient work by Jennifer T. Noon, Cindy Yates, and Ray Solbau.

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Freeze, R. A. and J. A. Cherry, 1979, Groundwater: Prentice-Hall, Englewood Cliffs, New Jersey, 604 p.

Lohman, S. W., 1972, Ground-Water Hydraulics: United States Geological Survey Professional Paper 708, 70 p. (Type Curves)

Morrison, H. F. and others, 1986, Resistivity Monitoring of Subsurface Contaminants: *in* Item 18, Executive Officer Summary Report of the August 20, 1986 meeting of the San Francisco Bay Regional Water Quality Control Board (also available from the Engineering Geoscience group at the University of California at Berkeley)

BECKER

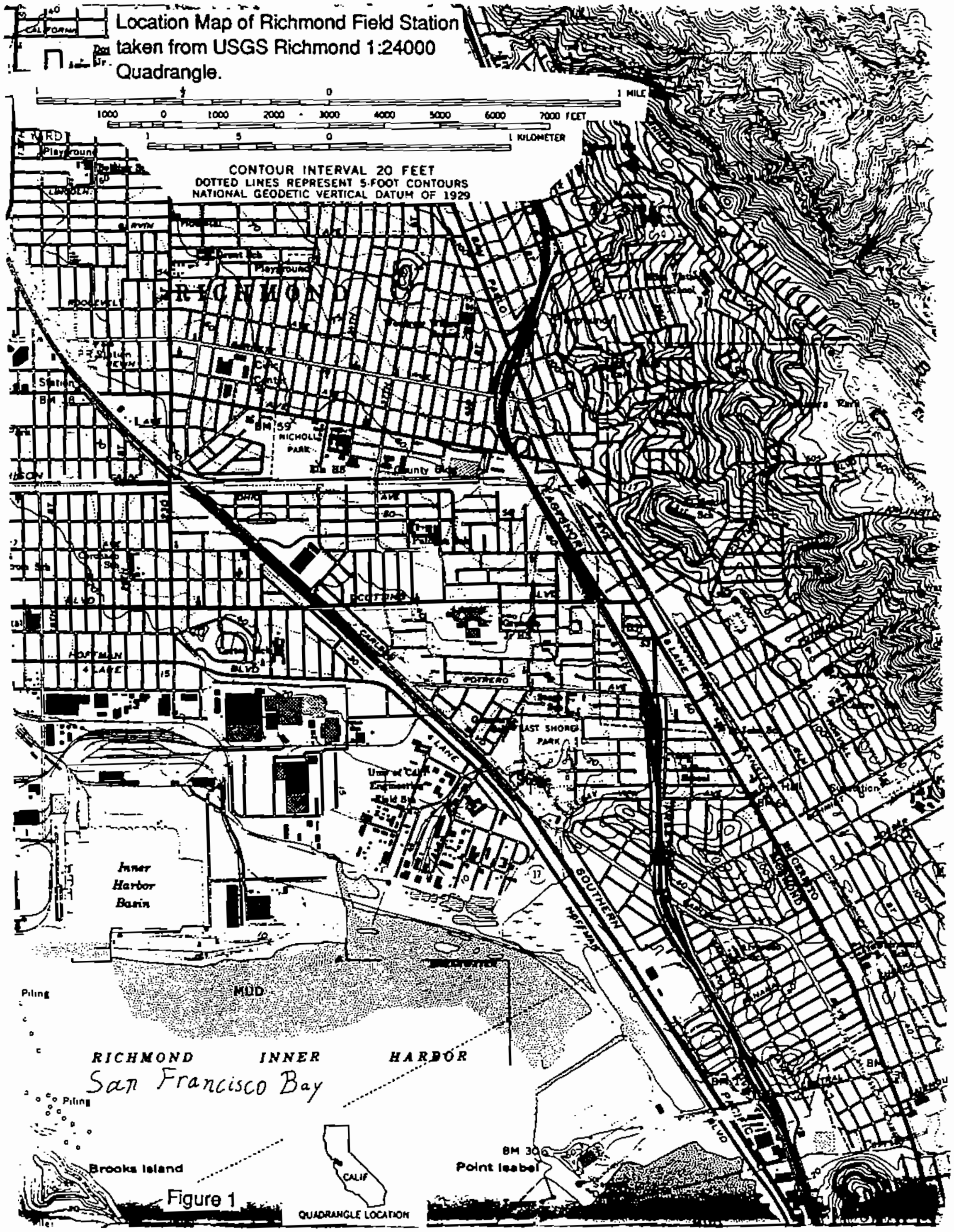
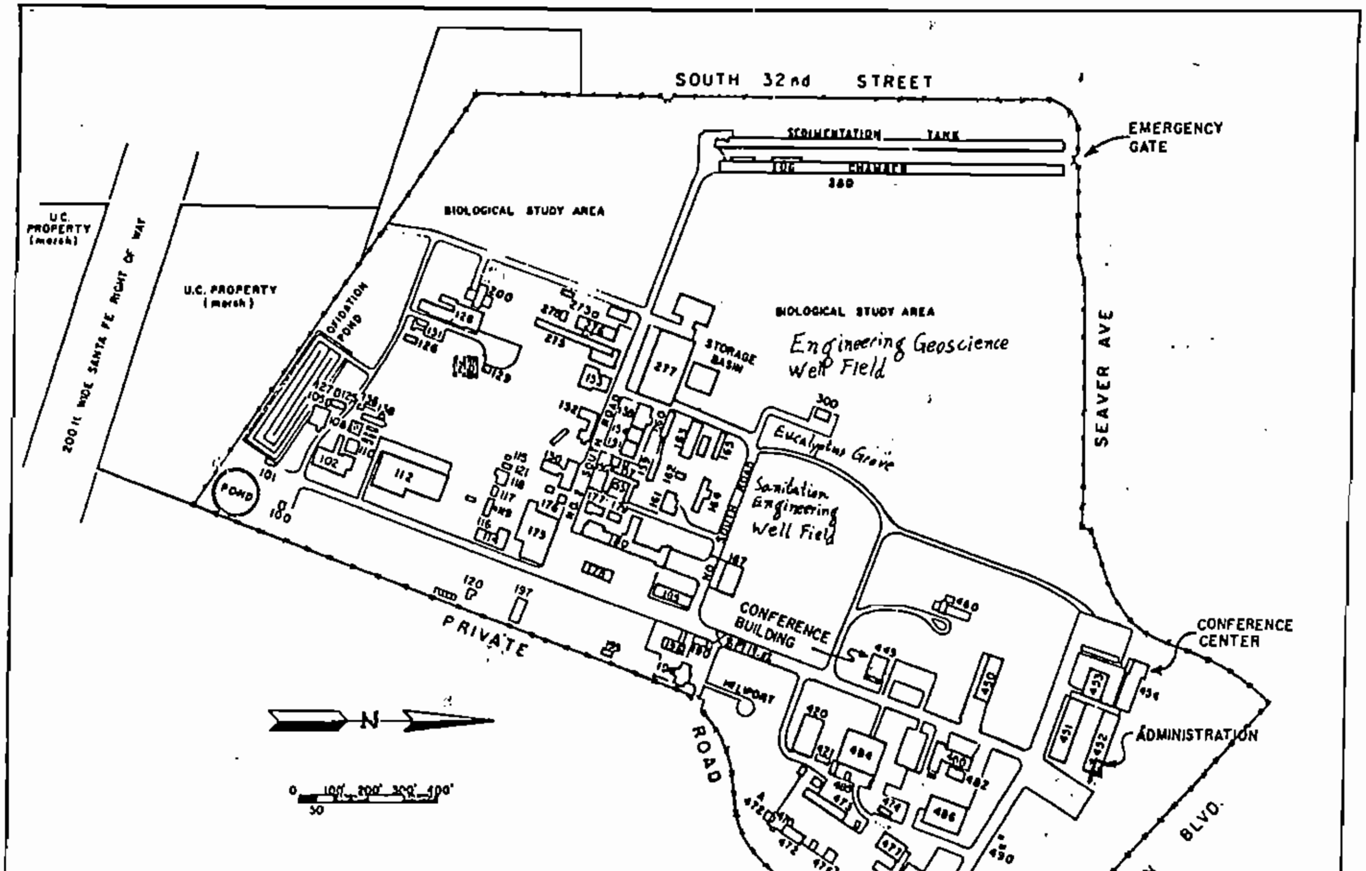


Figure 1



SITE PLAN

RICHMOND FIELD STATION

Figure 2

REVISED: SEPT 1975
MAY 21, 1976

Richmond Field Station

Engineering Geoscience Well Field

Map of Engineering Geoscience Wells

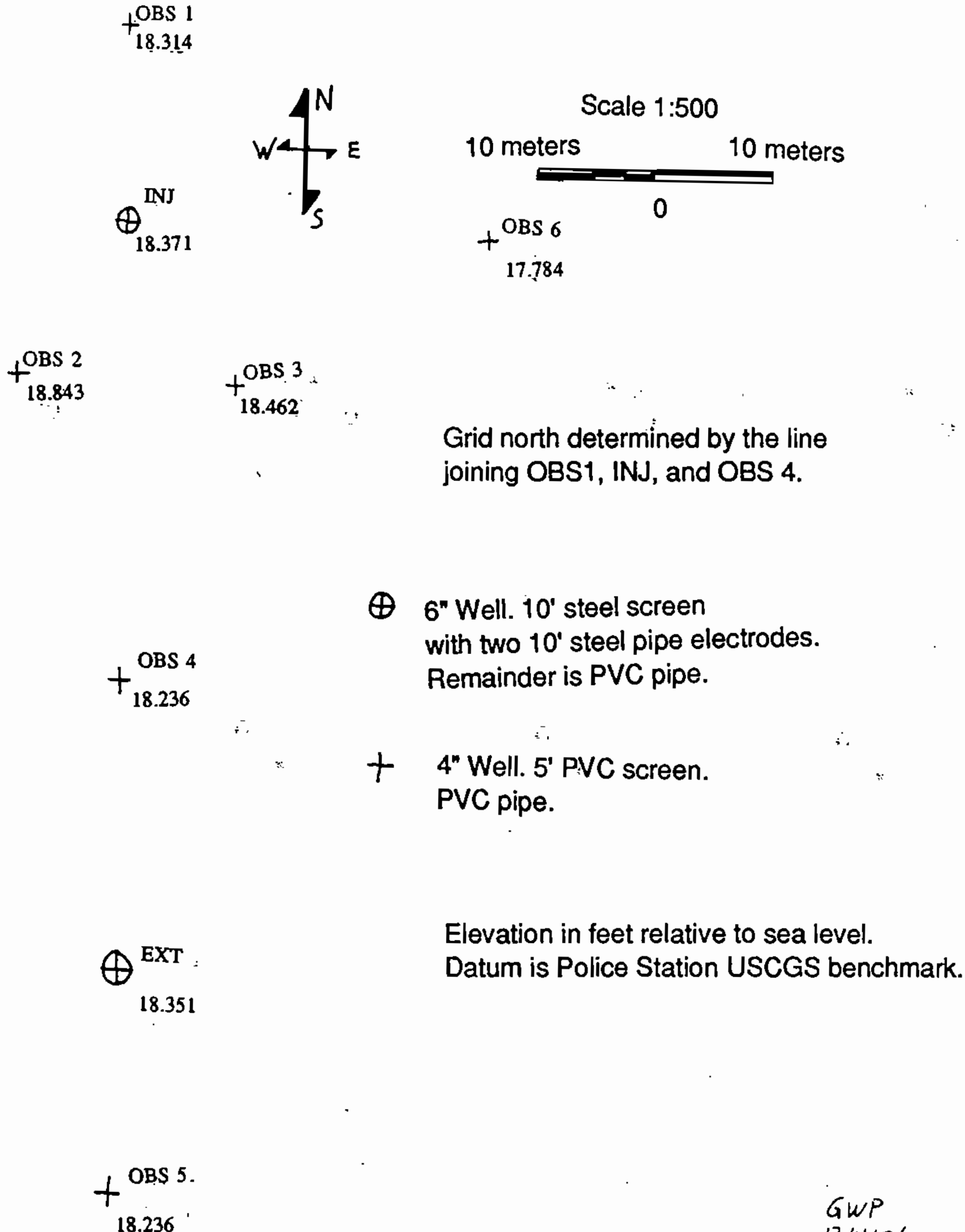


Figure 3

GWP
12/4/86

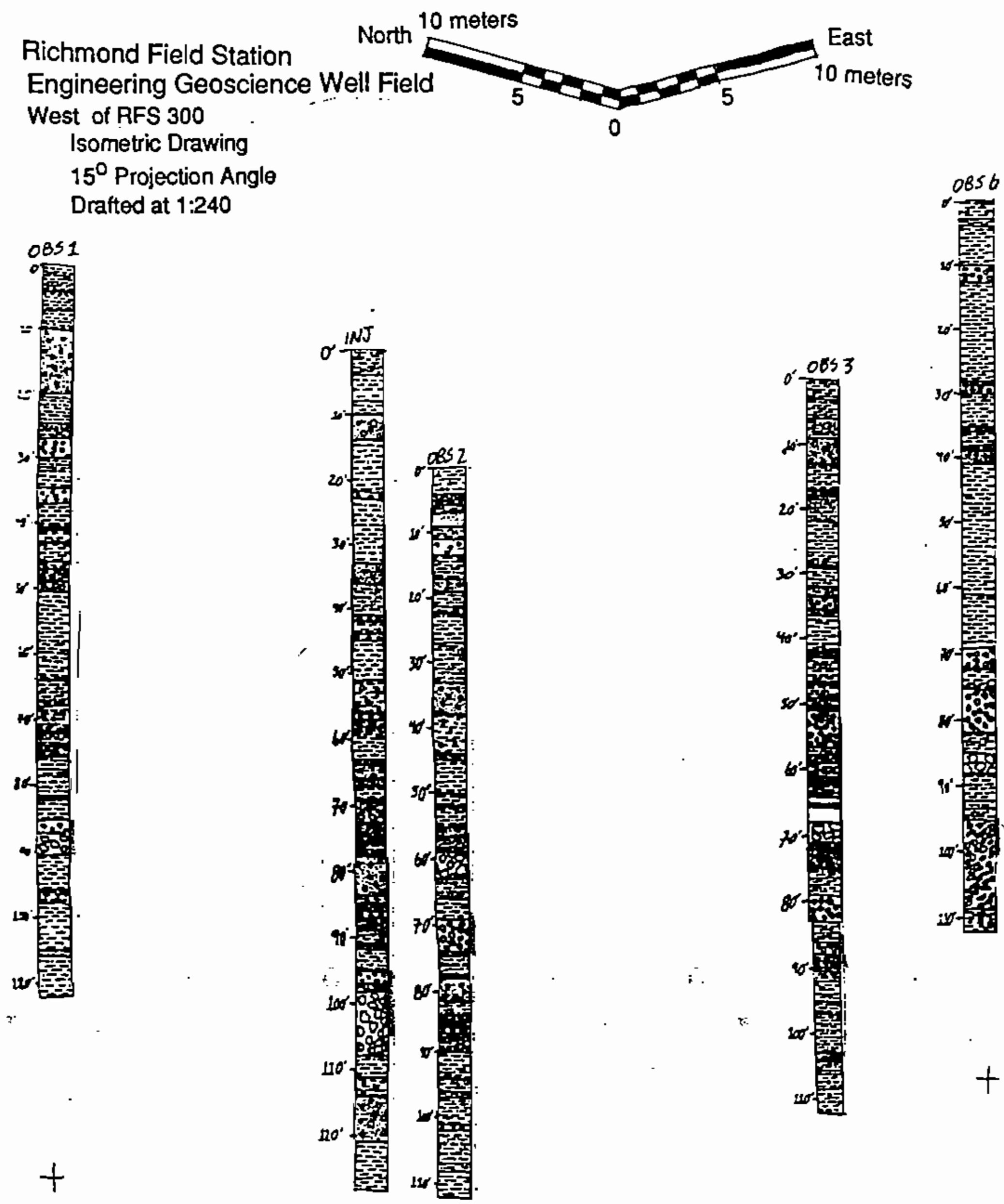

Richmond Field Station
Engineering Geoscience Well Field
West of RFS 300
Isometric Drawing
15° Projection Angle
Drafted at 1:240
North
10 meters
5
0
5
East
10 meters
OBS 1
INJ
OBS 2
OBS 3
OBS 6

Figure 4a

Legend for Graphic Well Logs and Correlation Diagrams

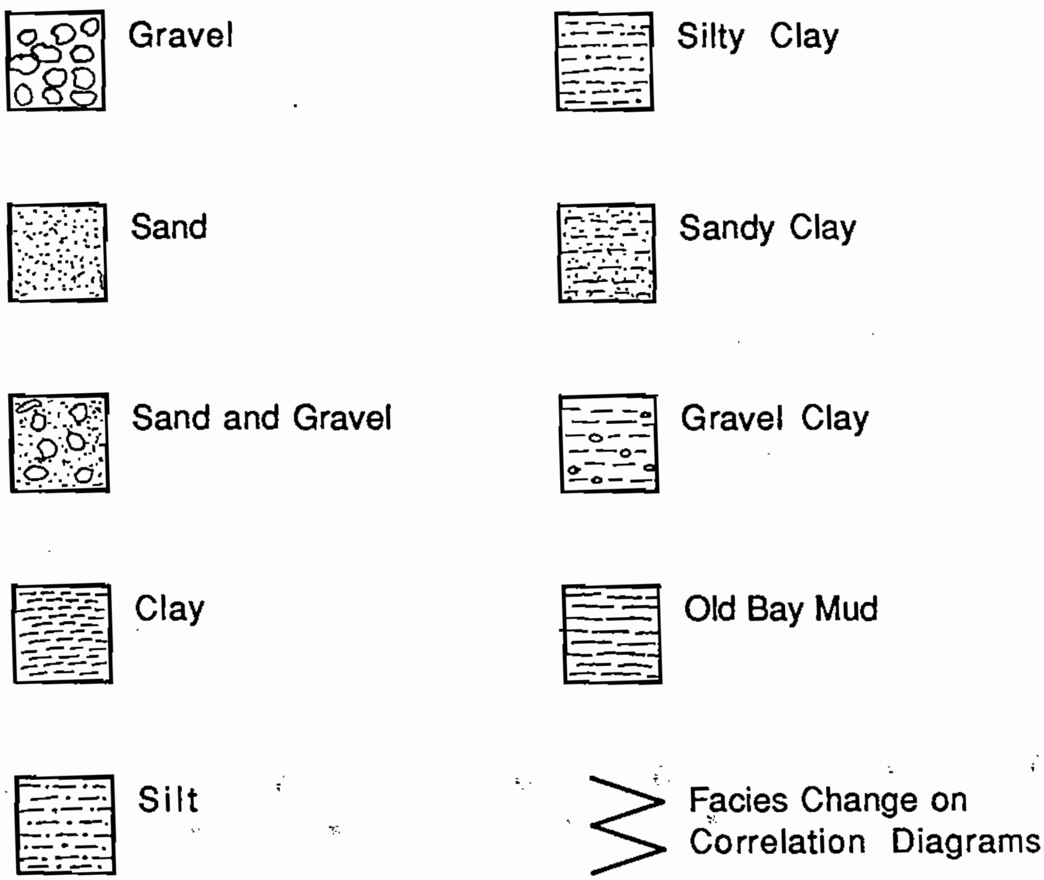


Figure 4b

Richmond Field Station

Engineering Geoscience Well Field

West of RFS 300

Overlay for Figure 4a

Stratigraphic Fence Diagram

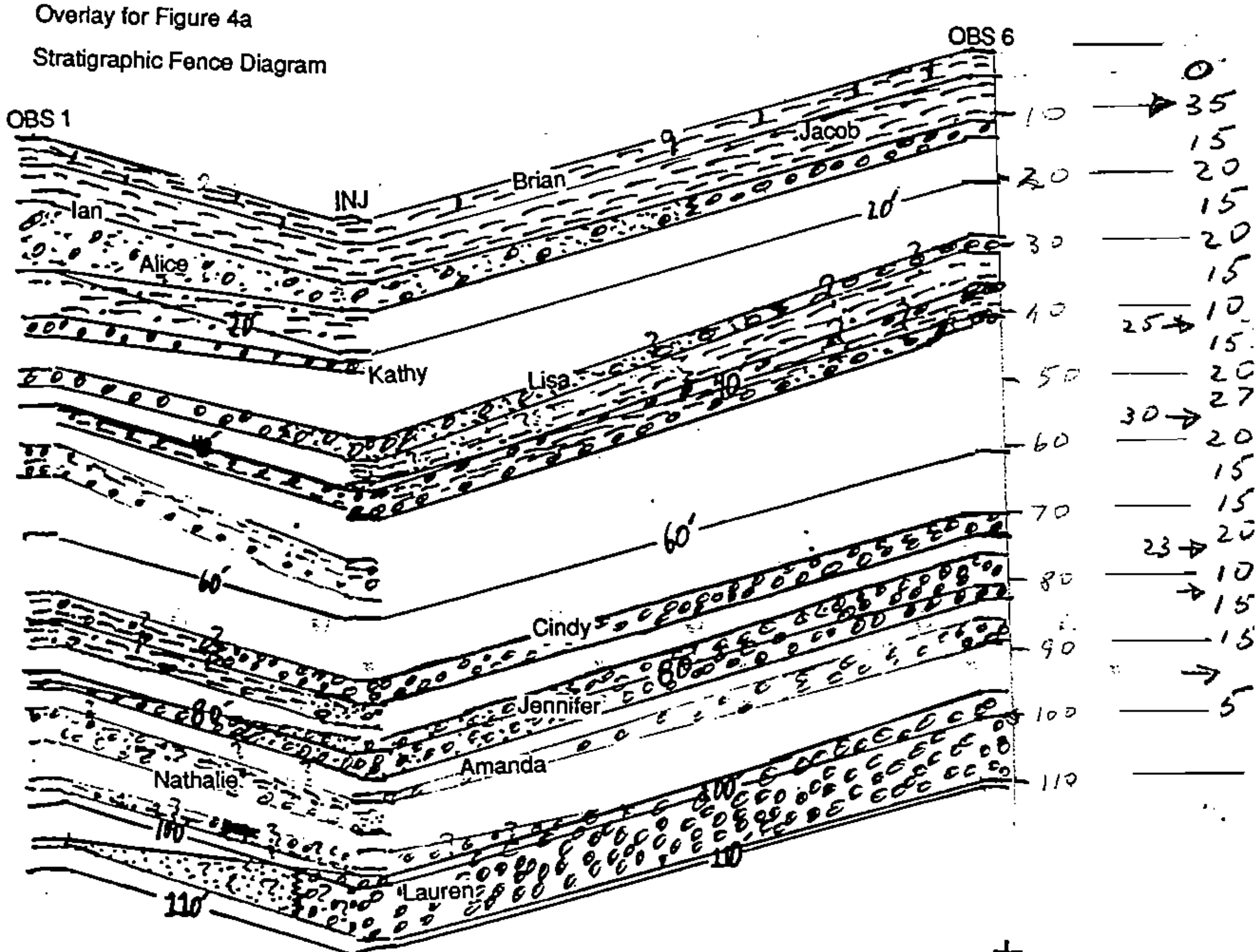


Figure 5

Greg Pouch
6 April 1987

Richmond Field Station
Engineering Geoscience Well Field
West of RFS 300
Overlay for Figure 4a
Stratigraphic Fence Diagram

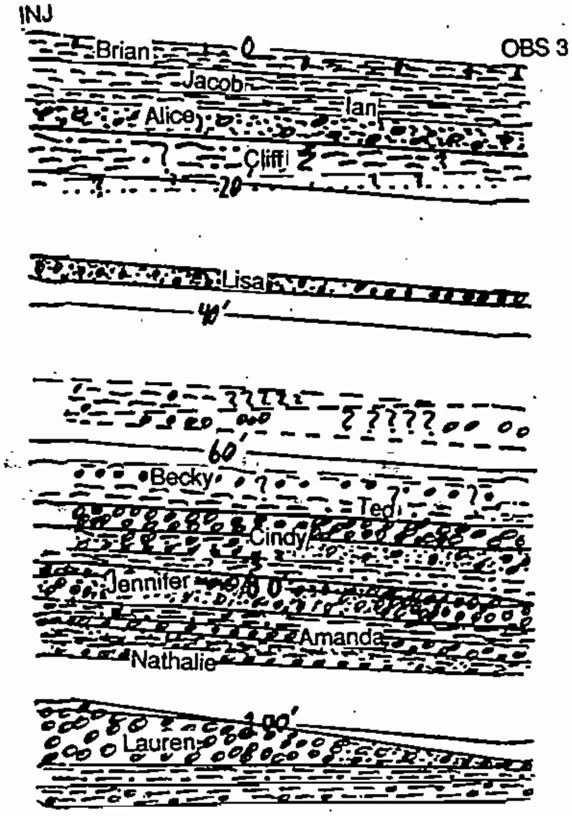


Figure 6

Greg Pouch
Begun 29 April 1987
Completed 1 May 1987

Richmond Field Station
Engineering Geoscience Well Field
West of RFS 300
Overlay for Figure 4a
Stratigraphic Fence Diagram

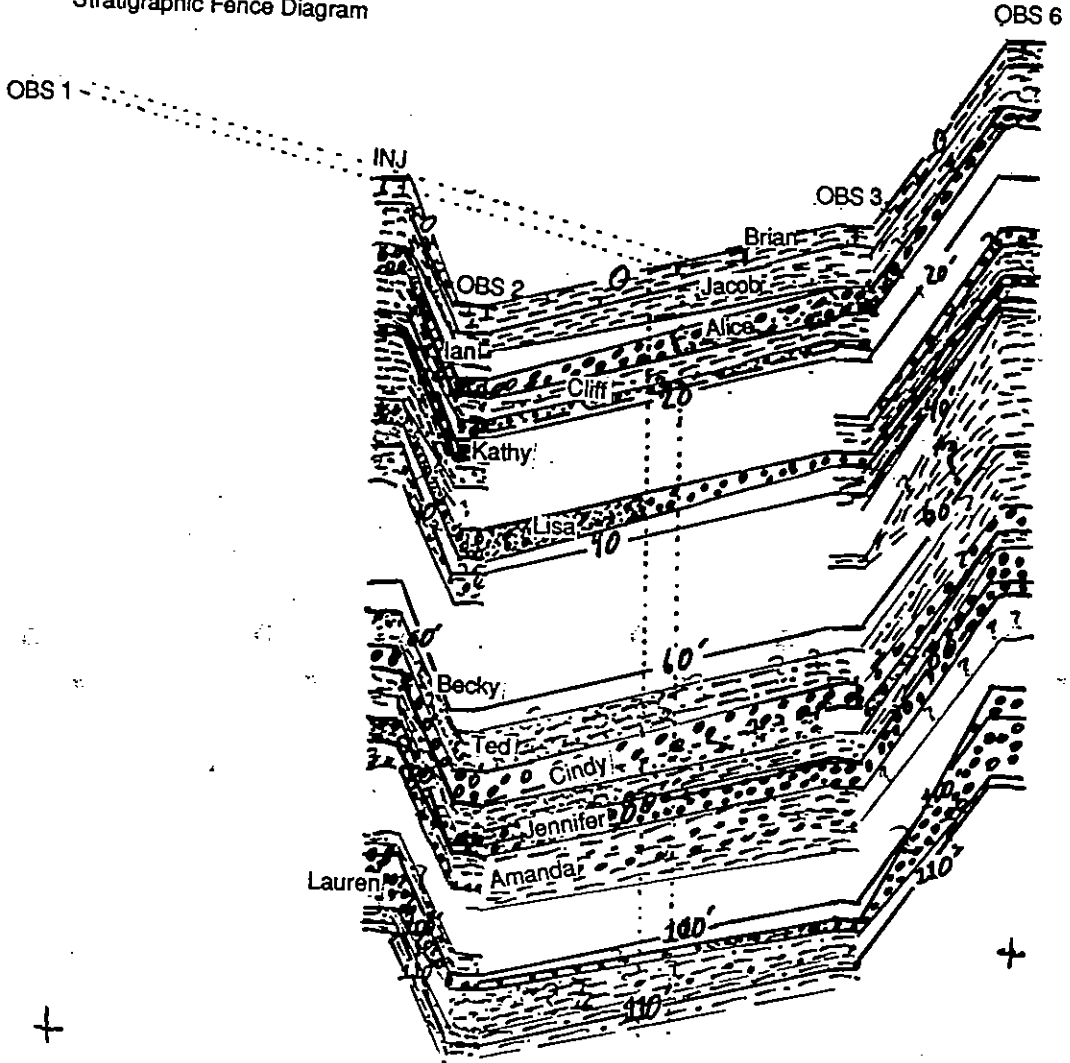


Figure 7

Greg Pouch
Begun 6 April 1987
Completed 29 April 1987

Richmond Field Station
Engineering Geoscience Well Field
West of RFS 300
Overlay for Figure 4a

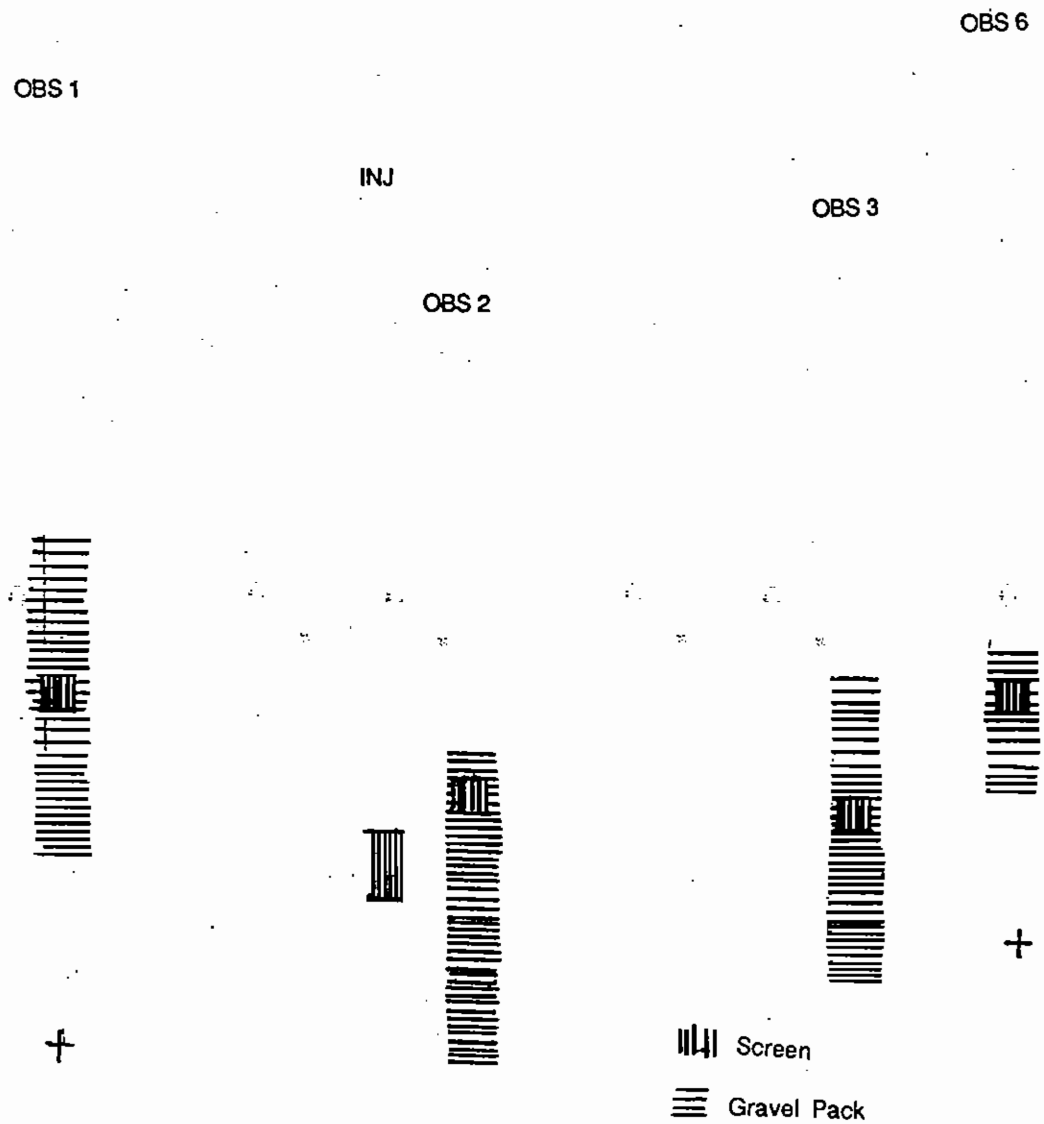


Figure 8

Richmond Field Station

Engineering Geoscience Well Field
West of RFS 300
Overlay for Figure 4a

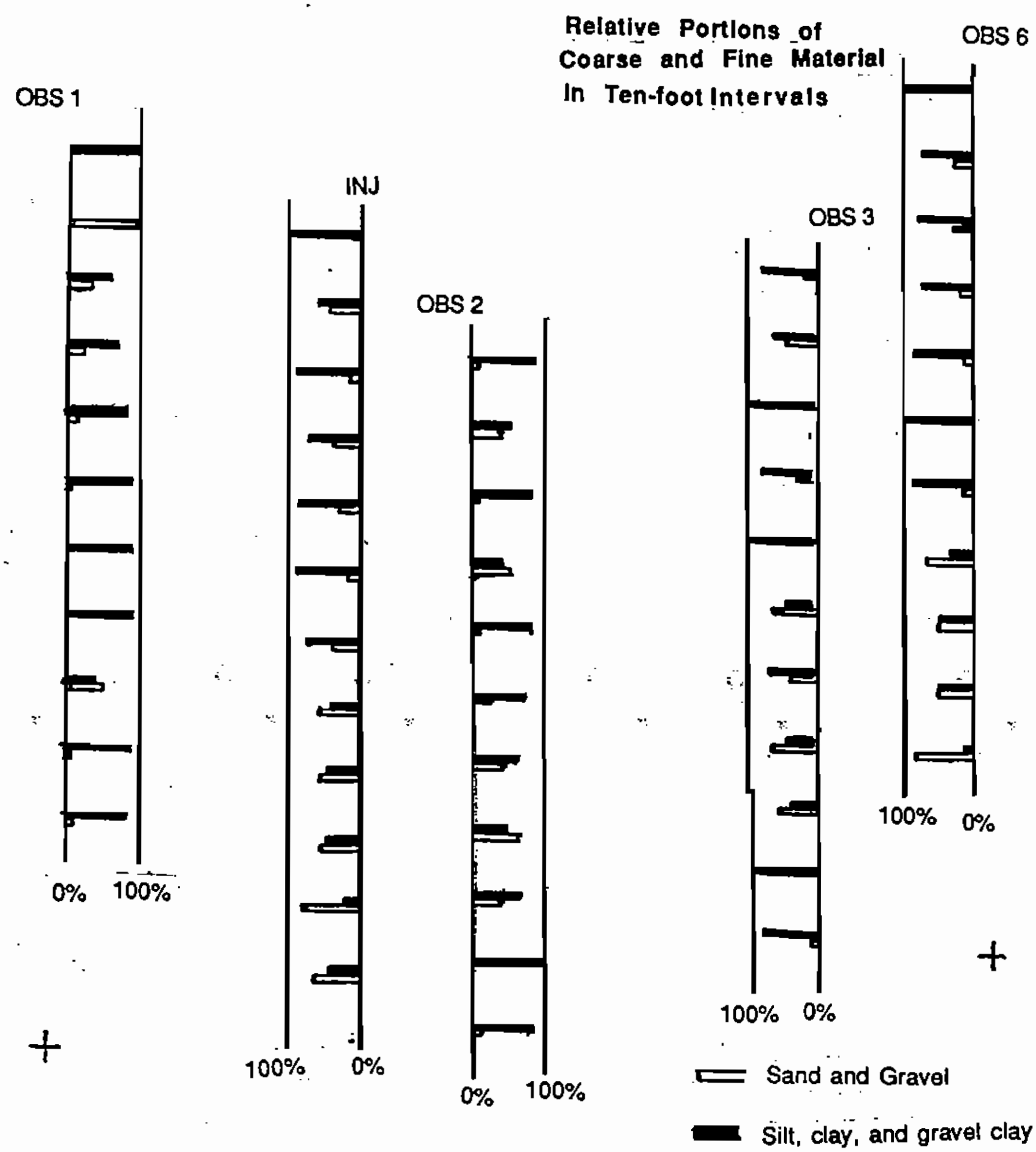


Figure 9

Richmond Field Station
Engineering Geoscience Well Field

(west of Building 300)

Graphic Well Logs in North-South Section

5 10 meters

10 meters 0

Vertical Scale 1:240

Horizontal Scale 1:250

Vertical Exaggeration 1.04X

Datum is ground level

(about 17' above mean sea level).

South North

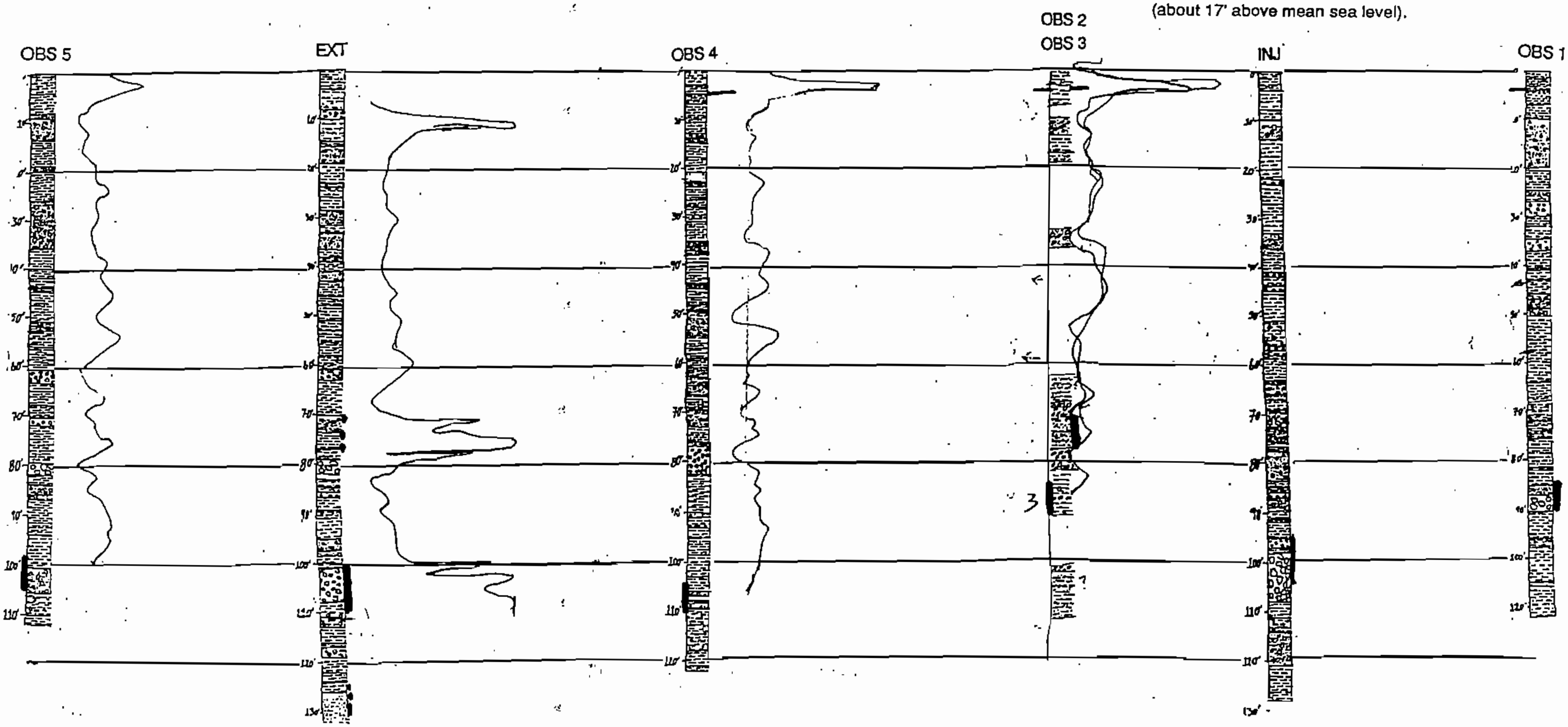


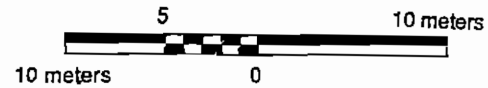
Figure 10

Richmond Field Station
Engineering Geoscience Well Field

(west of Building 300)

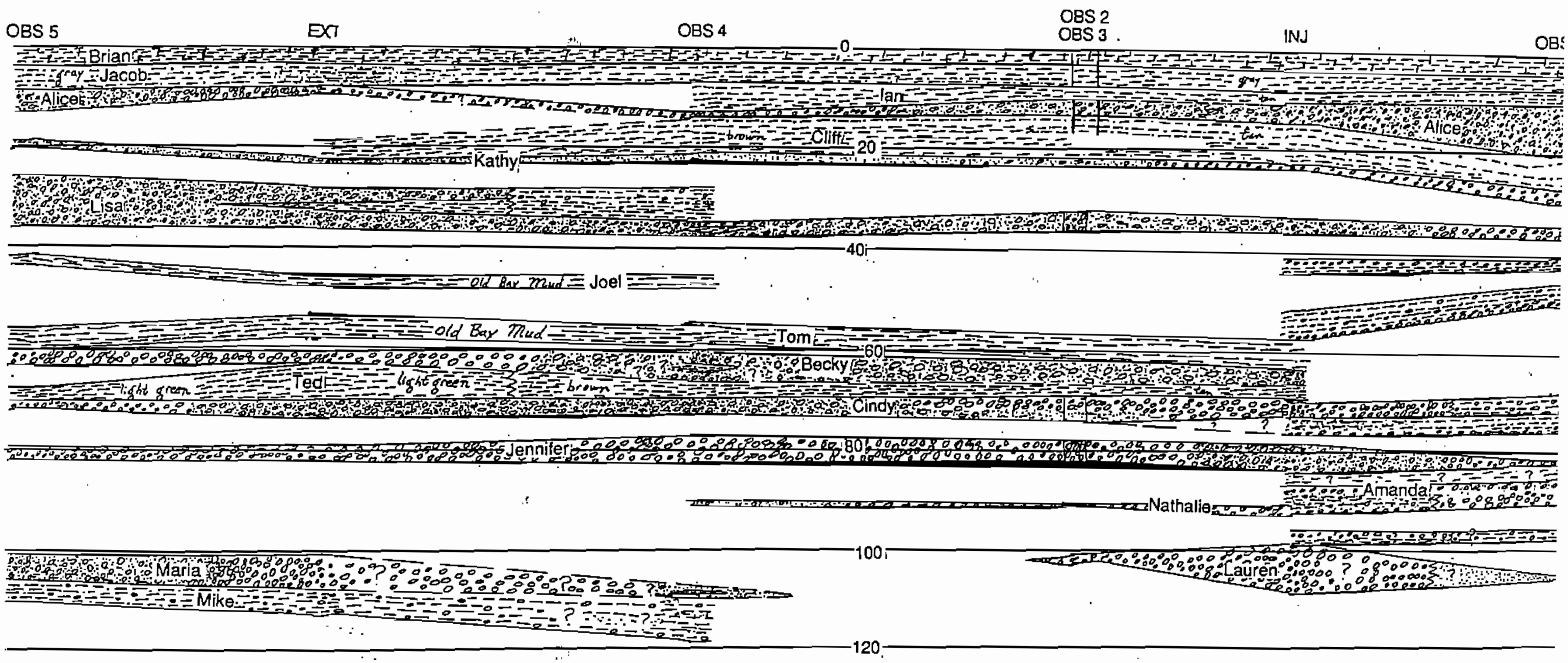
South

Stratigraphic Cross-section



Vertical Scale 1:240
Horizontal Scale 1:250
Vertical Exaggeration 1.04X
Datum is ground level
(about 17' above mean sea level).

North



GP

Figure 11

Geologic Correlations
Greg Pouch
Begun 3 June 1987

Richmond Field Station
Engineering Geoscience Well Field
(west of Building 300)

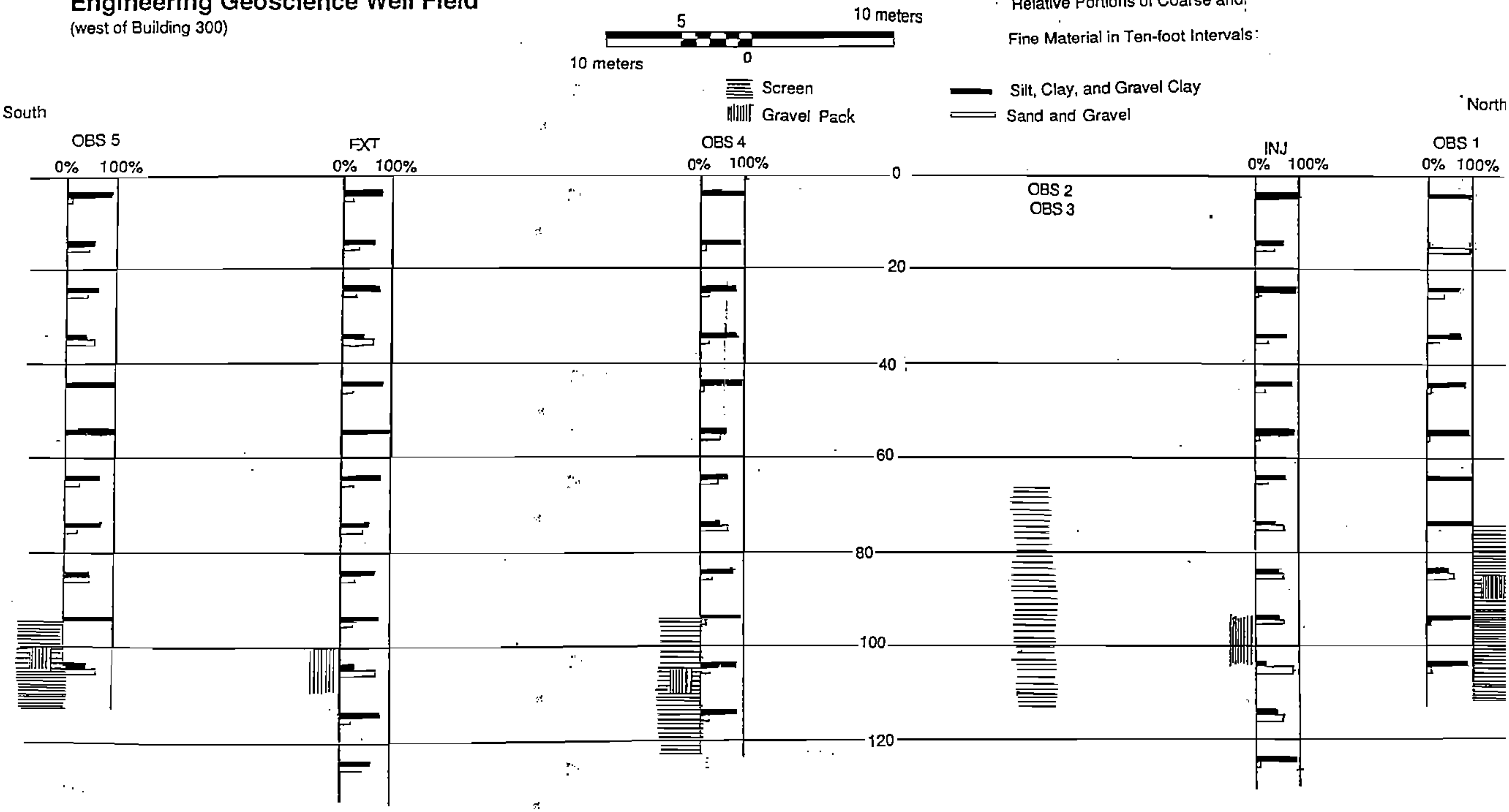


Figure 12

GP

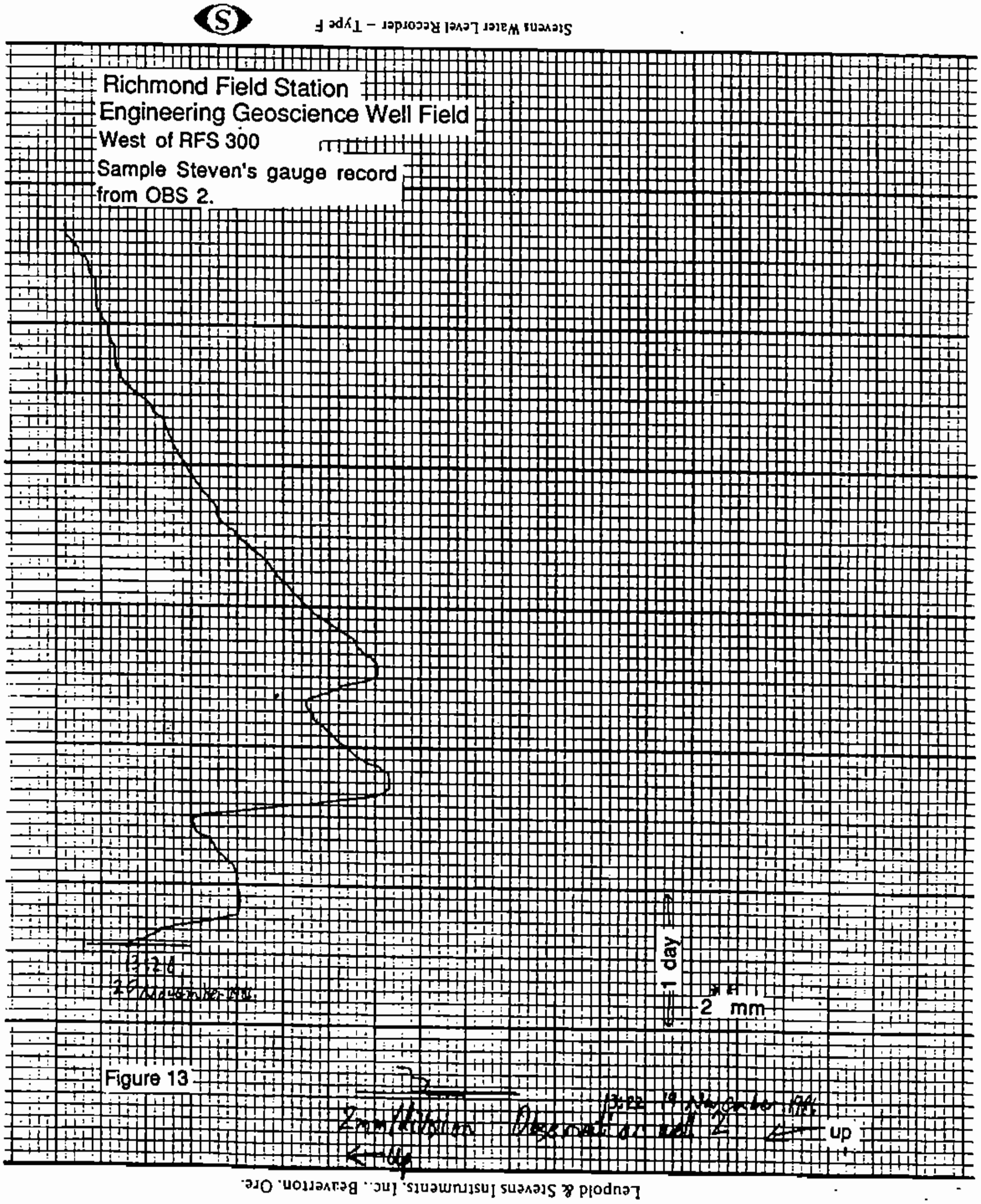
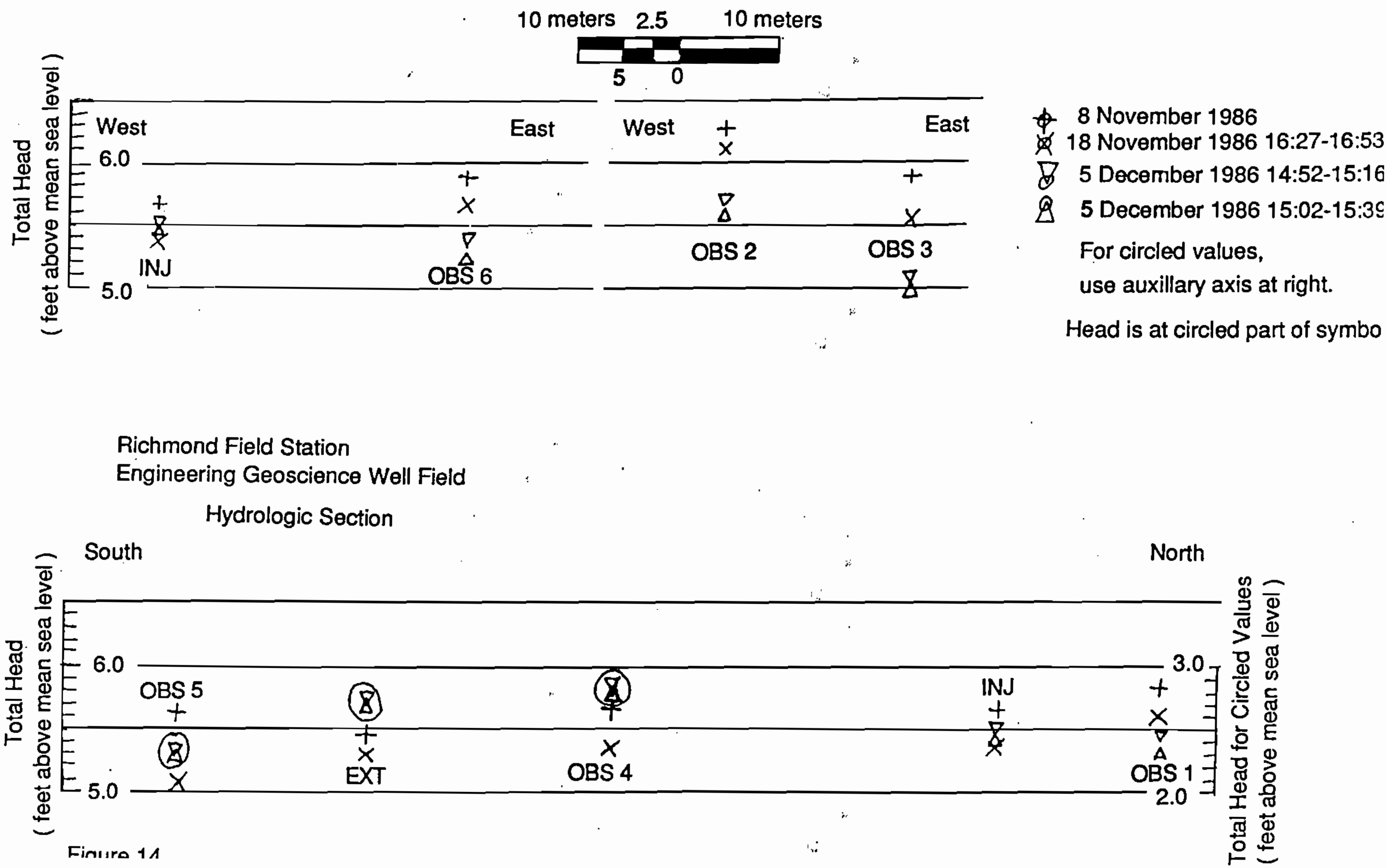
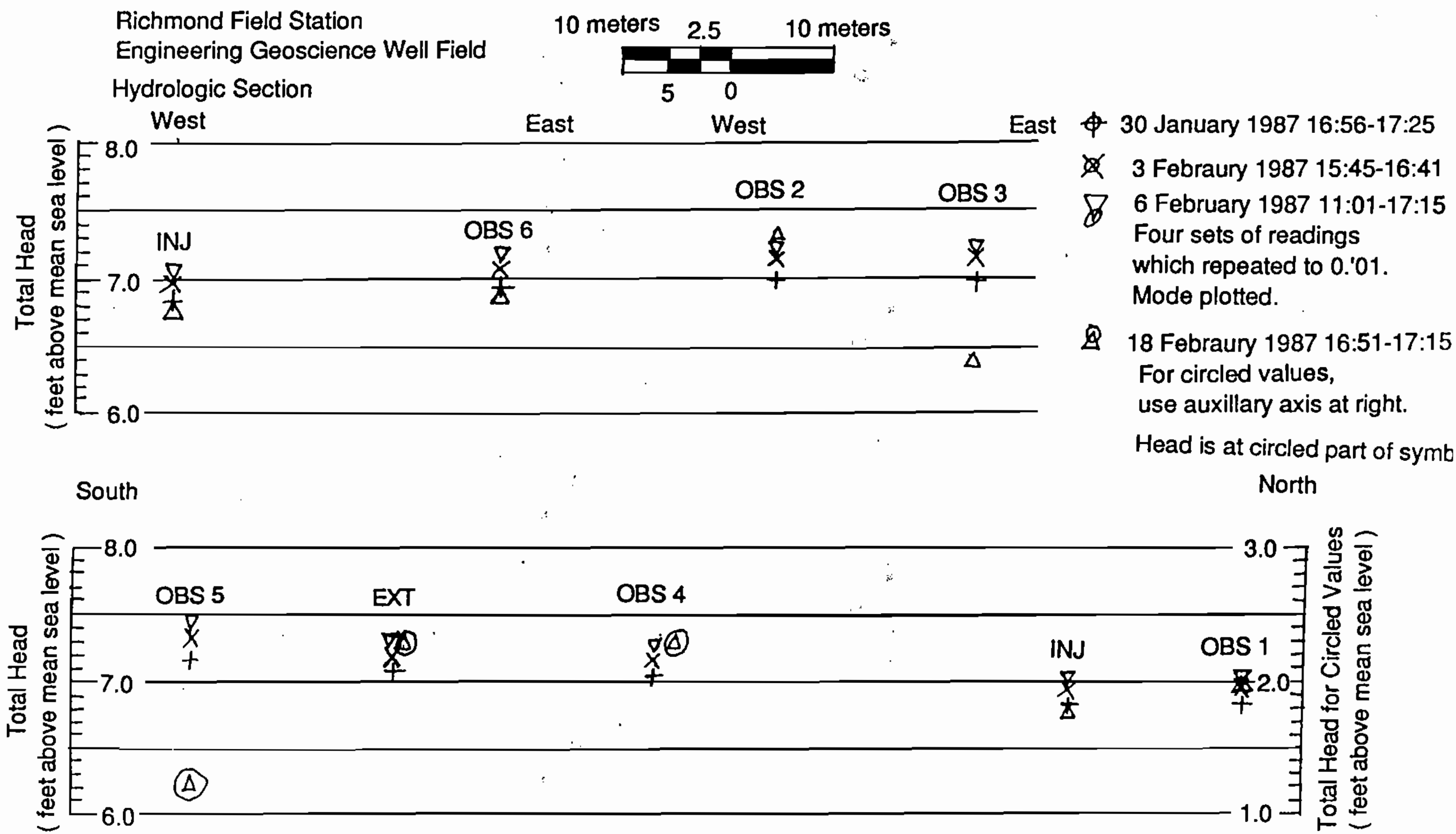

Stevens Water Level Recorder – Type F
Richmond Field Station
Engineering Geoscience Well Field
West of RFS 300
Sample Steven's gauge record
from OBS 2.
1 day
2 mm
up
Leupold & Stevens Instruments, Inc., Beaverton, Ore.

Figure 13



10 meters 2.5 10 meters
5 0
Total Head
(feet above mean sea level)
West
East
West
East
6.0
5.0
INJ
OBS 6
OBS 2
OBS 3
8 November 1986
18 November 1986 16:27-16:53
5 December 1986 14:52-15:16
5 December 1986 15:02-15:39
For circled values,
use auxillary axis at right.
Head is at circled part of symbo
Richmond Field Station
Engineering Geoscience Well Field
Hydrologic Section
South
North
OBS 5
EXT
OBS 4
INJ
OBS 1
3.0
2.0
Total Head for Circled Values
(feet above mean sea level)

Figure 14



Richmond Field Station
Engineering Geoscience Well Field
Hydrologic Section
10 meters
2.5
10 meters
5
0
West
East
West
East
Total Head
(feet above mean sea level)
8.0
7.0
6.0
INJ
OBS 6
OBS 2
OBS 3
30 January 1987 16:56-17:25
3 Februaury 1987 15:45-16:41
6 February 1987 11:01-17:15
Four sets of readings
which repeated to 0.'01.
Mode plotted.
18 Februaury 1987 16:51-17:15
For circled values,
use auxillary axis at right.
Head is at circled part of symb
South
North
OBS 5
EXT
OBS 4
INJ
OBS 1
3.0
2.0
1.0
Total Head for Circled Values
(feet above mean sea level)

Figure 15

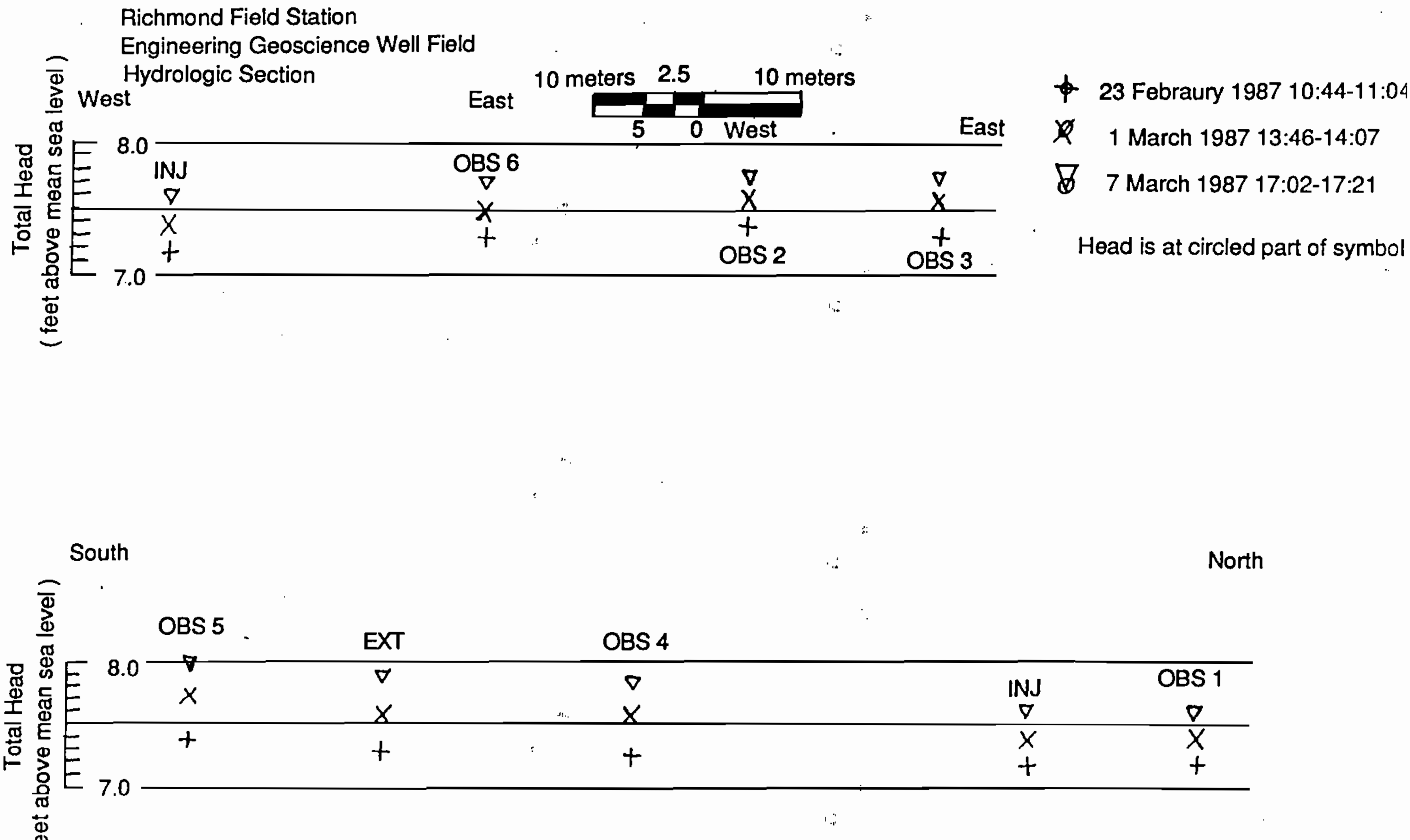

Richmond Field Station
Engineering Geoscience Well Field
Hydrologic Section
Total Head
(feet above mean sea level)
West
East
10 meters
2.5
10 meters
5
0
West
East
8.0
7.0
INJ
OBS 6
OBS 2
OBS 3
23 Februaury 1987 10:44-11:04
1 March 1987 13:46-14:07
7 March 1987 17:02-17:21
Head is at circled part of symbol
South
North
Total Head
(feet above mean sea level)
8.0
7.0
OBS 5
EXT
OBS 4
INJ
OBS 1

Figure 16

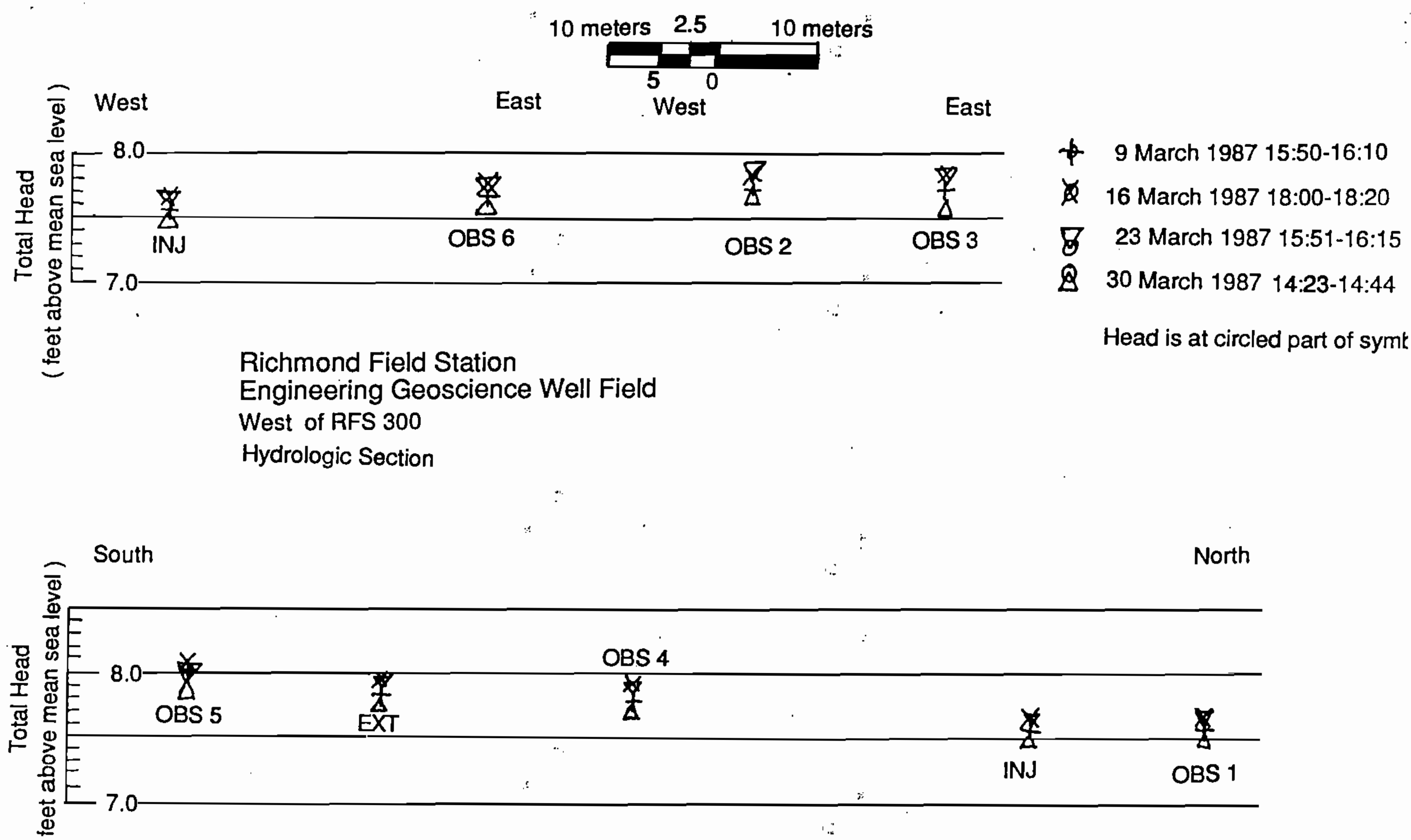

10 meters 2.5 10 meters
5 0
West
East
West
East
Total Head
(feet above mean sea level)
8.0
7.0
INJ
OBS 6
OBS 2
OBS 3
9 March 1987 15:50-16:10
16 March 1987 18:00-18:20
23 March 1987 15:51-16:15
30 March 1987 14:23-14:44
Head is at circled part of symb
Richmond Field Station
Engineering Geoscience Well Field
West of RFS 300
Hydrologic Section
South
North
Total Head
(feet above mean sea level)
8.0
7.0
OBS 5
EXT
OBS 4
INJ
OBS 1

Figure 17

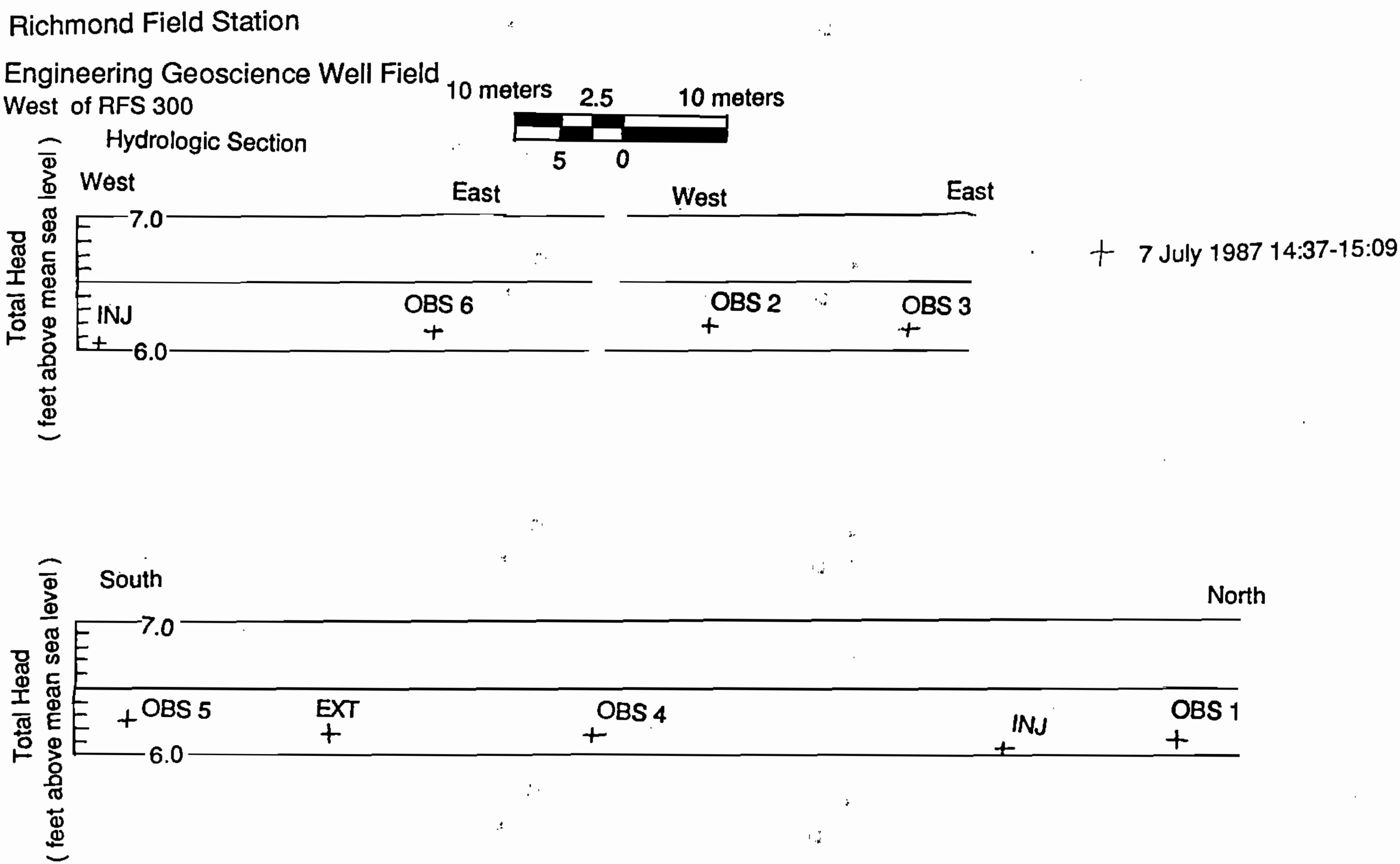

Richmond Field Station
Engineering Geoscience Well Field
West of RFS 300
Hydrologic Section
10 meters
2.5
10 meters
5
0
West
East
West
East
Total Head
(feet above mean sea level)
7.0
6.0
INJ
OBS 6
OBS 2
OBS 3
7 July 1987 14:37-15:09
South
North
Total Head
(feet above mean sea level)
7.0
6.0
OBS 5
EXT
OBS 4
INJ
OBS 1

Figure 18

Richmond Field Station
Engineering Geoscience Well Field
West of RFS 300
Drawdown Curve (log-log) for Pumping of INJ

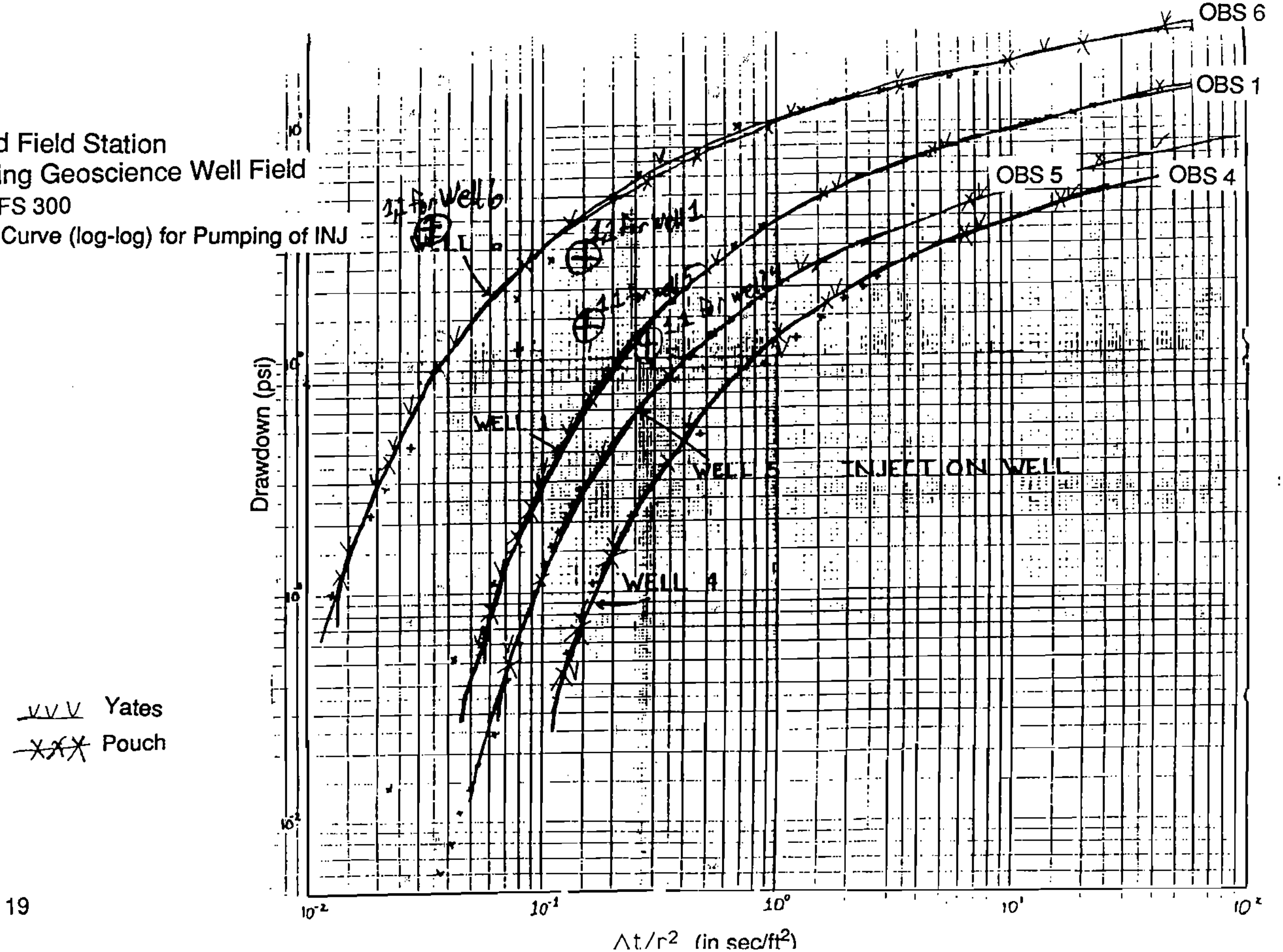


Figure 19

Richmond Field Station
Engineering Geoscience Well Field
West of RFS 300
Drawdown Curve (log-log) for Pumping of EXT

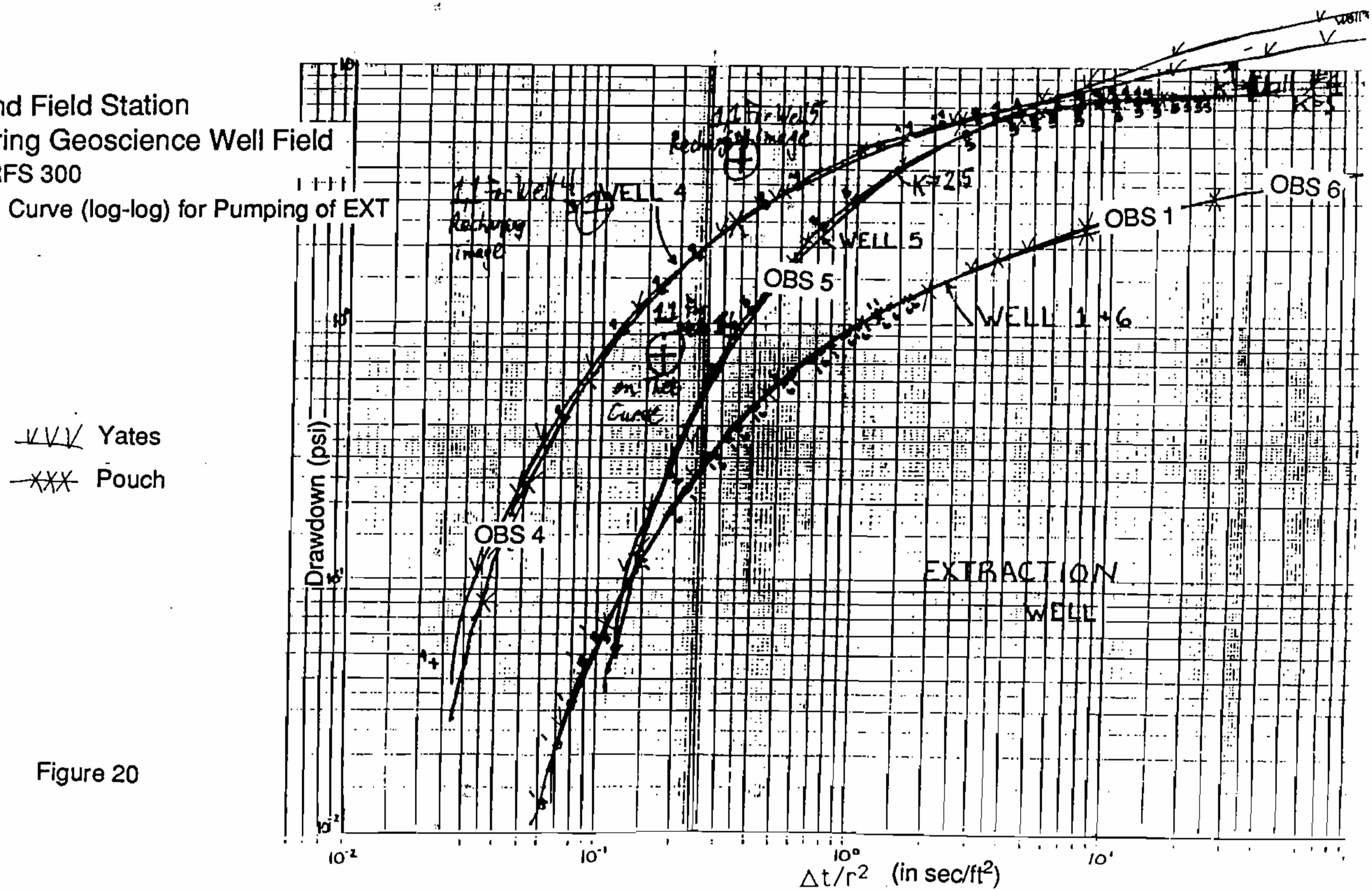
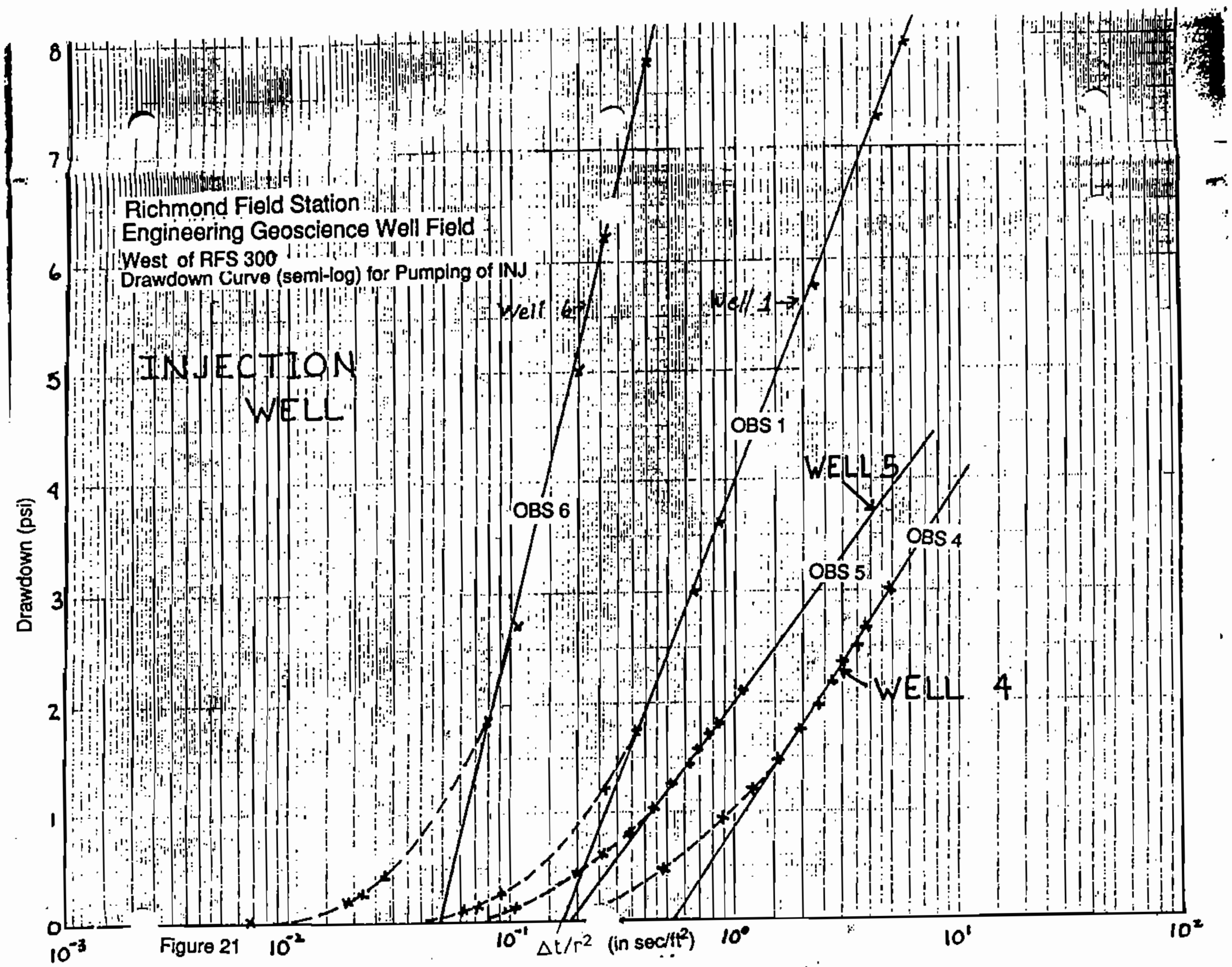
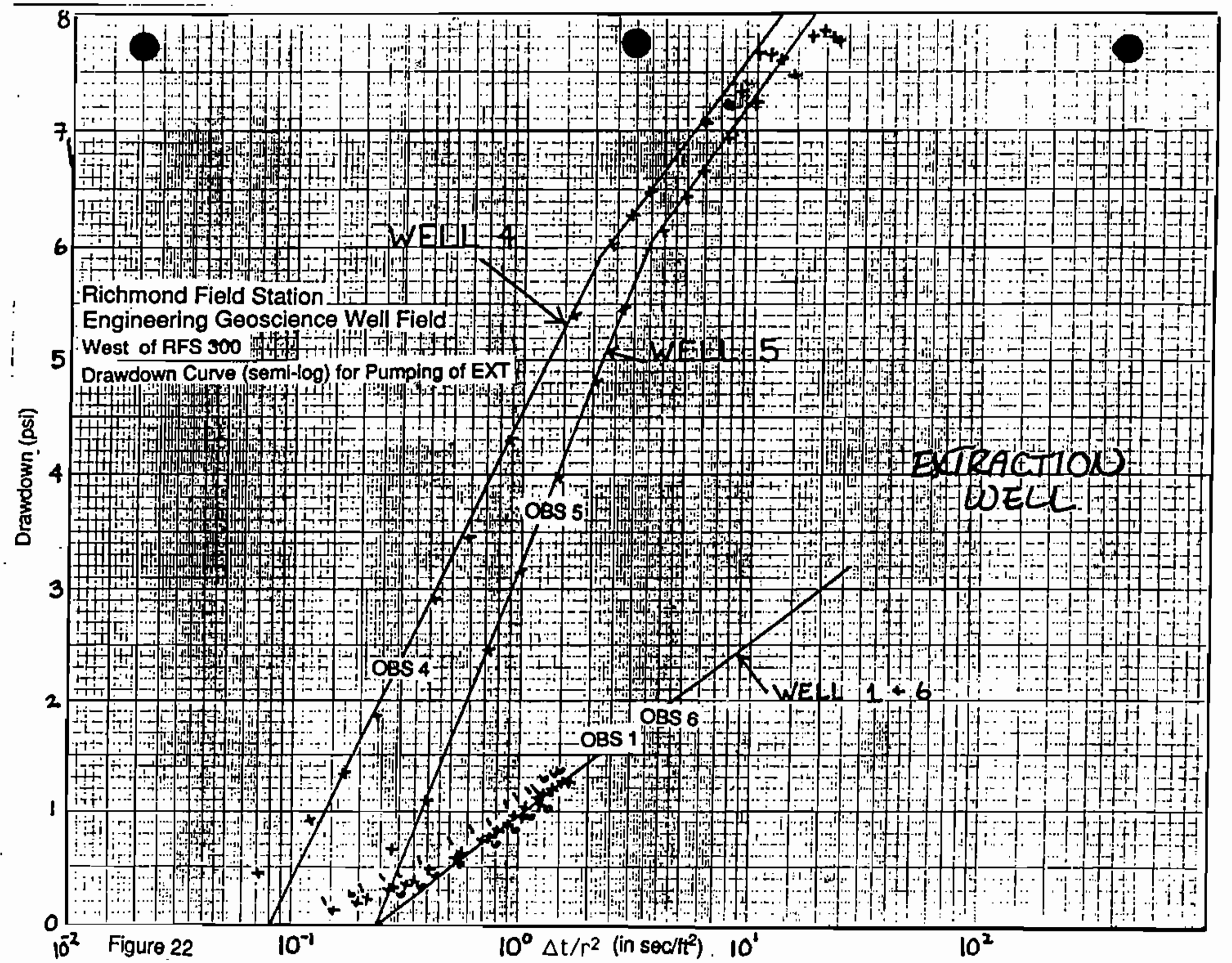


Figure 20



Richmond Field Station
Engineering Geoscience Well Field
West of RFS 300
Drawdown Curve (semi-log) for Pumping of INJ
INJECTION WELL
Well 6
Well 1
OBS 6
OBS 1
WELL 5
OBS 5
OBS 4
WELL 4
Drawdown (psi)
0
1
2
3
4
5
6
7
8
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
$\Delta t/r^2$ (in sec/ft²)

Figure 21


Richmond Field Station
Engineering Geoscience Well Field
West of RFS 300
Drawdown Curve (semi-log) for Pumping of EXT
Drawdown (psi)
0
1
2
3
4
5
6
7
8
10^{-2}
10^{-1}
10^{0}
$\Delta t/r^2$ (in sec/ft^2)
10^{1}
10^{2}
WELL 4
WELL 5
OBS 4
OBS 5
OBS 1
OBS 6
WELL 1 + 6
EXTRACTION WELL
Figure 22

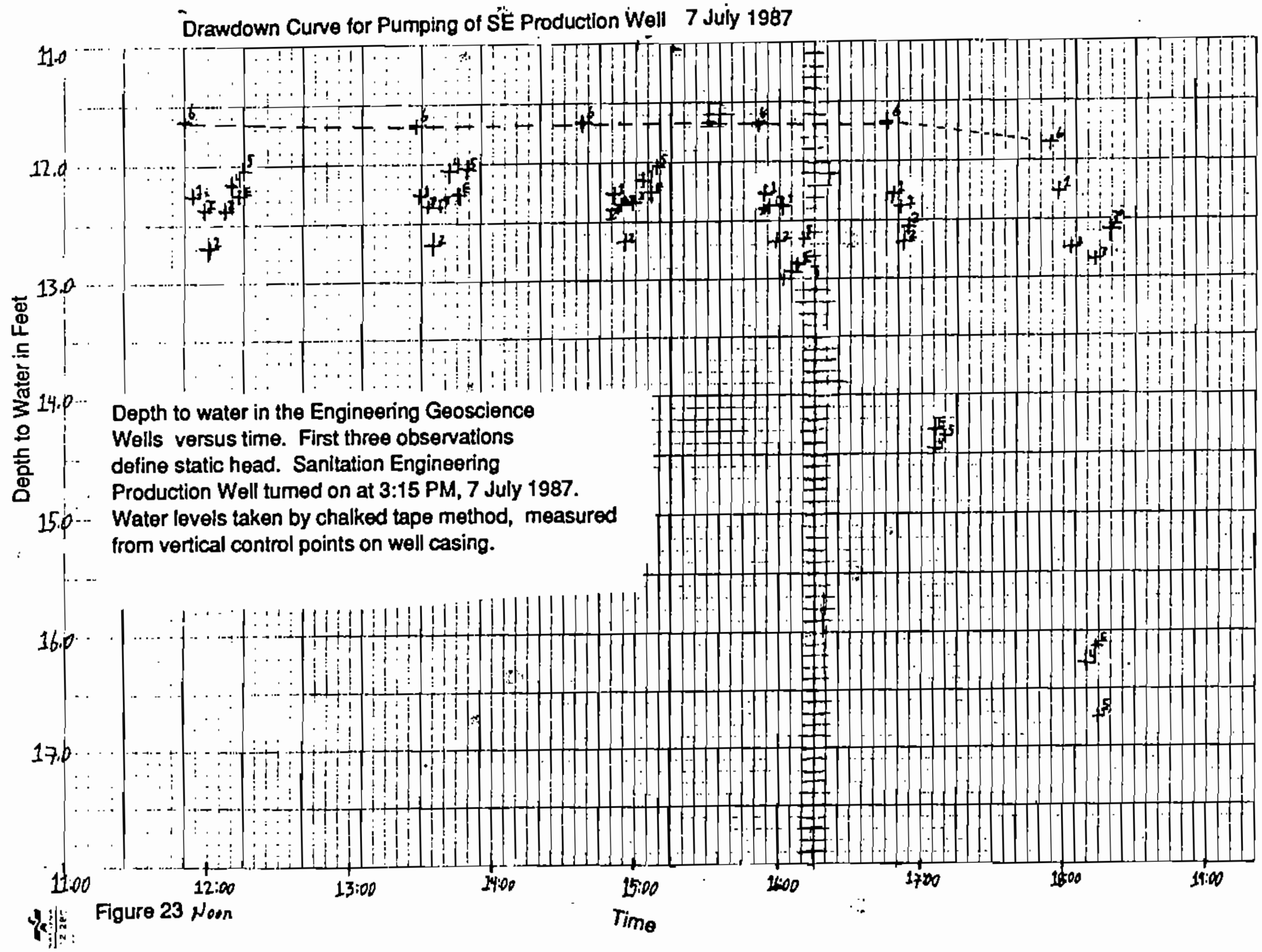


Figure 23 Noon

10 Squares to the Inch