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Geophysical Measurements of Gold-Bearing Gravels, Nevada County, Calif.

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Report of Investigations 7584

Geophysical Measurements of Gold-Bearing Gravels, Nevada County, Calif.

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UNITED STATES DEPARTMENT OF THE INTERIOR
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GEOPHYSICAL MEASUREMENTS OF GOLD-BEARING GRAVELS, NEVADA COUNTY, CALIF.

by

Benton L. Tibbetts[1] and James H. Scott[2]

ABSTRACT

Comprehensive geophysical measurements were made in the Tertiary Channel gravel deposits of Badger Hill, Calif., with the refraction seismograph, gravimeter, and well logging equipment, to develop a three-dimensional physical model of the gold-bearing gravels. Tests were also made of the applicability of magnetometer and electrical resistivity techniques.

Results of 14 seismic profiles revealed four distinct layers with velocities of 1,600 ft/sec for loose gravel, 5,900 ft/sec for compact gravel, 8,600 ft/sec for cemented, blue gravel, and 15,500 ft/sec for bedrock. The depth to bedrock along the middle of the channel varied from a minimum of 100 feet in the hydraulically mined pit area to a maximum of about 300 feet in the upper bench area immediately south of the pit. These geophysical methods revealed that 40 percent of the drill holes necessary to delineate the deposit could be eliminated, at a cost saving of at least 30 percent.

INTRODUCTION

The U.S. Bureau of Mines, with support from the Heavy Metals program, initiated a study in May 1968 in the Badger Hill segment of the Tertiary Channel gold-bearing gravel deposits (fig. 1) between the South and Middle Yuba Rivers, Nevada County, Calif. The objectives of this work were (1) to develop surface and in-hole geophysical equipment and field and interpretive techniques suitable for placer mining applications, (2) to use these measurements to provide a detailed three-dimensional physical model of the channel deposits necessary to quantitatively delineate the gold-bearing gravels in this area, and (3) to use this model as input for the design of various mining systems. The results should encourage the mining and tunneling industries to take advantage of cost saving and improved efficiency through advanced geophysical technology.

The principal tools for these investigations were the refraction seismograph, gravimeter, and magnetometer. A limited number of surface resistivity

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[1] Supervisory geophysicist.

[2] Research geologist.

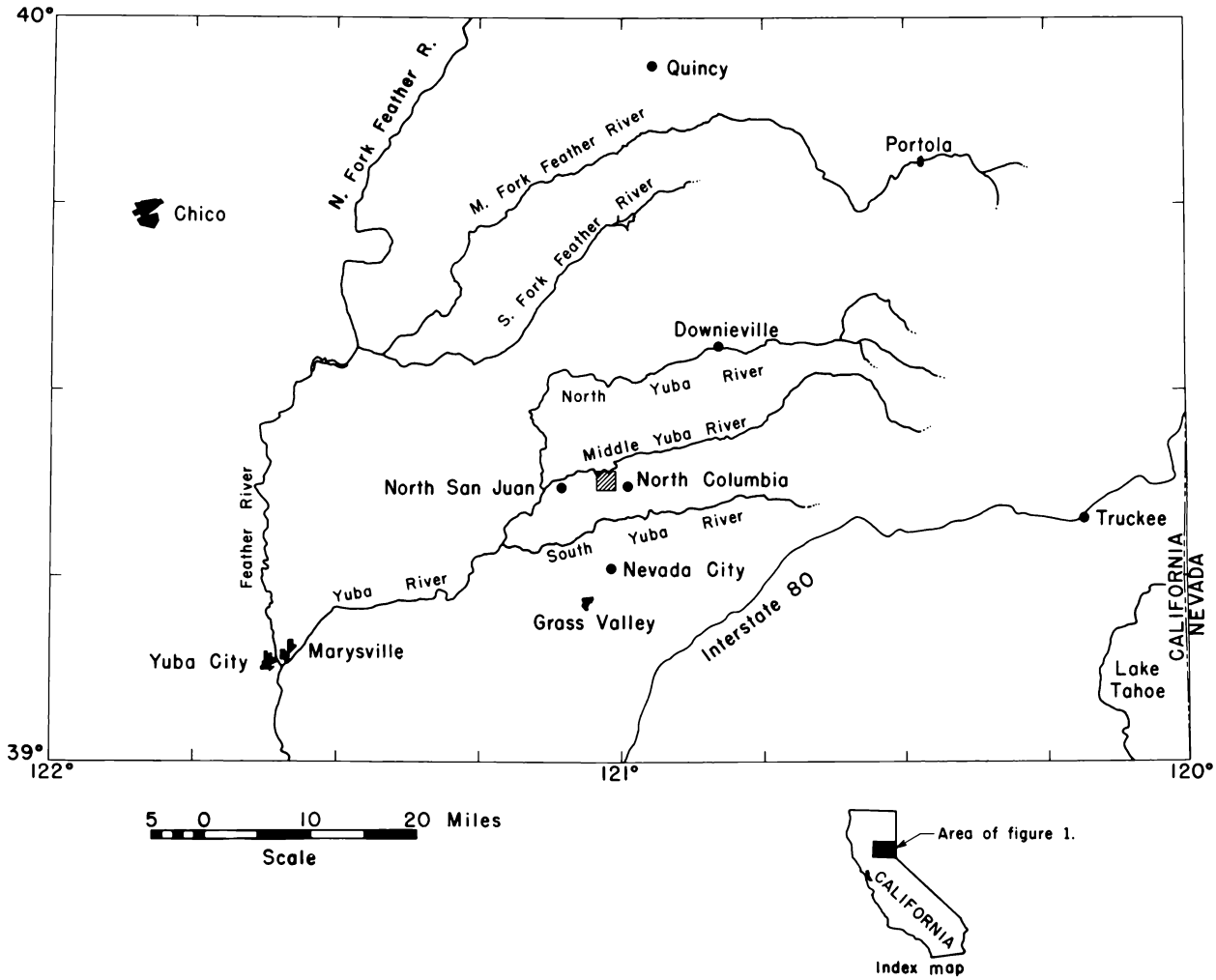

FIGURE 1. - General Location of Badger Hill, Calif. (Report Area Shaded).

measurements were made to determine the applicability of this method. Tops of various lithologic (cemented gravels) units and bedrock, which were obtained from holes drilled primarily for sampling and assaying purposes, were used as control for the seismic work. In figure 2, these holes are indicated as DH-1, 2, etc. Holes drilled by other Bureau of Mines personnel for hydrologic data, and indicated in figure 2 by DH-A, B, etc., were also utilized for geophysical corroboration. Down-hole velocity surveys, electric logs, and caliper logs were made in selected drill holes to provide velocity and lithologic control used in the final interpretation of the surface geophysical surveys. These geophysical tools and techniques were selected on the basis of reconnaissance geological studies and geophysical tests made by the U.S. Geological Survey in the area, particularly in the vicinity of the North Columbia Pit, about 2 miles east of the Badger Hill site (fig. 2), described by Peterson and others (3).[3]

[3]Underlined numbers in parentheses refer to items in the list of references at the end of this report.

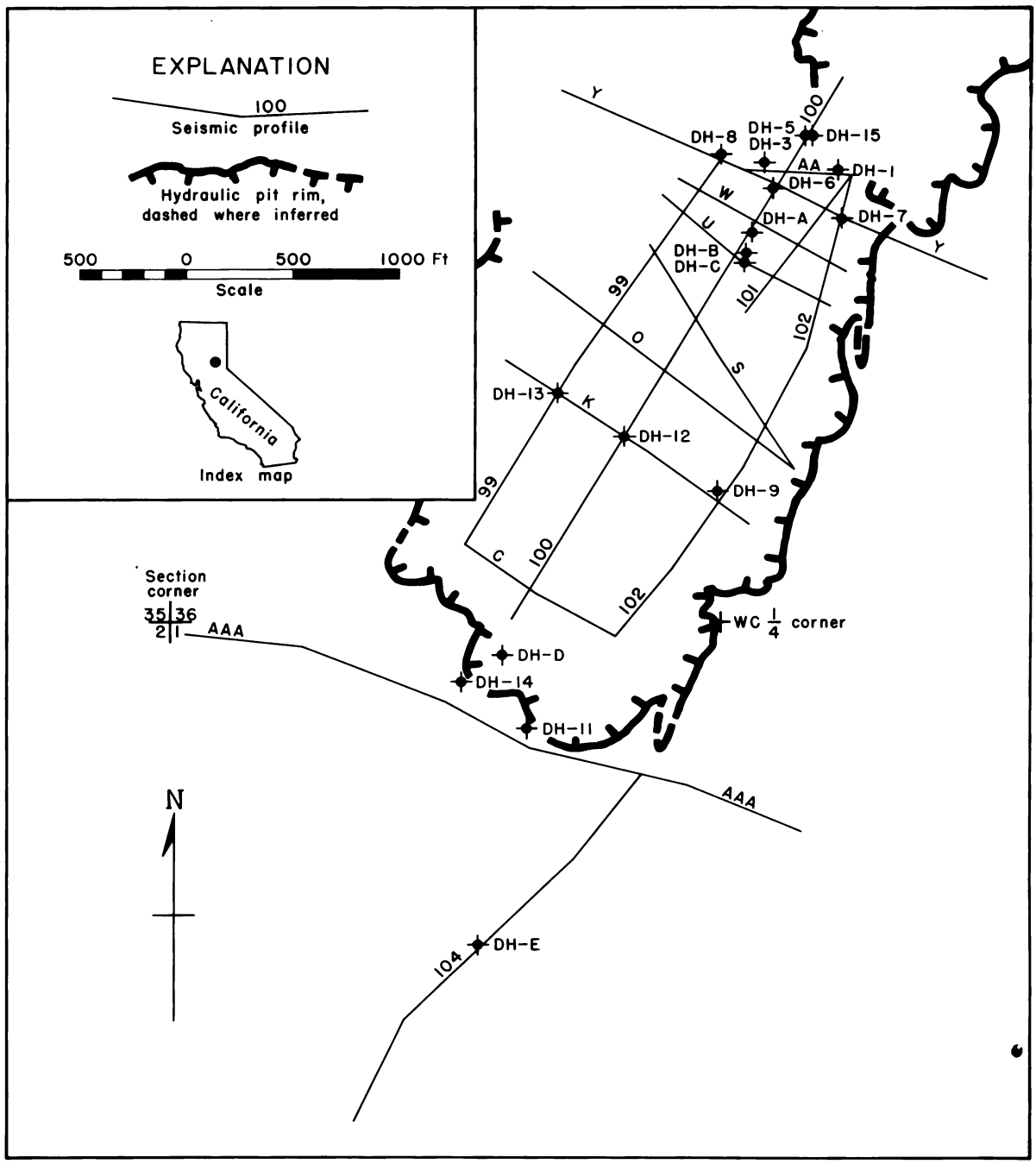

FIGURE 3. - Badger Hill Area, Showing Locations of Seismic Profiles, Drill Holes, and General Outline of the Hydraulic Pit.

A total of 14 seismic profiles were recorded. These varied in length from 500 to 3,000 feet, totaling 23,500 lineal feet (fig. 3). Twelve of these lines were run in the pit, and the remaining two lines were run in the upper bench area immediately to the south of the pit.

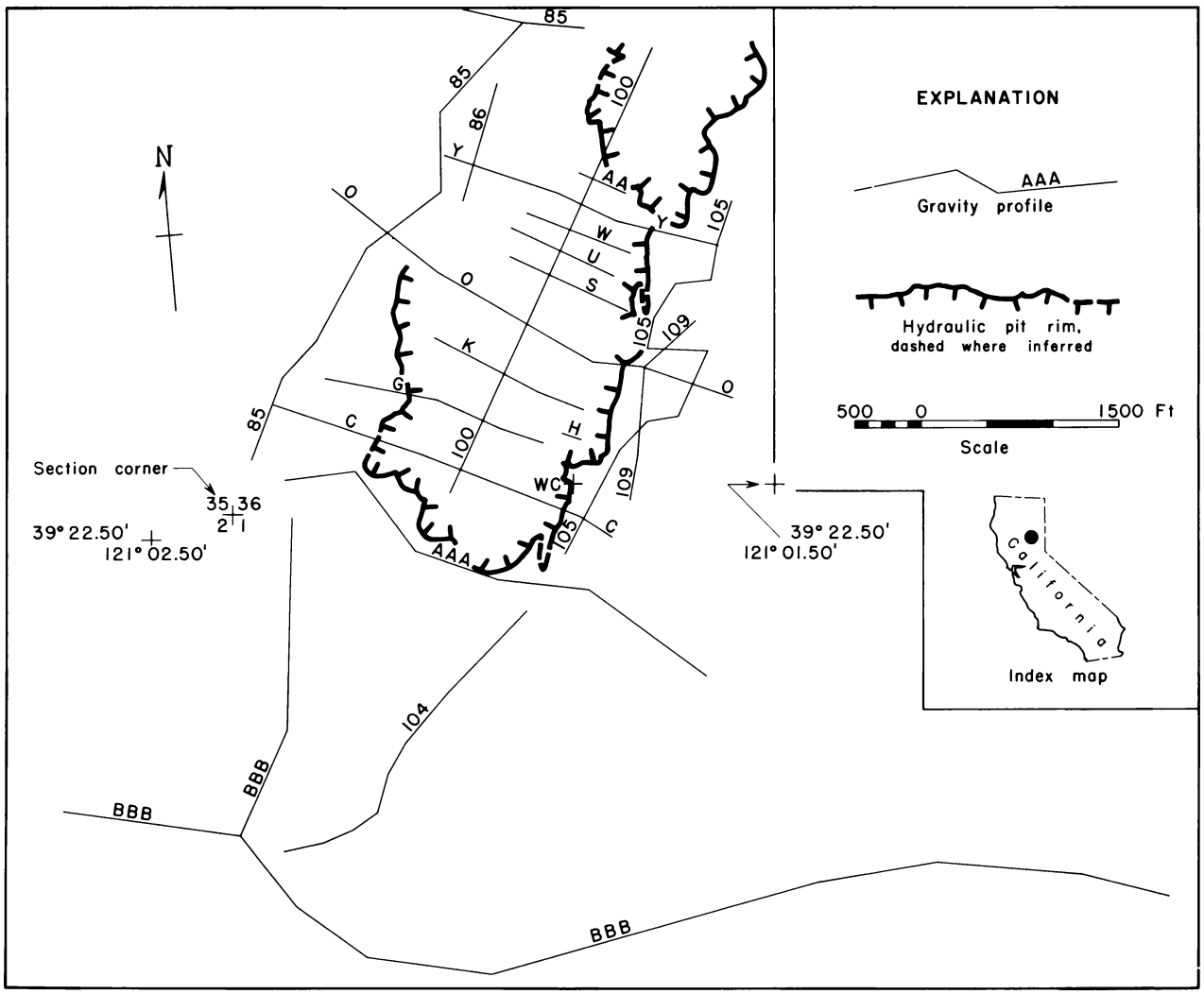

FIGURE 4. - Badger Hill Area, Showing Location of Gravity Lines and General Outline of the Hydraulic Pit.

Gravity readings were taken at about 300 locations in the Badger Hill area to provide a qualitative assessment of the configuration of the channel and to complement the seismic work (fig. 4). Magnetometer observations were made at about 1,000 stations in an effort to detect and delineate possible linear trends of magnetite and accompanying gold concentrations (fig. 5).

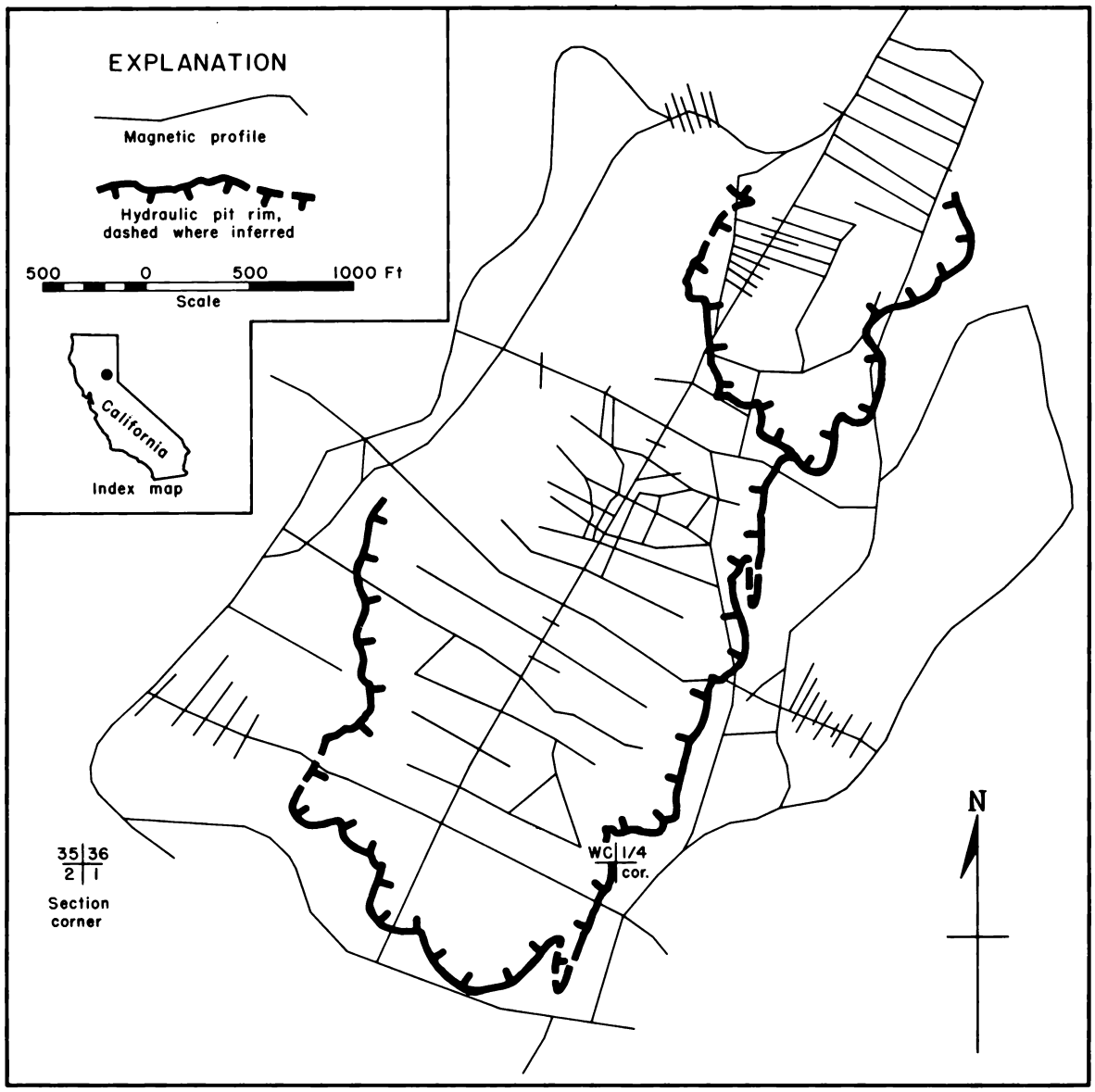

FIGURE 5. - Badger Hill Area, Showing Location of Magnetometer Profiles and General Outline of the Hydraulic Pit.

ACKNOWLEDGMENTS

We would like to thank the following property owners whose cooperation made field work in the Badger Hill area possible: the San Juan Gold Mining Company, James C. Anderson, Mary G. Campbell, Jim D. Chastain, Kate Daley, David Carl Dormeyer, Don McPherson, Delbert R. Schiffner, and the U.S. Bureau of Land Management. Special thanks go to Barry Marcellus for his invaluable work in reducing the gravity data, and to Robert Stahl for his professional assistance in describing the general geology of the Tertiary Channel.

GENERAL GEOLOGY

The Badger Hill site is located in a segment of a huge Tertiary gravel-filled channel lying in the area between the South and Middle Yuba Rivers in northern Nevada County, Calif. The gravel deposit, which is perched from 700 to 900 feet above the present streams, has been removed in part by hydraulic mining, creating an enormous pit known as the Badger Hill diggings. A vertical bank of gravel approximately 120 feet high separates the lower and upper workings. The lower pit was hydraulicked to bedrock laying bare a segment of the channel bottom approximately 2,000 feet long and 1,200 feet wide. The upper pit is approximately 3,000 feet long and 2,000 feet wide. Total relief in the pit area is about 200 feet. The altitudes range from 2,400 feet in the lower pit to about 2,600 feet on the high point of the upper bench (fig. 2).

Bedrock

Slates, phyllites, and quartzites constitute the bulk of the exposed bedrock in the lower pit at Badger Hill. These rocks are part of the late Paleozoic Calaveras Formation and crop out in belts striking north-northwest and dipping northeast. Granitic rocks and minor quartz veins intrude the metamorphic rocks.

Gravel Deposit

The channel fill is classified into lower and upper gravels. The lower gravel is coarse and poorly sorted. The upper gravel is considerably less coarse, better sorted, and contains many beds of clay and sand.

Within the lower gravel, two units are recognized, blue gravel and red gravel. The blue gravel fills the bottom of the main channel and ranges from 95 to 125 feet thick along the axis of the channel at Badger Hill. The blue gravel is characterized by a distinctive gray-blue color, the presence of secondary sulfides, a high density, and a relatively high percentage of large boulders within 20 feet of bedrock. The material is highly compacted and often is tightly cemented requiring drilling and blasting for primary fragmentation. About 71 percent of the blue gravel by weight is made up of pebble-, cobble-, and boulder-size material composed of metamorphic rocks, weathered rocks, and milky quartz. The remaining 29 percent of the blue gravel by weight consists of fine to coarse quartz sand and blue clay interspersed as pods or stringers in the blue gravels. Mixed with the blue gravel are minor amounts of gold, mica, black sand, pyrite, zircon, and carbonaceous material.

The overlying unconsolidated red gravel contrasts markedly in color with the underlying blue gravel, although the two units are similar in lithology and sorting characteristics. The red gravel has been oxidized, is stained brown by iron oxide, and generally lacks sulfides. Many of the cobbles and pebbles, where exposed to the atmosphere, are deeply weathered and crumble when hit with a hammer. Some display weathering rinds 1/2 inch to 1 inch deep. The thickness of the red gravel unit ranges from 20 to 80 feet in the upper pit at Badger Hill.

The white gravel in the upper portion of the channel is about 90 feet thick, is well exposed in the walls of the Badger Hill hydraulic pit, and constitutes the bulk of the channel deposit. About 5 percent of the white gravel by weight is made up of pebble-size material composed of milky white quartz. The remaining 95 percent by weight consists of fine to coarse quartz sand and clay.

Approximately 80 percent of the gold occurs in the blue gravel near bedrock. The remaining 20 percent is distributed erratically throughout the red and white gravels, from the ground surface to the blue gravel contact and from bank to bank in the channel fill.

INSTRUMENTATION AND FIELD PROCEDURES

All of the seismic recordings were made with an SIE Model RS-4[4] 12-channel refraction seismic system. Electro-Tech 7.5 and 30 Hz miniature geophones were used; the higher frequency detectors were found to be the more satisfactory. Geophone spacing ranged from about 50 feet to a maximum of 100 feet, limited by the length of the cable. Consequently, the maximum spread length was 1,100 feet. Most profiles required more than one spread to effect the coverage necessary, up to three. On the longer profiles, such as AAA east-west, and the 100-profile north-south, the spreads were identified as AAA-W, AAA-M, and AAA-E, and 100-N, 100-M, and 100-S, respectively. On profiles of intermediate length where two spreads were used, the M (for middle) designation was omitted.

The configuration of shot points along the 12-geophone spread consisted of either one or three interior shot points, a shot point at each end, usually about 10 feet from the last geophone, and a shot point offset from each end of the spread by a few hundred feet, depending upon the depth to bedrock, the length of the spread, and the relative elevation of the offset shot point to that of the spread. The interior shot points were used to provide information on the complicated near-surface layers. These shot points were located between geophones 3 and 4, 6 and 7, and 9 and 10. One shot was always fired at the center of the spread between geophones 6 and 7. Explosive charges ranged in size from one stick of 40-percent gel (about 1/3 pound) to a maximum of 100 pounds. Common sizes were 3 pounds for the interior shot points, 20 pounds for the end shot points, and 50 pounds for the offset shot points.

Most of the charges were detonated in a shallow hole dug with a shovel about 1 or 2 feet deep, depending upon the thickness of the loose material on the surface. A few charges were placed at the bottom of holes dug with a truck-mounted auger to depths of about 3 to 25 feet. The improvement in record quality was not enough to justify the additional time and cost required for using the auger.

Ground elevations of the geophone stations and shot points were surveyed with a transit and measuring tape to a vertical accuracy of 0.1 foot and a horizontal accuracy of about 1 foot.

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[4]Reference to specific makes and models of equipment is made for identification only and does not imply endorsement by the Bureau of Mines.

Because of the common necessity of accurate elevations, gravity readings were made at most seismic geophone stations in addition to extensions of the seismic lines well beyond the limits of the pit. Additional readings were made at intermediate points between seismic lines to provide detailed gravity coverage of the area. A La Coste and Romberg Model G gravity meter was used for this work.

Initial magnetometer observations were made using a fluxgate meter which measures the vertical component of the earth's magnetic field to an accuracy of about ±10 gammas. In the later stages of the field work, two portable proton precession magnetometers were acquired. These instruments provided the advantages of higher sensitivity (±1 gamma), total field in direct digital readout, and freedom from orientation and leveling errors. The proton meters were found to be superior with respect to reliability, speed, and convenience of operation.

Electrical resistivity instruments were employed for the few surface resistivity measurements that were made.

Down-hole velocity surveys were made with a 12-detector Vector cable with ceramic pressure transducers positioned on the cable at 10-foot intervals. The cable was lowered into the drill hole and surface shots were detonated for recordings made on the SIE Model RS-4 seismic unit.

Electric logs and caliper logs were made with a custom designed portable well logging system. The following types of electric logs were obtained: single-point resistance, self-potential, and 8-, 16-, 32-, and 64-inch normal resistivity.

SEISMIC DATA REDUCTION

Travel times of the seismic waves from the shot to each geophone were picked to the nearest millisecond. After the first field measurements were made, an attempt was made to interpret the results using the conventional methods of determining apparent velocities by visually fitting straight-line segments to travel-time plots of the observed data, and subsequently calculating thicknesses of the refracting layers by time-intercept and delay-time computations. Accuracy, using these conventional calculation techniques, was difficult to achieve because of the wide scatter of travel-time plots caused by changes in surface elevation, thickness, and velocity of the near-surface layer, and because of the complexity of the layering. These changes were primarily a consequence of the hydraulic mining operations of the area about a century ago. Hence, tedious elevation and weathering corrections were applied to each trace as a first step in obtaining accurate thicknesses of the refracting layers. Interpretation was further complicated by inhomogeneities in the two uppermost gravel layers that resulted from poor sorting and the presence of irregular seams of sands, clay, and mudstones. Since one of the objectives of the program was a quantitative determination of the volume of gravel of different degrees of compaction, accurate delineation of depositional layers and total depth to bedrock of the channel were needed. Conventional interpretation procedures failed to provide satisfactory results. Therefore a

computer program was developed that applied corrections for the erratic near-surface layer and delineated the deeper layers by a mathematical modeling procedure based on tracing seismic rays through a two-dimensional model (5). High accuracy of the computer solution was achieved through an iterative process designed to fit the model to the field data so as to minimize the discrepancy between computed ray-path times and field-measured first arrival times. The seismic interpretation program is divided into the following three main parts.

Part 1.--Control cards and data cards are read into computer memory. After data read in, a time-distance graph of raw data may be made on the high-speed printer by control-card option. Next a reference data plane is determined by least-square fitting a line through geophone positions. All refraction time measurements are corrected to this datum after establishing the velocity of layer 1 by averaging all direct arrival data. Another time-distance graph of the datum-corrected refraction measurements may be plotted by control-card option.

Part 2.--The following steps comprise the second part:

1. Velocity is estimated for layer 2 by two regression techniques.

2. Depths and horizontal positions are computed for points representing seismic rays entering and emerging from the interface between layers 1 and 2. This computation is accomplished by making an initial approximation by the delay-time technique followed by an iterative ray-tracing procedure, which yields improved accuracy after each iteration. Rays are traced according to Snell's Law from each shot point to each geophone. Time discrepancies between the traced rays and field measurements are minimized by a convergent iterative process in which the layer interfaces are adjusted successively for best fit.

3. With the base of layer 1 defined, the layer is, in effect, stripped away by subtracting times associated with ray path segments in layer 1 from all measured times associated with rays traveling through layer 1 to deeper layers.

4. A new time-distance graph showing these results is plotted under control-card option. In areas where terrain is very rugged and layer 1 is very erratic in thickness, this time-distance graph shows a remarkable improvement in smoothness over the graphs that are plotted before layer 1 is stripped away. The objective of this approach is to obtain a time-distance graph that is least affected by surface and near-surface time or velocity anomalies, so that the human interpreter may determine which layer is represented by each arrival time with more confidence and accuracy.

5. The program estimates the velocities of layers below layer 2 by a combination of regression techniques.

Part 3.--Interfaces of layers beneath layer 2 are determined by the same technique used to define the interface between layers 1 and 2. A first approximation is made by the delay-time method, and then the approximation is

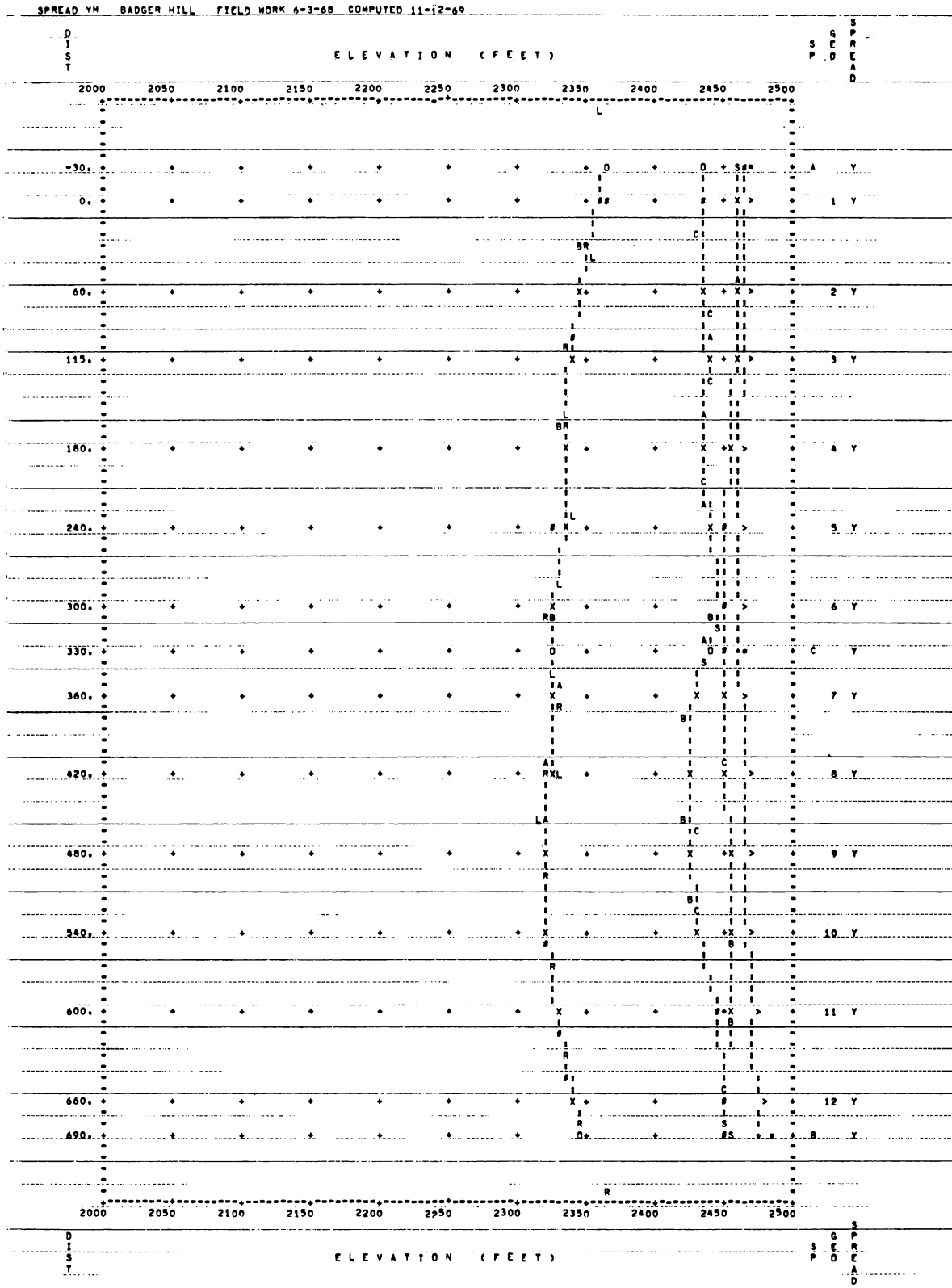

FIGURE 6. - Computer Plot of Seismic Profile YM.

improved by the iterative ray-tracing procedure. Each layer interface is worked on separately, starting with the interface between layers 2 and 3 and working downward. After these layer computations are completed, a final adjustment is made in the position of the interface between layers 1 and 2 so as to reduce the average time discrepancy for sets of rays associated with individual shot points and detectors. Then a final ray-path-tracing iteration is made, starting with the base of layer 2 and going downward. A cross-sectional profile showing the resulting interpretation is plotted on the high-speed printer after the computer analysis is complete. An example of the computer plot of Badger Hill Spread YM (Y-middle) is shown in figure 6.

The version of the program used to interpret Badger Hill seismic data was designed with the following limits, which may be easily changed to accommodate larger problems as required:

	Limit (maximum per problem)
Layers	5
Spreads	5
Shot points per spread	7
Geophones per spread	12

Typical running time on the Burroughs 5500 computer was 1 to 2 minutes per spread of 12 geophones and five to seven shot points for a three- to four-layer problem.

Almost all of the results subsequently described were obtained through use of this program. The program is considered to be a major contributing factor to the successful application of the seismic method.

ANALYSIS OF SEISMIC PROFILES

The location of the 14 seismic profiles is shown in figure 3. Most of the seismic lines were laid transverse to the trend of the channel in keeping with the objective, to determine the configuration of the bottom of the channel, as well as to delineate the deepest part of the channel where accumulations of gold are most likely to occur.

The sequence of laying out and shooting the seismic profiles began with the installation of line 100 as a base line for subsequent geophysical work in the pit area. The general sequence of shooting that followed was with the transverse lines beginning at the north end of the pit and progressing southward to line K. Following the development of the computer program, lines 100 and K were reshot to take advantage of the optimum shot point to geophone arrangement designed to facilitate accurate interpretation by the computer program. Lines 101, 102, 99, AAA, and 104 were shot in that order in the later phases of the field work.

Line Y was extended much farther out on the flanks of the channel than the other transverse profiles to assure that the total width of the channel

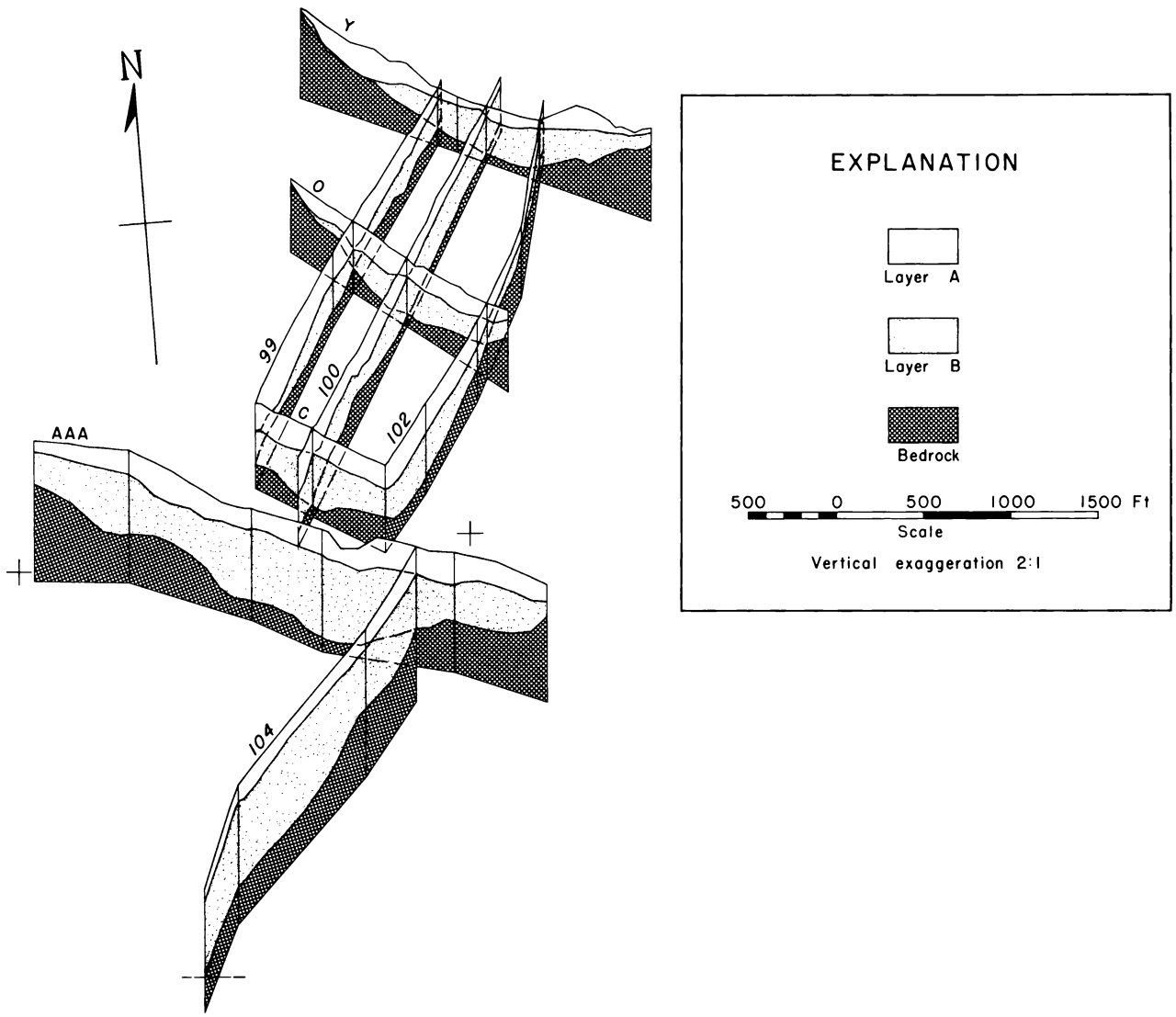

FIGURE 7. - Fence Diagram Showing a Generalized Three-Dimensional Model Developed From Seismic-Refraction Profiles.

was covered and its limits defined. Line AAA was similarly designed, particularly since it was outside (south of) the pit.

The fence diagram (fig. 7) presents a generalized three-dimensional picture of the results of all seismic work. Figures 8-21 are two-dimensional cross sections showing the interpreted results of individual seismic profiles.

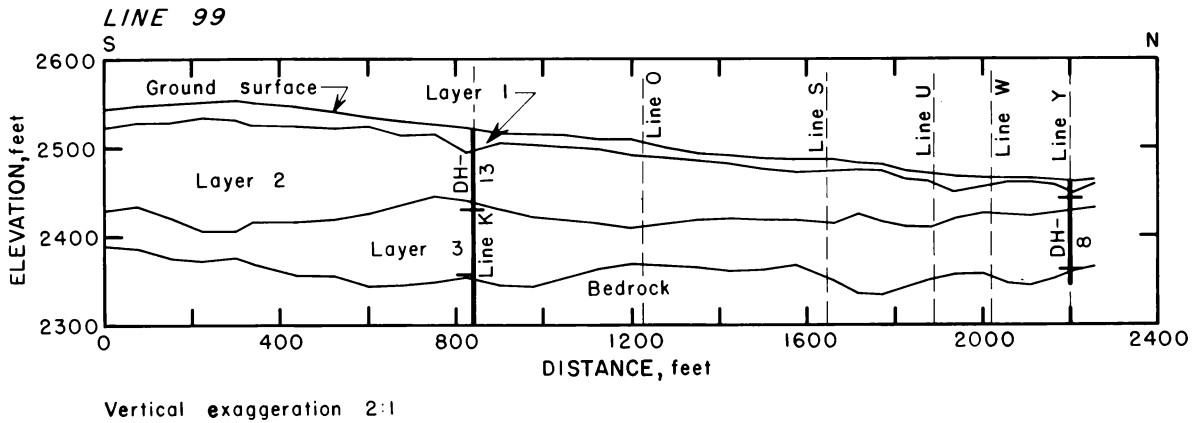

FIGURE 8. - Cross Section Showing Results of Seismic-Refraction Profile 99, and Drill Hole Depths to Layers 3 and 4.

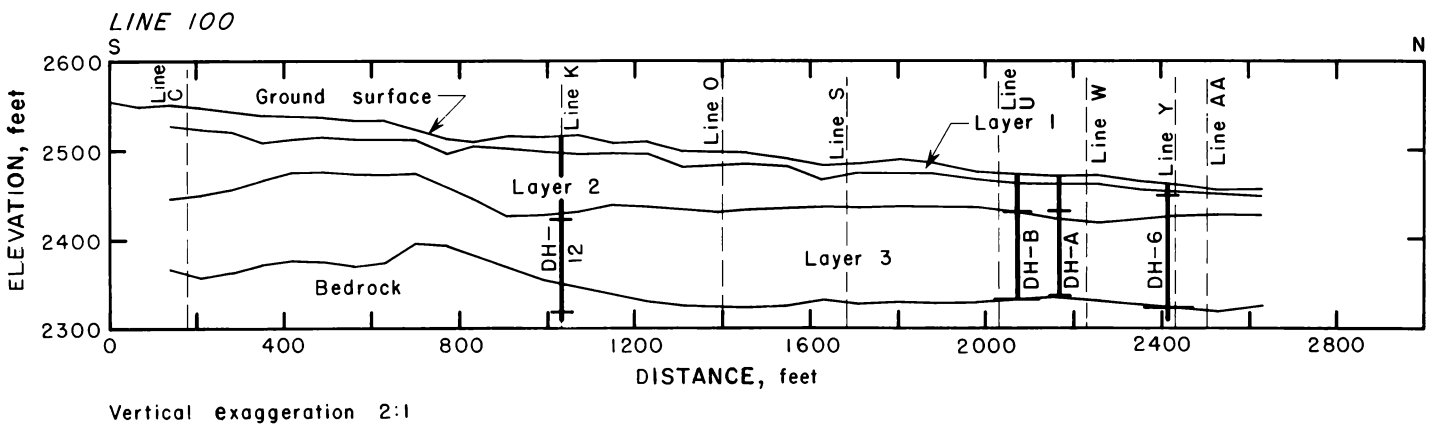

FIGURE 9. - Cross Section Showing Results of Seismic-Refraction Profile 100, and Drill Hole Depths to Layers 3 and 4.

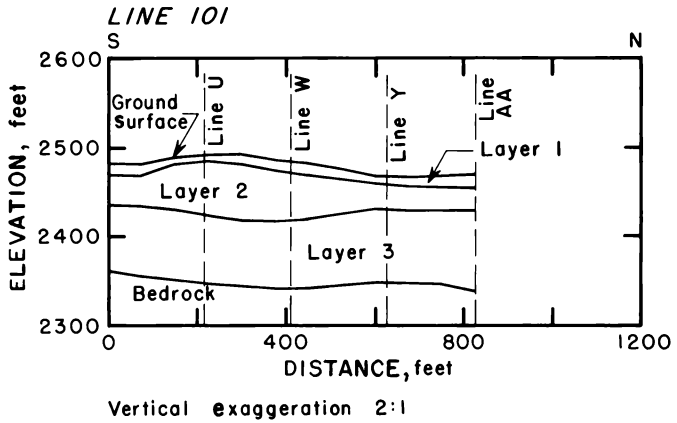

FIGURE 10. - Cross Section Showing Results of Seismic-Refraction Profile 101.

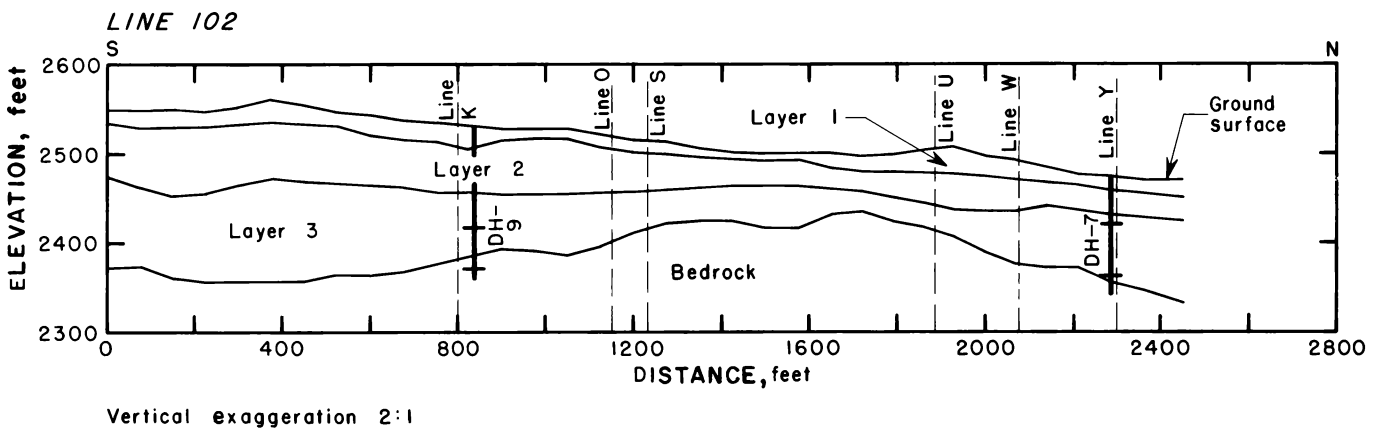

FIGURE 11. - Cross Section Showing Results of Seismic-Refraction Profile 102, and Drill Hole Depths to Layers 3 and 4.

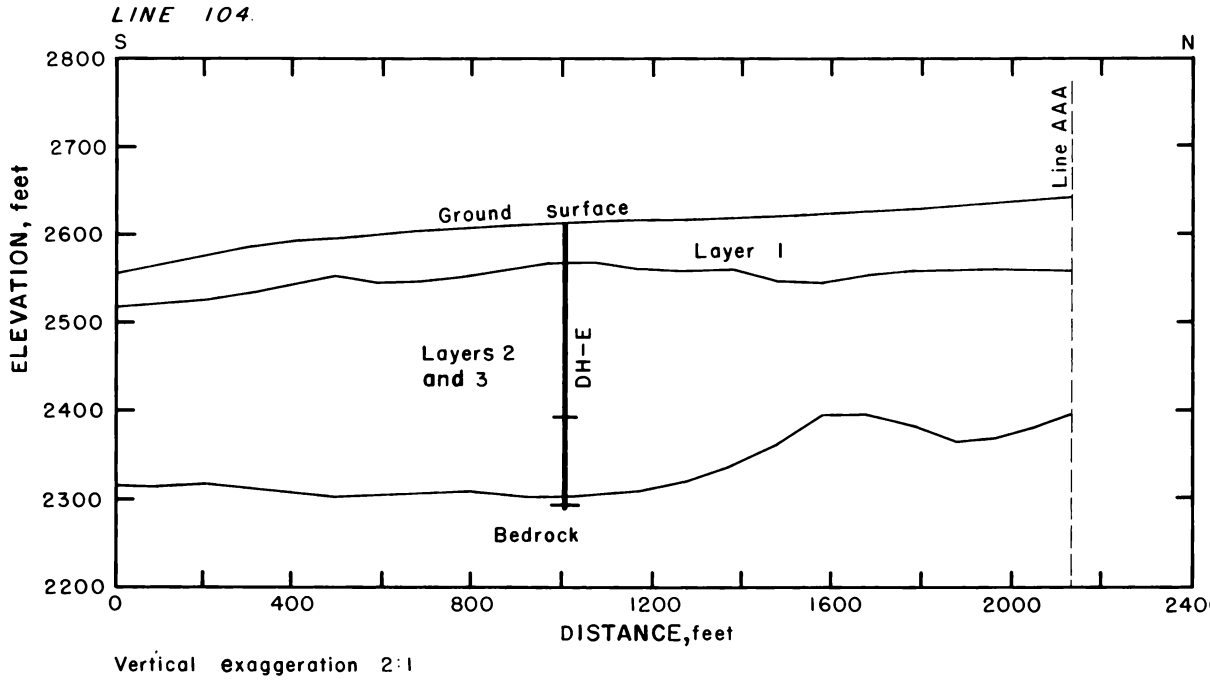

FIGURE 12. - Cross Section Showing Results of Seismic-Refraction Profile 104, and Drill Hole Depths to Layers 3 and 4.

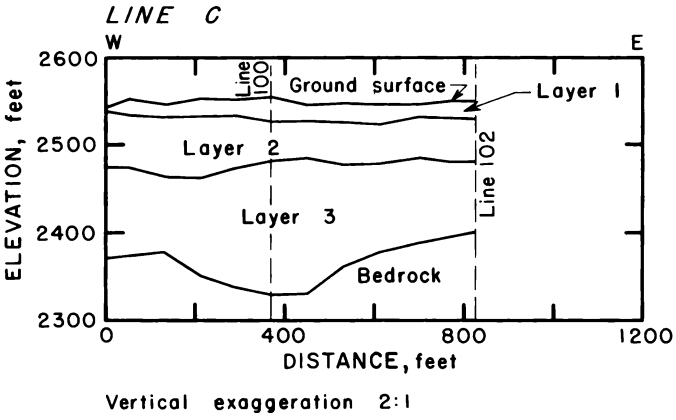

FIGURE 13. - Cross Section Showing Results of Seismic-Refraction Profile C.

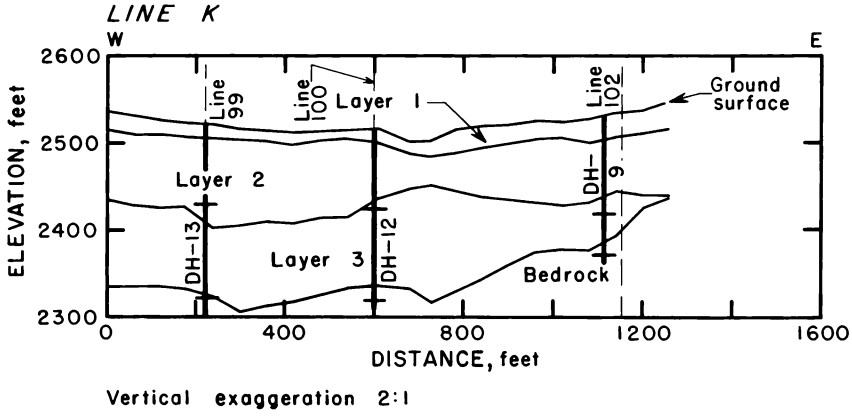

FIGURE 14. - Cross Section Showing Results of Seismic-Refraction Profile K, and Drill Hole Depths to Layers 3 and 4.

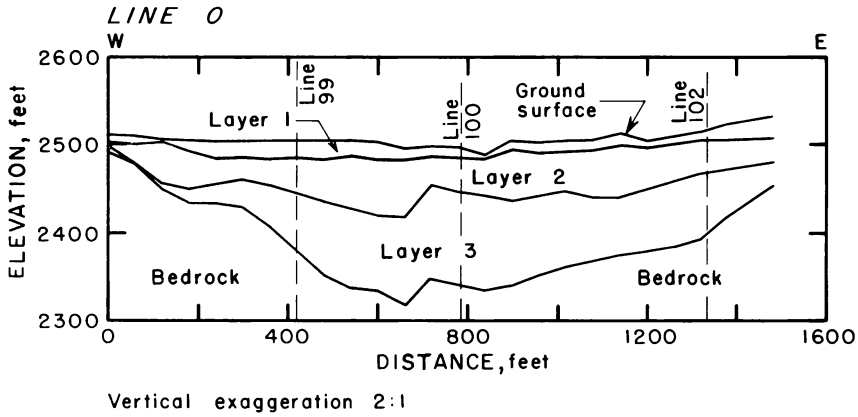

FIGURE 15. - Cross Section Showing Results of Seismic-Refraction Profile O.

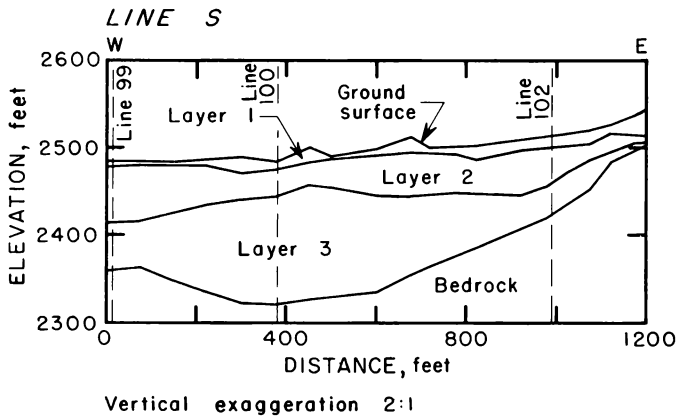

FIGURE 16. - Cross Section Showing Results of Seismic-Refraction Profile S.

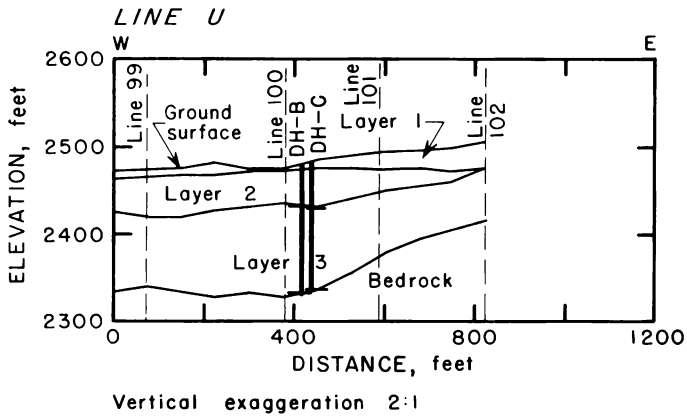

FIGURE 17. - Cross Section Showing Results of Seismic-Refraction Profile U, and Drill Hole Depths to Layers 3 and 4.

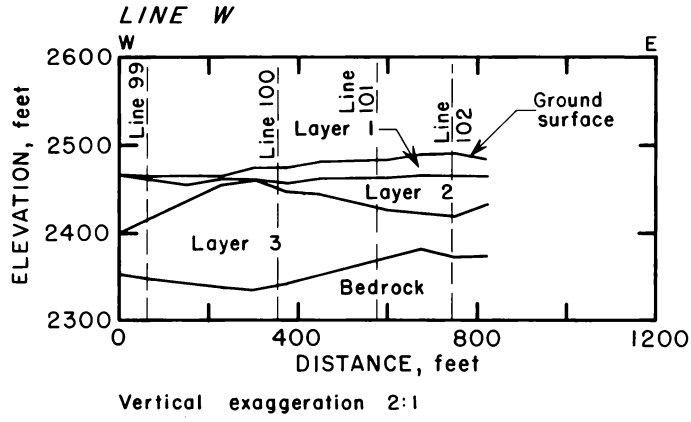

FIGURE 18. - Cross Section Showing Results of Seismic-Refraction Profile W.

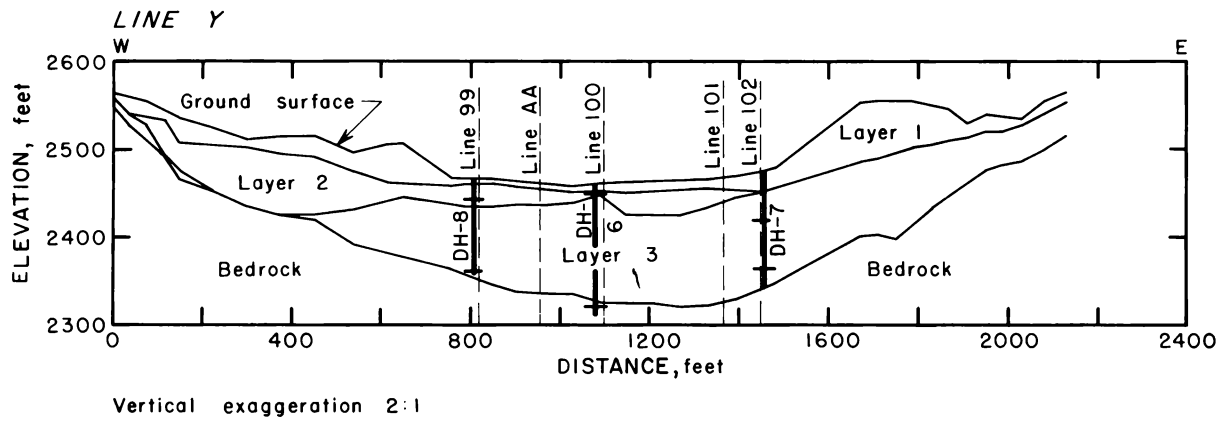

FIGURE 19. - Cross Section Showing Results of Seismic-Refraction Profile Y, and Drill Hole Depths to Layers 3 and 4.

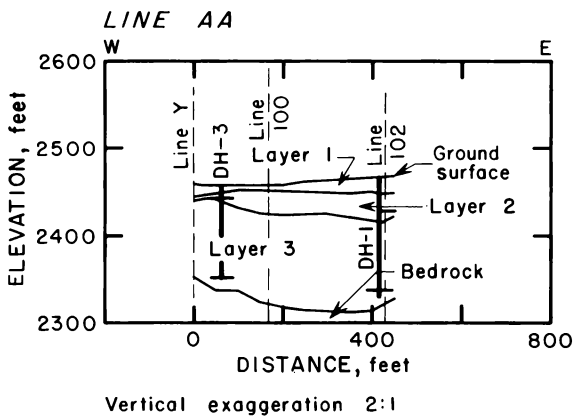

FIGURE 20. - Cross Section Showing Results of Seismic-Refraction Profile AA, and Drill Hole Depths to Layers 3 and 4.

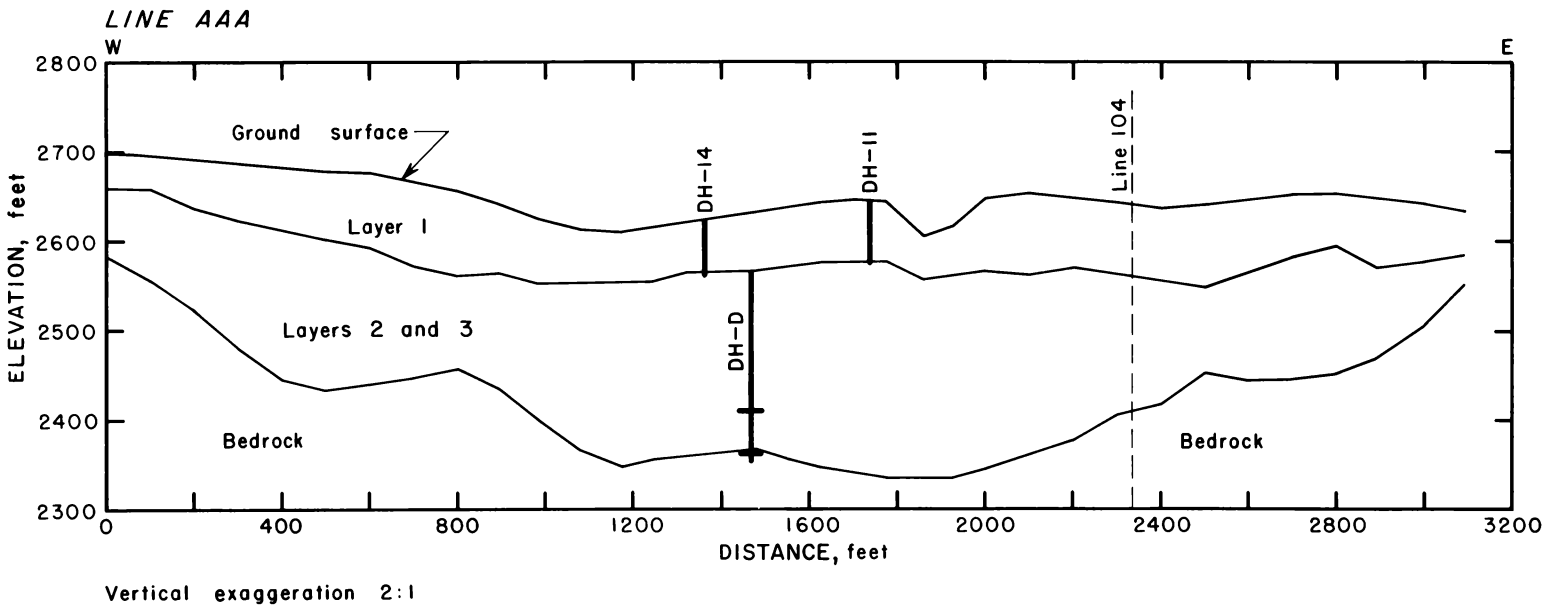

FIGURE 21. - Cross Section Showing Results of Seismic-Refraction Profile AAA, and Drill Hole Depths to Layers 3 and 4.

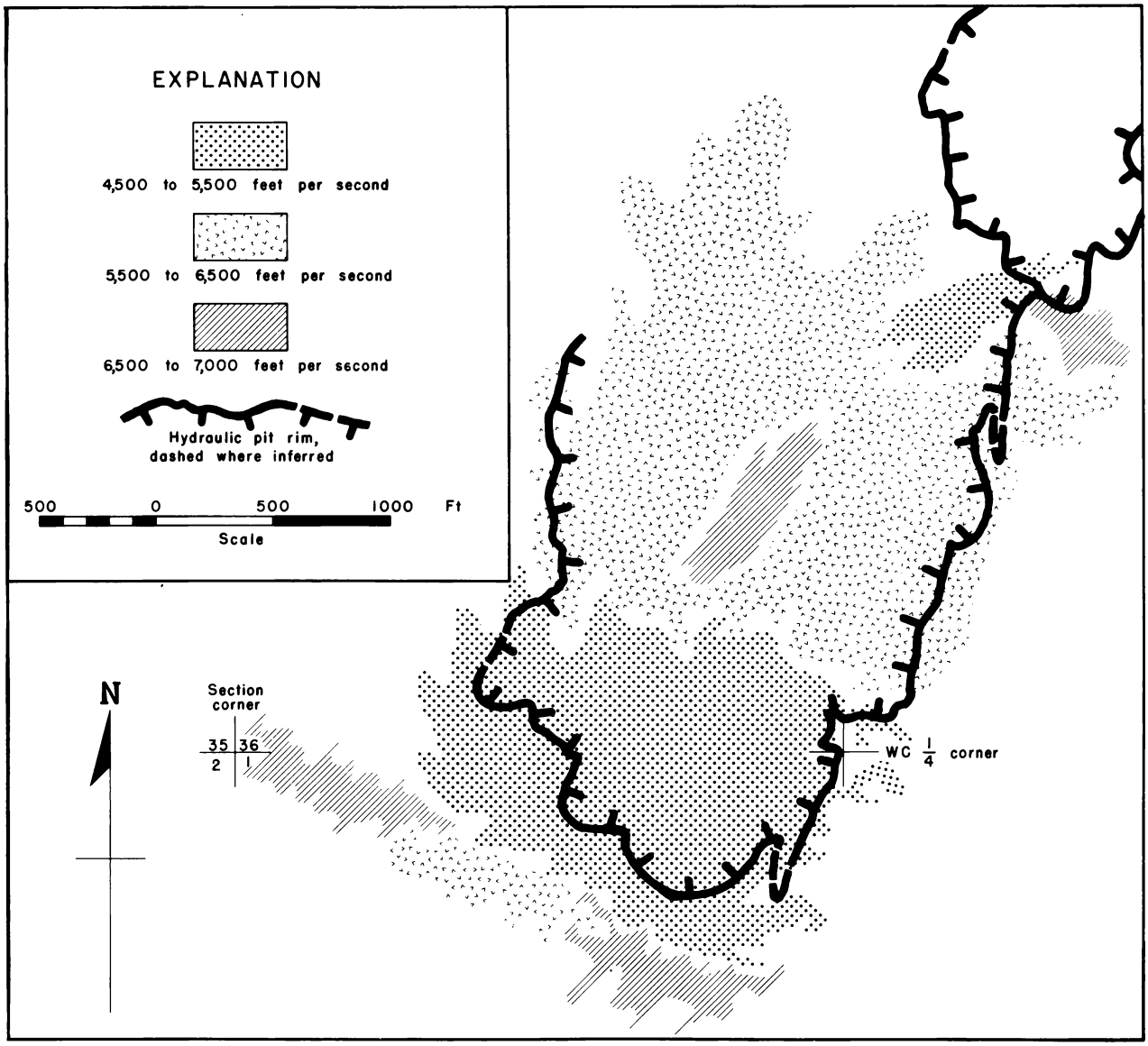

FIGURE 22. - Areal Distribution of Seismic Velocities Through Layer 2.

Interpretations of all of the seismic profiles run in the area revealed that four distinct layers are present according to velocity values as shown in table 1. The velocity of layers 1 and 3 varied only slightly and in a random manner. However, variations in the velocity of layers 2 and 4 appear to be spatially significant as indicated in figures 22 and 23. Figures 24 and 25 are structural contour maps on the blue gravel and bedrock, respectively. These maps were intended to provide information on the location of the deepest part of the channel and the thickness of the auriferous blue gravel layer.

TABLE 1. - Velocity values of distinct layers as determined by seismic profiles

Layer	Unit	Average velocity (ft/sec)	Velocity range (ft/sec)	Thickness (ft)
1	Loose gravel.....	1,600	1,420- 2,000	30
2	Compact gravel.....	5,900	5,000- 7,200	40
3	Cemented, blue gravel.....	8,600	7,500-10,000	80
4	Bedrock.....	15,500	13,000-17,000	-

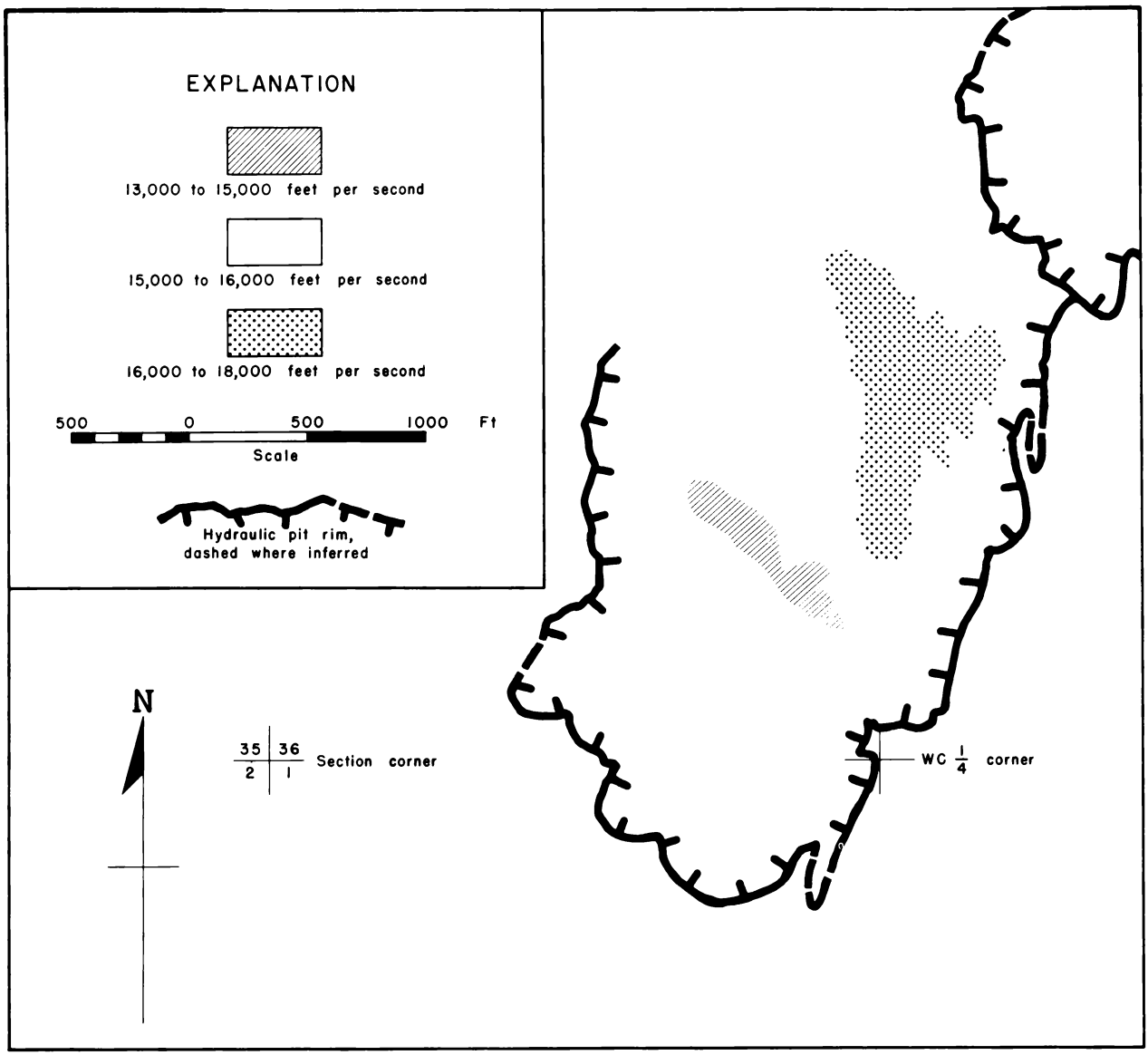

FIGURE 23. - Areal Distribution of Seismic Velocities Through Layer 4.

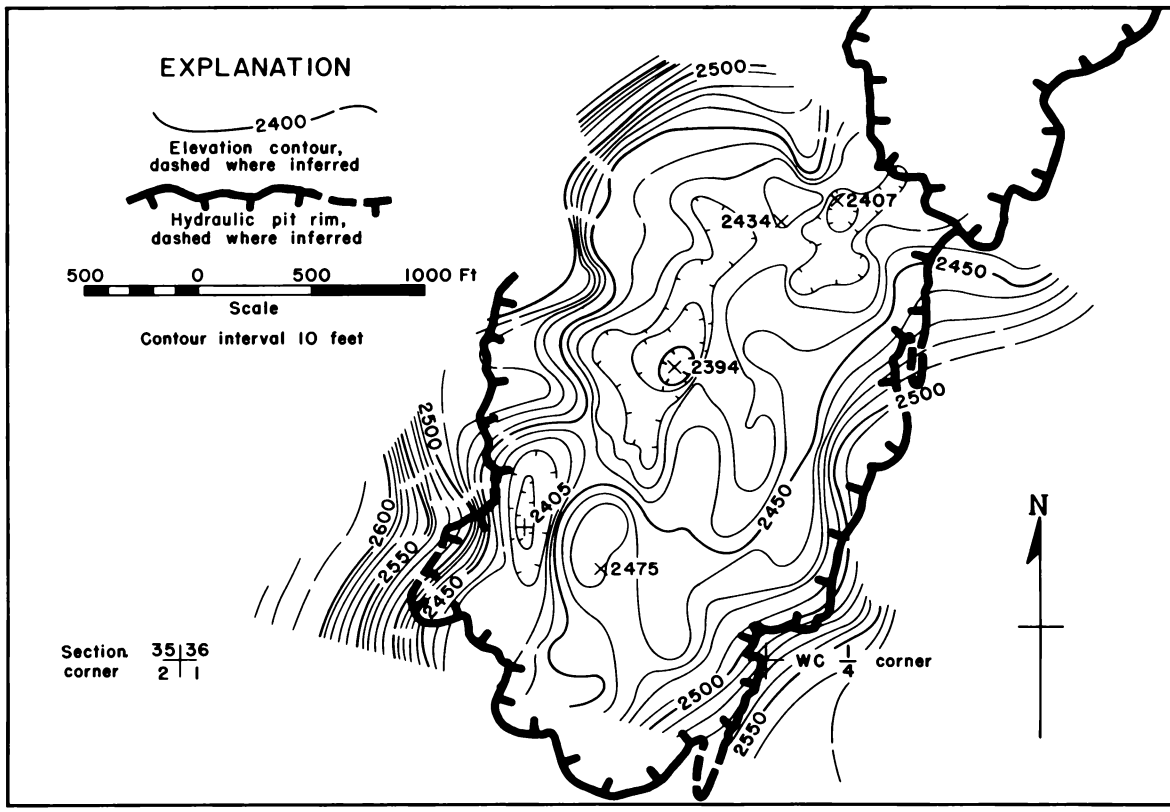

FIGURE 24. - Structural Contour Map of Layer 3.

It will be noticed on the fence diagram (fig. 7) that three layers are shown, and are designated as A, B, and C to differentiate between the cross sections (figs. 8-21) where four layers are shown and are identified as layers 1, 2, 3, and 4. Layer A is equivalent to layers 1 and 2, B is equivalent to 3, and C is equivalent to 4. This was done to facilitate construction of the fence diagram because layer 1 is relatively thin in most places.

Drill hole data that were used for lithologic control in the interpretation of the seismic work is considered to be accurate within about ±10 percent. Most of the drill holes were cored into bedrock and, in all but approximately two of the holes, this limit of credibility is applicable. The difficulty in determining accurately the top of bedrock in these excepted wells was apparently caused by an increased amount of weathering at this interface.

In general, the drill hole data were used as control and spotted on the interpretive cross sections if the holes were within about 50 feet of the seismic profile. On profile AAA, DH-D lithologic unit tops were extrapolated to DH-14 since the latter was located on the rim of the upper bench and was drilled only to 56 feet to the approximate surface elevation of DH-D, which was in the hydraulic pit area. (See fig. 3.)

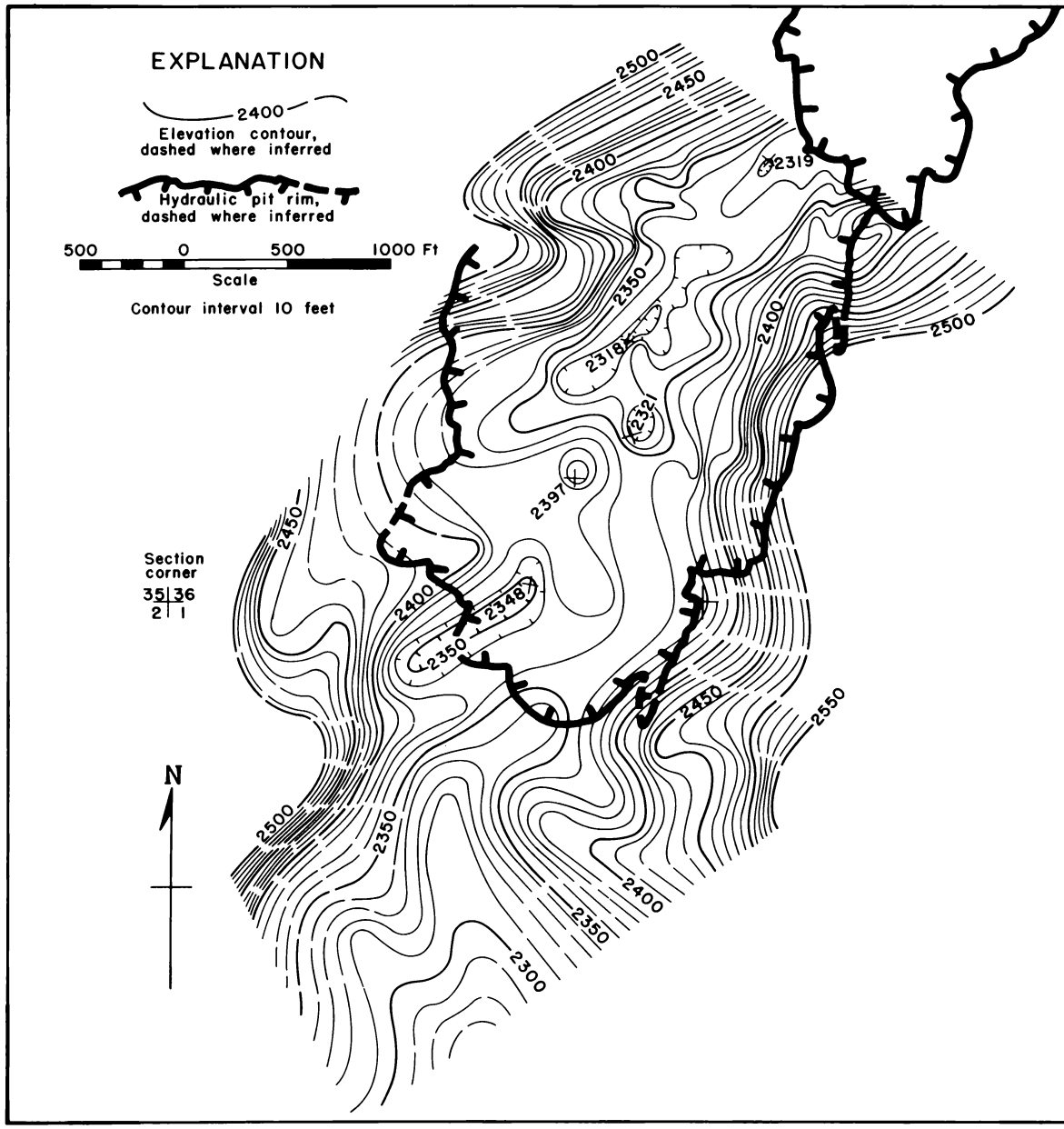

FIGURE 25. - Structural Contour Map of Layer 4.

WELL LOGGING MEASUREMENTS AND INTERPRETATION

The following geophysical well logs were obtained in the Badger Hill area: electrical resistivity logs with the normal electrode configuration 8- and 32-inch spacings, single-point electrical resistance logs, self-potential logs, and caliper (borehole diameter) logs. These logs were obtained in uncased sections of drill holes 1, 3-7, 9, 12-13, A, B, C, D, and E shown on the index map (fig. 3). The logs were used to provide control information for hydrologic studies (6), and for making correlations of lithology within the gravels. The 8-inch normal resistivity logs were the best for

making lithologic correlations because they provided greater detail and better information on the abrupt changes in resistivity than the 32-inch normal logs, and were less adversely affected by hole-diameter variations than the single-point resistivity logs. Results of interpretation and correlation of the 8-inch normal electrical resistivity logs are presented as transparencies (figs. 26-29) which can be placed over figures 9, 12, 14, and 19, respectively, for comparison with the depth interpretation of some of the seismic-refraction measurements.

The interpreted correlations of these logs indicate that three distinct beds of low-porosity gravel are detectable throughout the project area. These beds are labeled A, B, and C on figures 26 to 29. Bed C, which directly overlies bedrock, is characterized by the highest electrical resistivity (greater than 50 ohms per meters) and the lowest porosity of the three beds. Bed B, which occurs 30 to 50 feet above C, has a resistivity nearly as high as bed C (slightly less than 50 ohms per meters) and a porosity nearly as low as bed C. Bed A, which occurs about 50 feet above bed B, has a moderately high resistivity (about 25 ohms per meters) and a moderately low porosity. These three beds are generally separated by gravel that has relatively low resistivity and high porosity. A few scattered lenses of low-porosity gravel also occur between beds A, B, and C, but they have a limited horizontal extent. Bed A generally corresponds with the top of the blue gravel, which is also generally represented by the top of seismic-refraction layer 3.

In terms of possible future mining, the significance of beds A, B, and C is that they represent hard layers that would be difficult to remove with stripping machinery. The fact that the beds can be detected by electric logs means that their depths and thicknesses can be determined in advance of mining. Hence, stripping problems can be anticipated and minimized by proper planning. In an actual mining operation empirical correlations can be made between rippability and electrical resistivity determined quantitatively from logs, so that the degree of difficulty of stripping can be predicted with reasonable accuracy in a quantitative manner.

Preexcavation logging would also be useful for detecting the low resistivity, high porosity layers that generally occur between beds A, B, and C. These layers would be expected to be the most permeable and therefore would transmit the greatest amount of ground water that could hamper mining operations. Advance knowledge of their existence and location would make it possible to avoid or minimize the problems presented by these potential aquifers.

The results of the in-hole geophysics program in the Badger Hill area indicate that well logs can be used effectively to extract a great deal of information from drill holes that are required for other purposes anyway (for example, depth to bedrock control, hydrologic studies, and sample assaying). Since the total cost of logging is low compared with drilling, the additional information can be obtained from logs relatively inexpensively. In any future program in the Badger Hill area it is recommended that density and/or sonic velocity logs be made in addition to electric and caliper logs. Interpretation of these logs will make it possible to determine porosity quantitatively and will afford a more accurate means of predicting rippability and other engineering aspects of mining.

RIPPING-BLASTING SEISMIC MODEL

A three-dimensional velocity model was developed from seismic-refraction measurements made in an open pit ripping-blasting experimental test area adjacent to the 75-foot cliff in the lower (northern) end of the pit. The procedure consisted of running a 110-foot refraction seismic profile along the edge of the cliff, utilizing the shot point to geophone arrangement described earlier, with five shot points but with 10 feet between geophones. The loose surficial material (1,300 ft/sec) was removed with a bulldozer and front loading tractor; another 110-foot seismic line was run in approximately the same orientation as before; the heavy equipment was then used to remove all of the 1,900 ft/sec gravel and most of the 4,100 ft/sec moderately compact gravel layer; a third and final seismic profile was run in about the same orientation as before, revealing a short segment of 4,100 ft/sec material at one edge of the area; the remaining seismic data indicated the 8,300 ft/sec velocity material (blue gravel). The seismic line was not long enough to depict the bedrock refractor, which was indicated by the longer profiles in this general area of the pit to be about 16,000 ft/sec. The approximately 110-foot-square area was then drilled and blasted, removing the remaining moderately compact gravel layer and the upper part of the blue gravel deposits.

ANALYSIS OF GRAVITY DATA

Results of the reduction of the gravity observations are indicated on the final Bouguer gravity contour map (fig. 30) which qualitatively reveals the general configuration of the channel. The principal value of the gravity method in this type of geologic environment and in experiments of this nature is as a reconnaissance tool prior to seismic work and/or together with seismic data to complement the latter.

Gravity base station readings were made at approximately 4-hour intervals to minimize drift errors. The close station spacings (50 to 100 ft) allowed readings to be taken on the average of about every 5 minutes, allowing many stations to be read between base station readings. This not only facilitated drift corrections, but also avoided the times of day when drift and tidal corrections were maximums.

The inner-zone terrain corrections were complicated by the extreme irregularity of the ground surface caused by previous hydraulic mining operations. The technique developed to overcome this local terrain problem was one of summation of corrections calculated by independent methods. Visual terrain descriptions were made at each station for zones A and B, which included the slope of the terrain in four quadrants, elevation differences of the hills or cavities in the four quadrangles, slope of and distance to individual hills or cavities in the quadrants, and descriptions of any other significant terrain features. The methods used to calculate the terrain corrections from the visual-station terrain descriptions were Sandburg Inclined Plane (4), Terrain Effect Profiles (1), and Robbins' one-half slope terrain correction graph (written communication from Stephan L. Robbins, U.S. Geological Survey, Menlo Park, Calif., 1969). The terrain effect for any type of feature or irregularity can be computed either by using one of these methods singularly or by

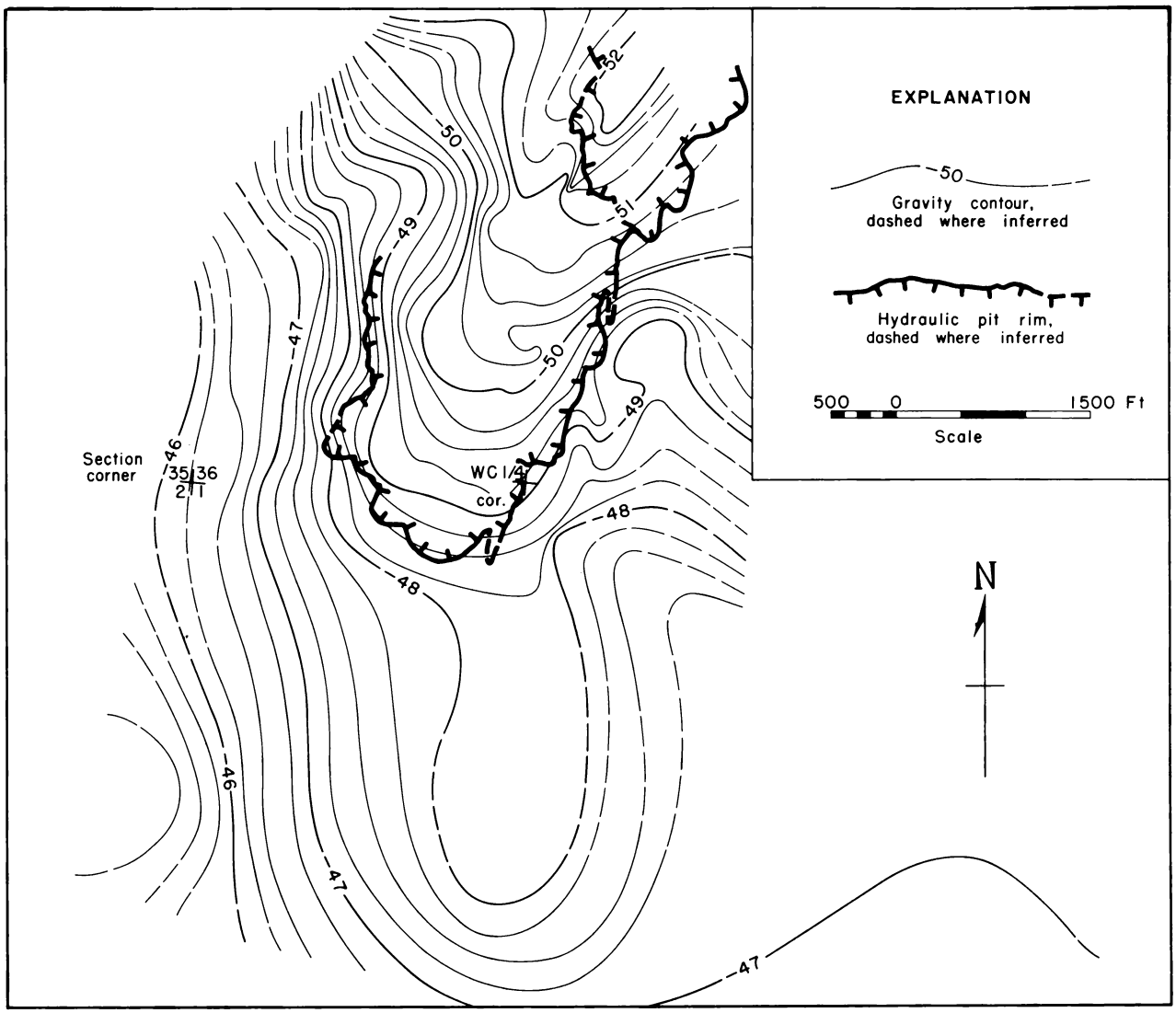

FIGURE 30. - Complete Bouguer Gravity Map of Badger Hill Area With General Outline of Hydraulic Pit.

computing the contribution of various types of irregularity by each method and summing the result for a total correction.

Terrain corrections for zones C to O were computed by reading elevations from topographic maps using Hayford Bowie zone divisions. The elevations were read into a computer program along with station elevations subsequent to sorting stations into groups with similar zone compartment elevations to obtain the terrain correction.

The gravitational effect of topographic features diminish rapidly with distance from a gravity station. In a closely spaced station survey such as this, the most significant effect of topography is experienced from station to station, as zones A and B. The effect of remote topography can thus be

considered a constant for stations with the same elevation. The transition from individual station corrections of zones A and B to a constant correction for all stations at the outer zones was divided into two steps. First, a computer program was developed to calculate corrections for each station elevation from one set of constant compartment elevations for zones I to O. Next, computer corrections for zones C through H for each station elevation were calculated, but different compartment elevations were determined by grouping stations into a circle with a radius that gives a constant compartment elevation for zones C through H of the group of stations in that circle. Corrections from these two methods were added to the A and B zones correction. The complete terrain correction (zones A through O) are then added to the other gravity station data to compute the complete Bouguer anomaly by means of a computer program.

The gravity computer program was developed (written communications from S. H. Burch, U.S. Geological Survey, Menlo Park, Calif., 1969) to provide greatest possible accuracy for mining applications. The program uses the international gravity formula for data reduction and applies corrections for elevation (free air and Bouguer), latitude, instrument drift, tidal, earth curvature, and terrain variations, and provides a complete Bouguer anomaly value for two values of density. One value of density, 2.67 g/cm^3, was used to tie this survey to regional gravity surveys. The other value of density is designated by the user and is introduced by input card option.

The latter density is for surficial material and is determined by a technique of repetitive computing and plotting of data, each plot representing data values computed from a different density. The density that yields the smoothest plot over the terrain irregularities is chosen as the best value for the data reduction. The application of this empirical technique of density determination produced a value of 1.80 g/cm^3 for the Badger Hill area. The complete Bouguer anomaly map for a 1.80 density reduction is shown in figure 30.

ANALYSIS OF MAGNETOMETER DATA

A total of about 1,000 magnetometer measurements were made in the area. About half of these measurements were made with a vertical field fluxgate meter and the remaining half were made with a total-field proton meter. The general agreement between the results from the two types of instruments were surprisingly good. About 10 percent of the total measurements were repeat readings made with the proton meter to calibrate the data taken with the vertical field meter. A composite magnetic anomaly map was made by combining all magnetometer measurements. Results are shown in figure 31.

The only corrections found necessary to apply to the magnetic data were drift and diurnal corrections for the fluxgate magnetometer and corrections for the diurnal variation of the earth's magnetic field for both fluxgate and proton magnetometers. The diurnal correction was determined for the proton magnetometer by setting up a stationary meter at a location within 2 miles of the Badger Hill area, and recording continuously while field measurements were being made with the other meter. For the fluxgate magnetometer, composite drift and diurnal corrections were made by repeating measurements at a base station at half-hour intervals.

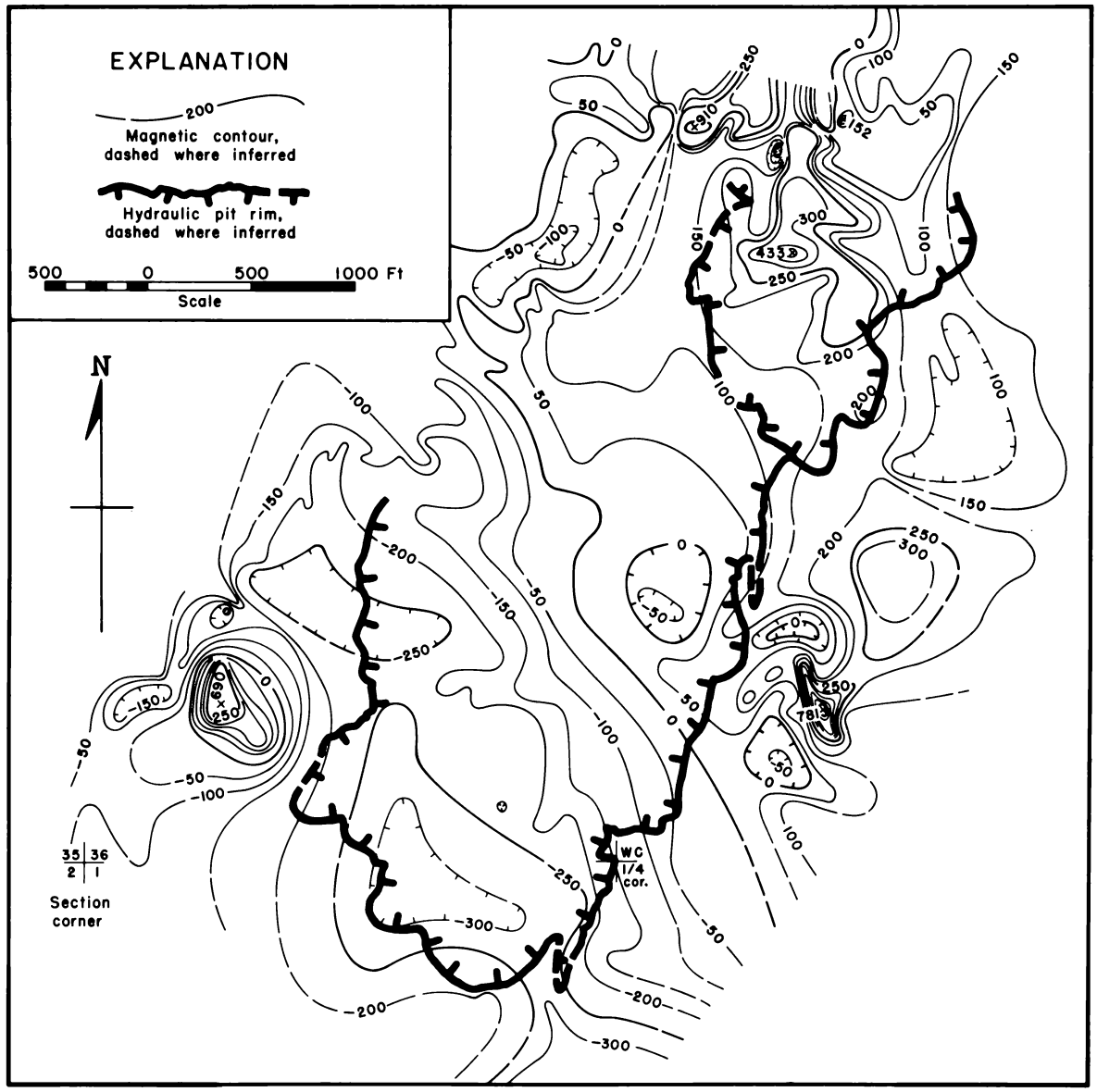

FIGURE 31. - Magnetic Contour Map of Badger Hill Area Showing General Outline of Hydraulic Pit.

Because of its higher sensitivity (±1 gamma) the proton magnetometer was used to check some of the small magnetic high anomalies indicated by the fluxgate meter that were thought to indicate possible concentrations of magnetite and gold. These anomalies failed to stand up, indicating that they were the result of small errors associated with the fluxgate magnetometer readings.

Figure 31 also indicates a few large magnetic anomalies on the flanks of the channel that are probably unweathered igneous intrusive masses that coincide roughly with topographic ridges bordering the channel proper. In the final analysis, however, the magnetometer was found to be a relatively ineffective geophysical delineation tool for experiments of this nature and in this type of geologic environment.

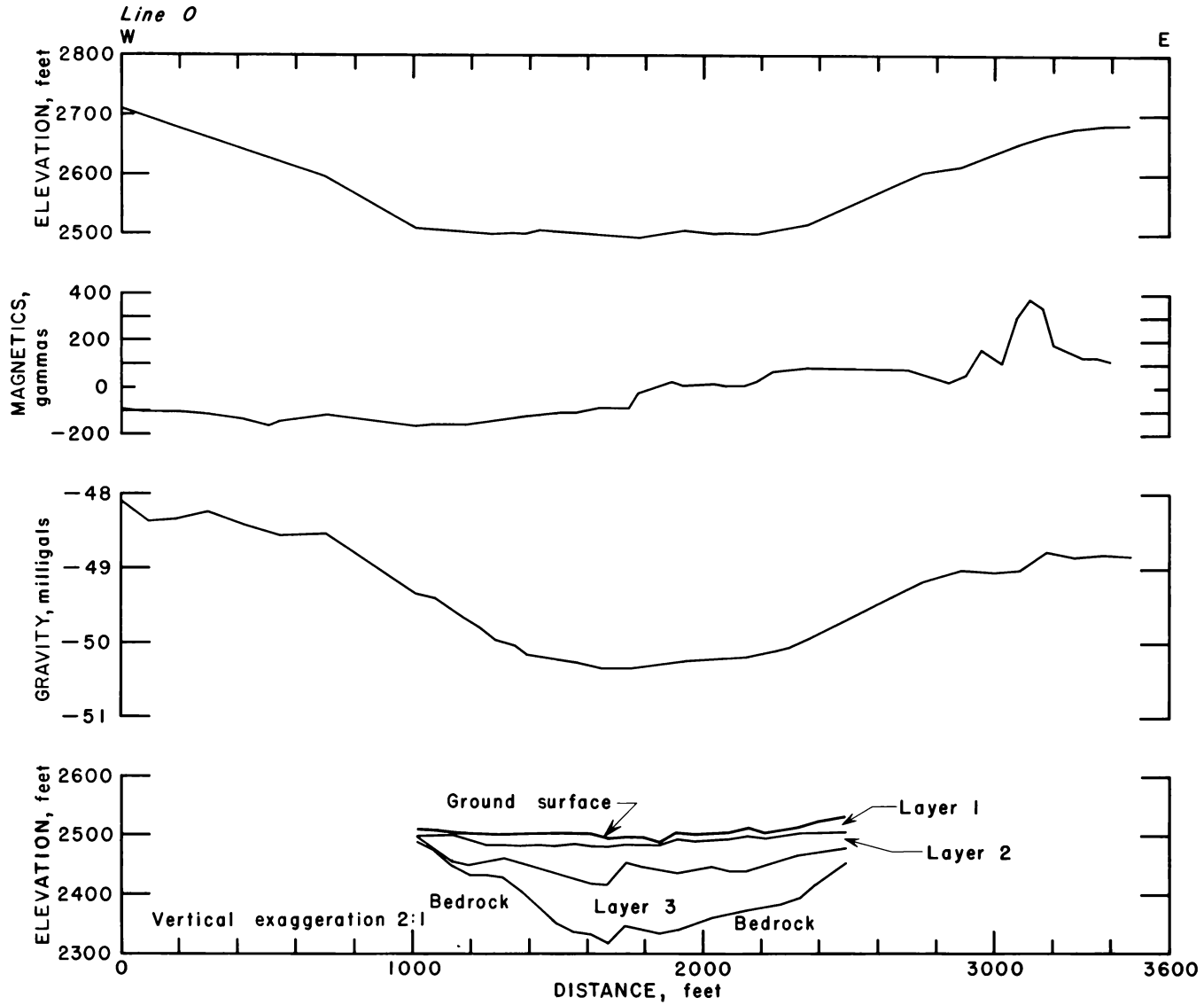

FIGURE 32. - Map Showing Topographic Profile, Magnetic, Gravity, and Seismic-Refraction Data for Profile O.

A composite, two-dimensional, interpretive cross section was prepared for each of three representative seismic-refraction profiles, combining data from each of the three major geophysical delineation techniques (figs. 32-34). These profiles reveal the relative degree of correlation of gravity and magnetic measurements with seismic-refraction measurements, using seismic measurements as the standard.

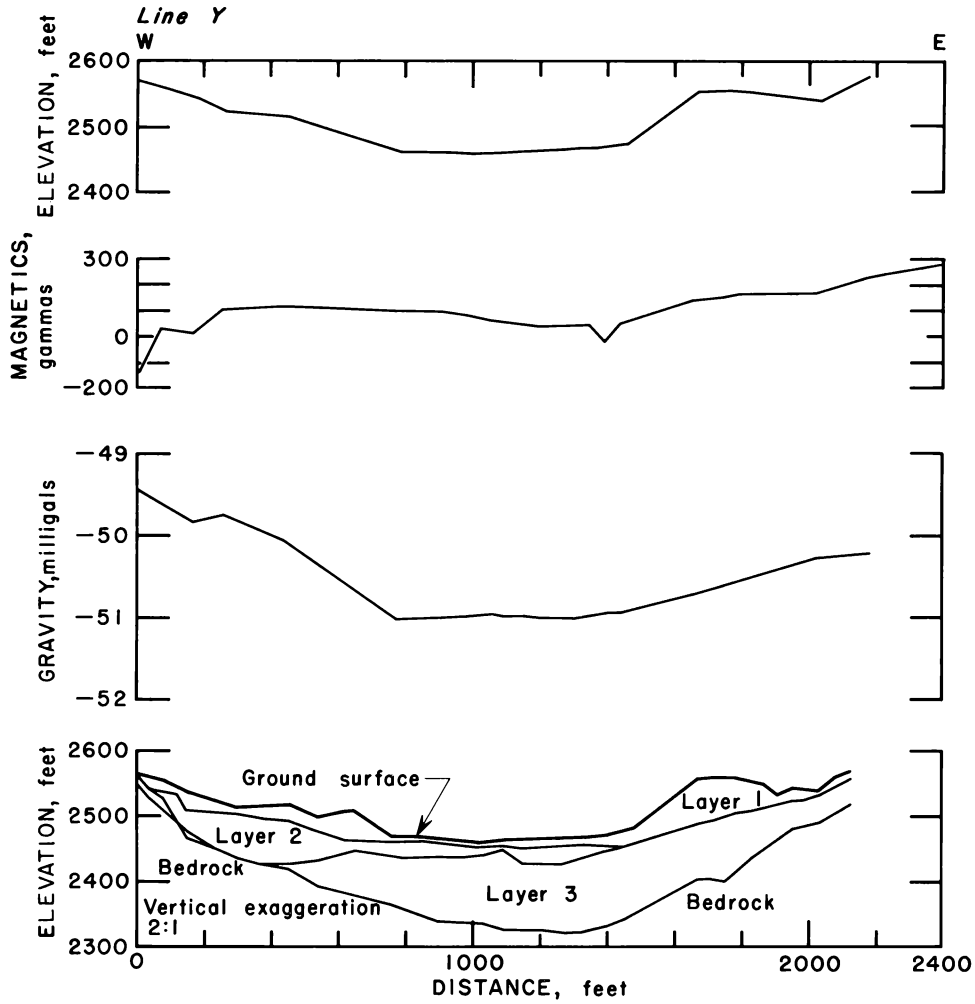

FIGURE 33. - Map Showing Topographic Profile, Magnetic, Gravity, and Seismic-Refraction Data for Profile Y.

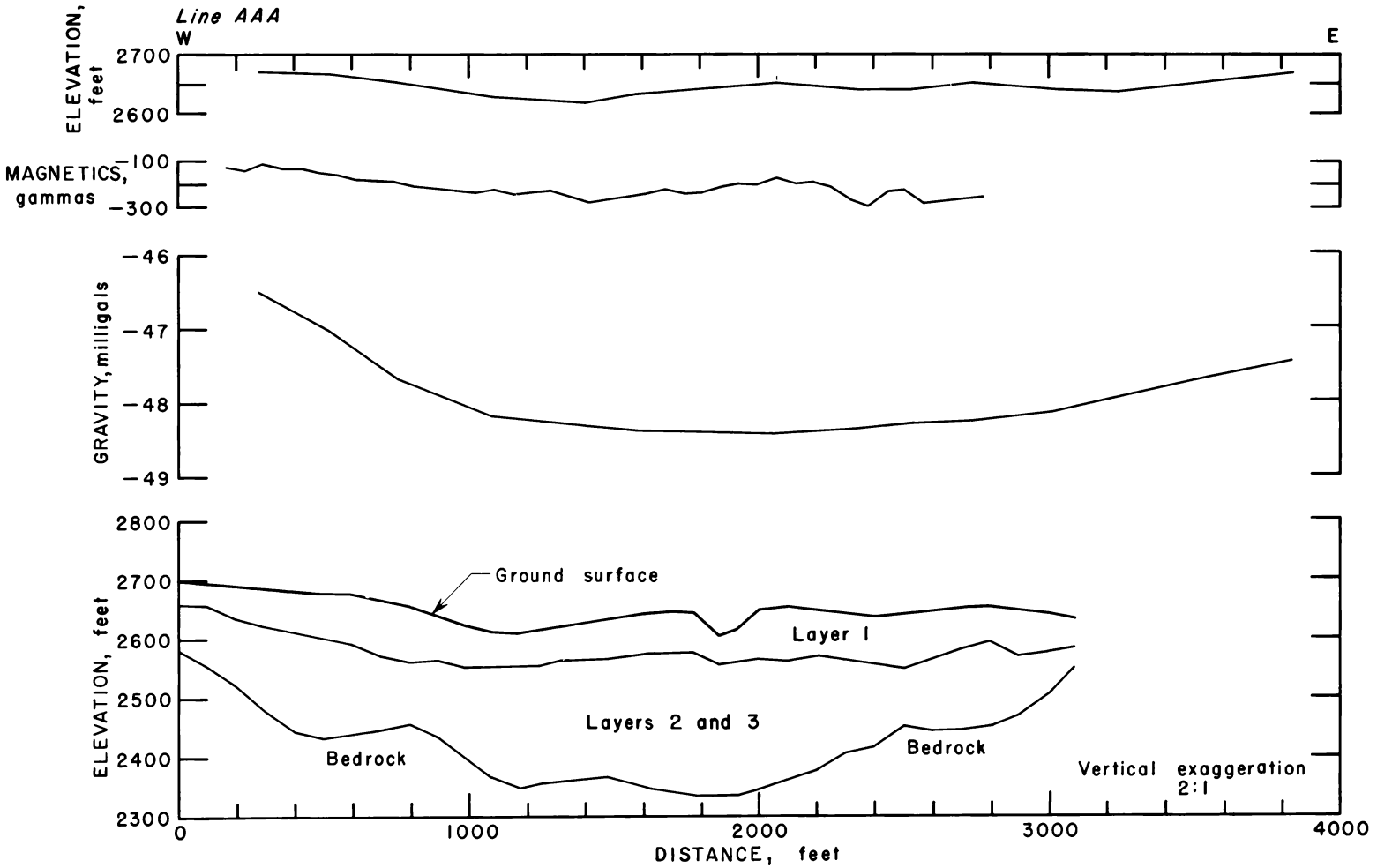

FIGURE 34. - Map Showing Topographic Profile, Magnetic, Gravity, and Seismic-Refraction Data for Profile AAA.

CONCLUSIONS

The five geophysical techniques tested in the Badger Hill area are discussed below in the order of their relative value in achieving the objectives of this program.

1. The seismic-refraction method was found to be the most effective tool for determining the configuration of the bedrock surface beneath the Tertiary gravels as well as for delineating the distinct layers within the gravel deposits.

2. Well logs were valuable in providing information on identification and correlation of the various lithologic units within the gravels, and for indicating the relative hardness of layers for estimates of relative rippability.

3. The gravity method was judged to be useful as a reconnaissance tool for qualitatively delineating the location and configuration of the channel in advance of seismic surveys.

4. The magnetometer was found to be of little value as a geophysical measurement technique for the objectives of this experiment because of the lack of linear concentrations of magnetite and gold. This does not necessarily preclude its effectiveness in similar environments where such concentrations do occur.

5. The electrical resistivity method was found to be of little value in this work because it could not be interpreted to delineate different gravel layers with sufficient accuracy. This was caused by the fact that the three gravel layers above bedrock decreased in resistivity with depth, leading to a nonunique resistivity-depth solution.

Perhaps the principal advantage to be realized from utilizing these geophysical methods to delineate quantitatively the total Tertiary Channel gravel deposit is economic. A conservative estimate reveals that 40 percent of the drill holes necessary to delineate the deposit could be eliminated at a cost saving of at least 30 percent.

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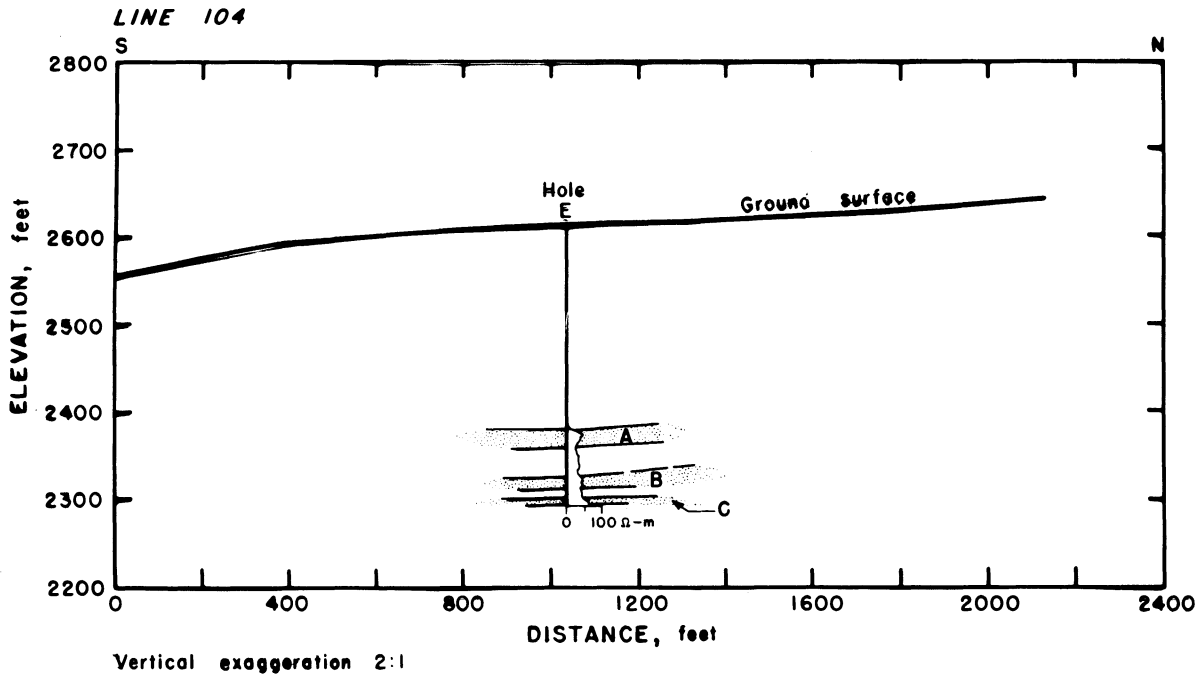

FIGURE 27. - Transparency Showing Results of 8-Inch Normal Resistivity Logs To Be Placed Over Figure 12.

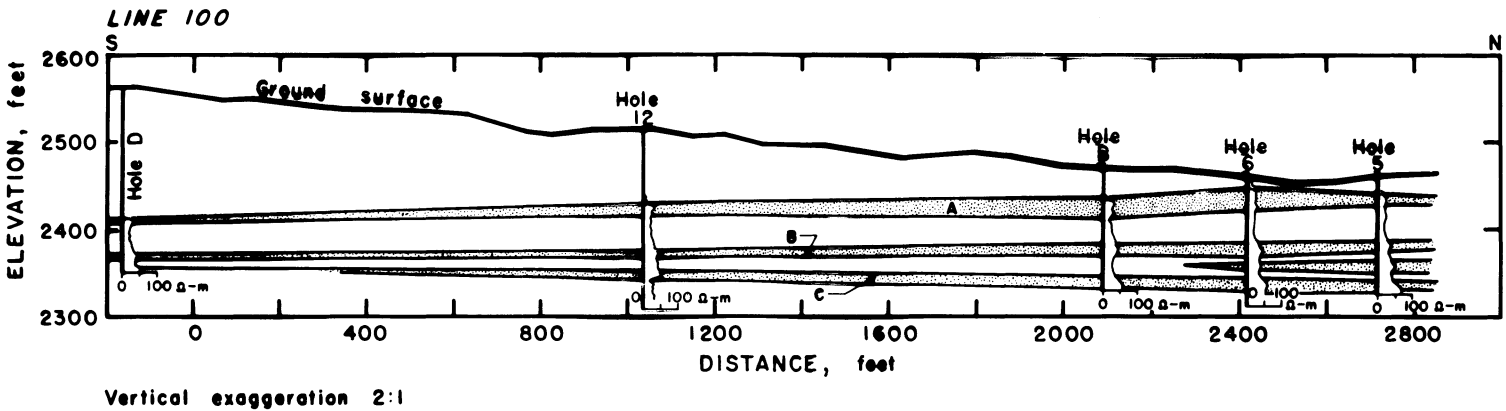

FIGURE 26. - Transparency Showing Results of 8-Inch Normal Resistivity Logs To Be Placed Over Figure 9.

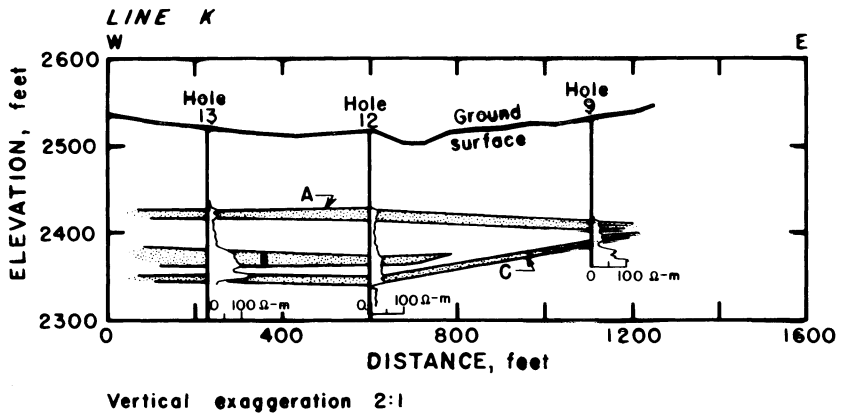

FIGURE 28. - Transparency Showing Results of 8-Inch Normal Resistivity Logs To Be Placed Over Figure 14.

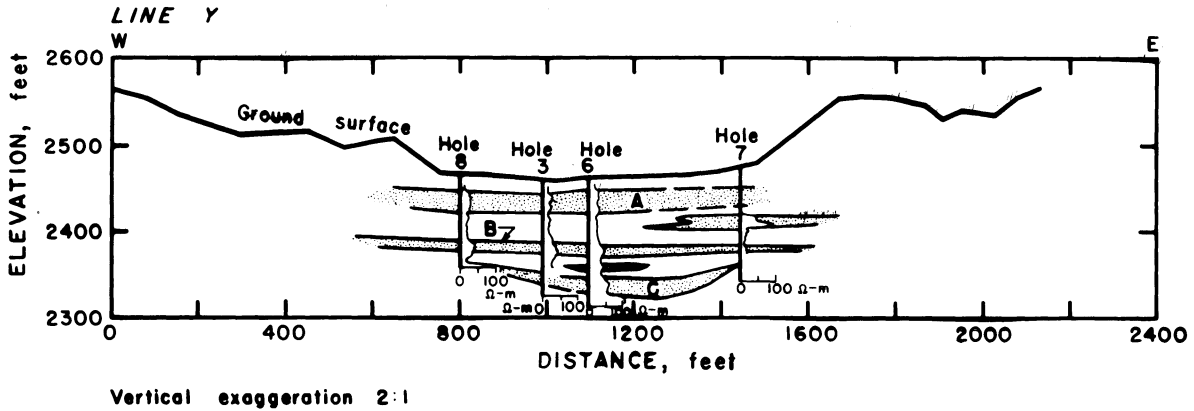

FIGURE 29. - Transparency Showing Results of 8-Inch Normal Resistivity Logs To Be Placed Over Figure 19.

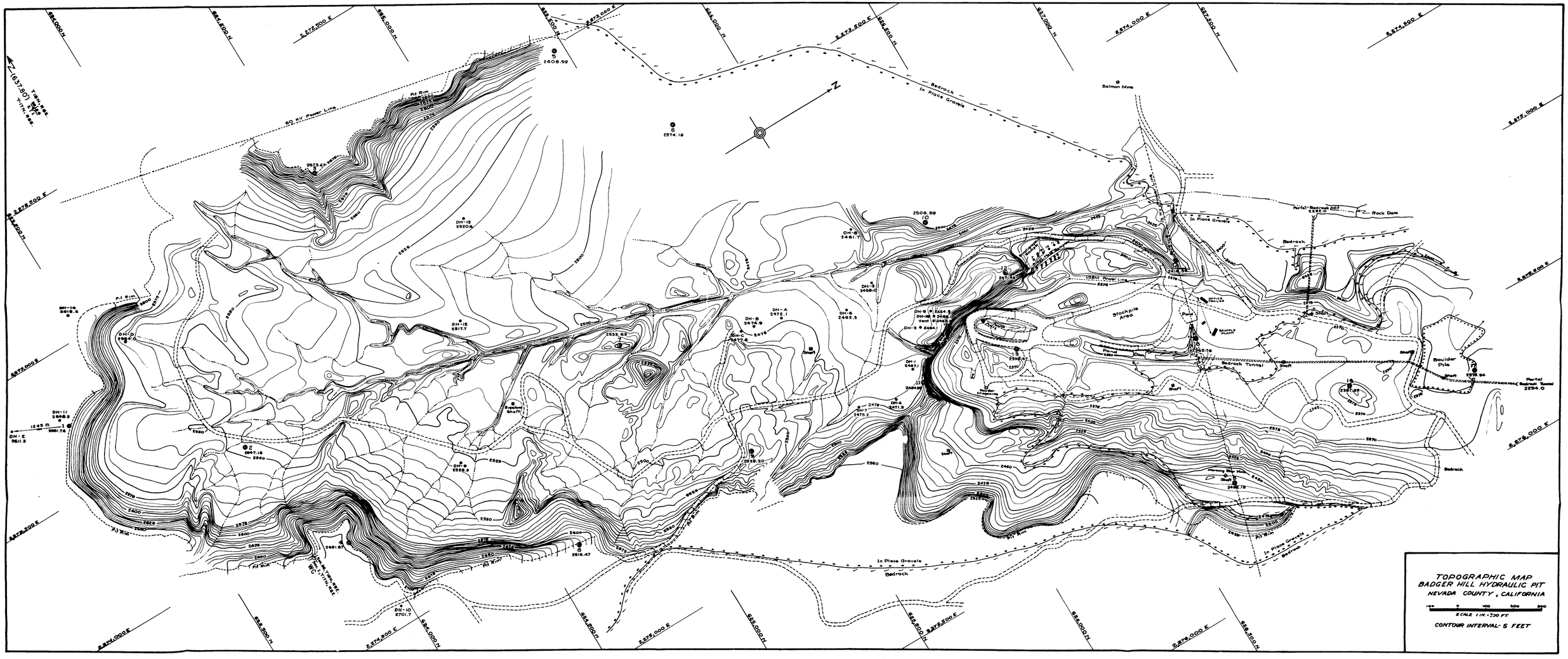

FIGURE 2. - Topographic Contour Map of Hydraulic Pit Area in Badger Hill.