UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Preliminary Seismic-Velocity and Magnetic Studies of a Carbonate Rock-Sinkhole Area in Shelby County, Alabama

by

Carter H. Miller,[1] John R. Ege, Jack K. Odum, and John J. Golob, Jr.

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

[1]U.S. Geological Survey, Denver, CO

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ABSTRACT

Subsidence and collapse of residuum that overlies cavernous carbonate bedrock can be a serious geologic hazard in the southeastern United States. Results of preliminary seismic-velocity and magnetic studies in Shelby County, Alabama indicate considerable rugosity at the surface of carbonate rocks buried by residuum. The rugosity apparently produced relatively low-quality compressional-wave seismograms and made impossible an interpretation of shear-wave seismograms that were measured both along ground-surface traverses and down a borehole. The correlation of high-magnetic anomalies with thicker sections of iron-rich residuum is suggested from interpretation of seismic profiles, boreholes, and outcrop patterns. Strength parameters computed from measured compressional and estimated shear-wave velocities and densities indicate that the carbonate rocks have shearing strengths at failure and elastic moduli that are several hundred times greater than those of the residuum.

INTRODUCTION

Ground-water level fluctuations, naturally and artifically induced, and the alteration of natural drainage patterns are major causes for subsidence and sinkhole formation. Subsidence and sinkholes developed in areas underlain by carbonate rocks (limestone, dolomite, and marble) result from the interrelation between rock, water, climate, vegetation, topography, and the presence or absence of unconsolidated deposits overlying the carbonate bedrock. Slightly acidic ground water moving along bedding planes, joints, fractures and faults create openings in the carbonate rock by dissolving and removing soluble minerals. The mantle of overlying unconsolidated deposits comprising mainly residuum (clay remaining from dissolution of the carbonate rock) becomes involved in the subsidence process by ground-water removal and transport of soil particles downward into bedrock openings. Voids form in the residuum at the bedrock interface which can enlarge and migrate upward until failure of the residuum arch occurs. At that point, a pit or sinkhole appears at the surface. Figure 1 shows the effect of ground-water level fluctuations on the development and collapse of residuum arches and the forming of sinkholes at ground surface.

This type of geologic hazard is particularly prevalent over the southeastern United States where there are extensive areas of carbonate karst. Of particular interest are sink areas of central Alabama, where previous studies have been done by Powell and LaMoreaux (1969), Newton (1971; 1976), and Warren (1973; 1976), LaMoreaux and Associates (three parts, 1977).

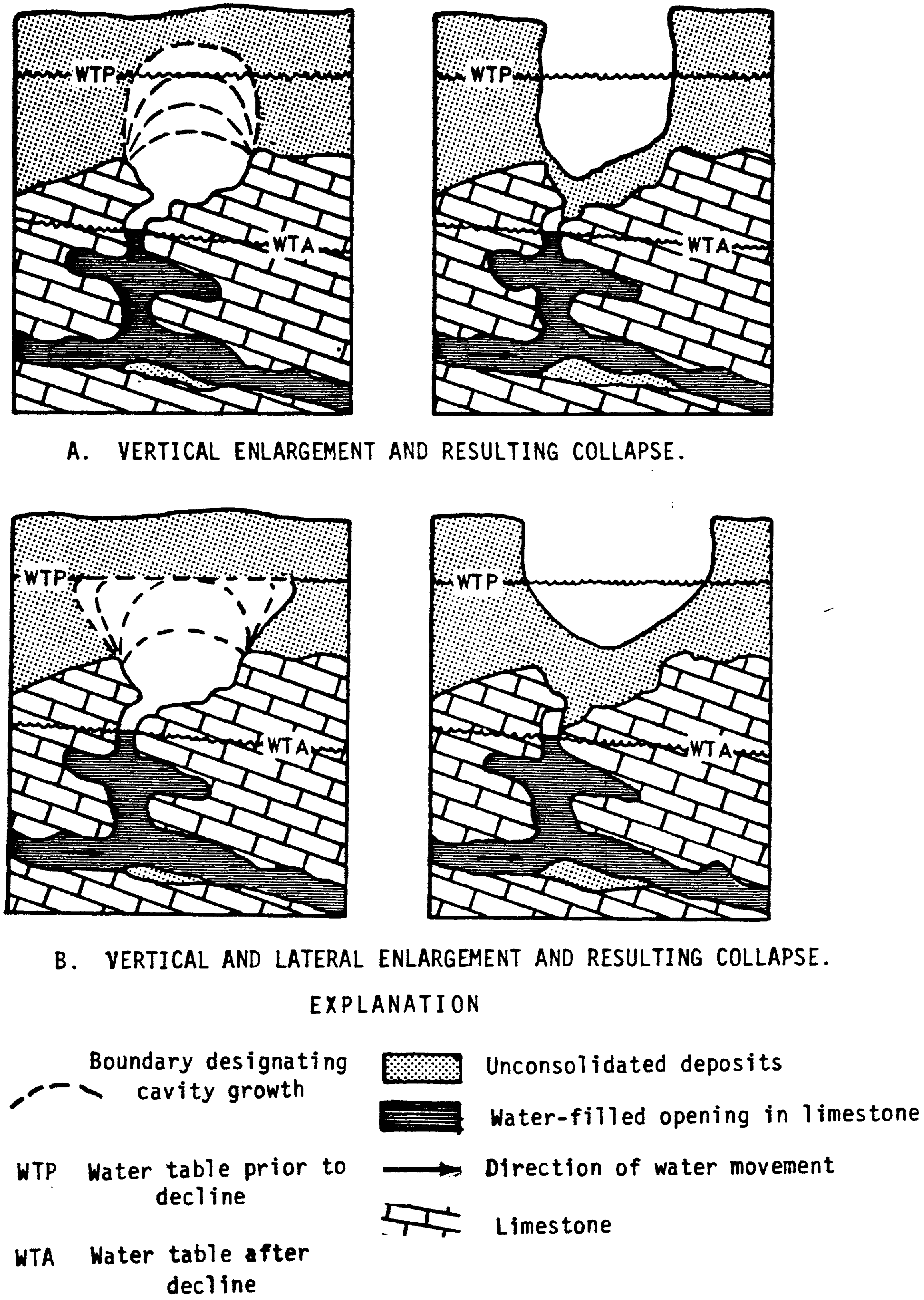

FIGURE 1.--Sinkholes induced by a change in water level, declining in this case (Newton, 1976). Most of the deformation occurs in the unconsolidated deposits rather than in the carbonate bedrock.

The U.S. Geological Survey in cooperation with Vulcan Materials Corporation is engaged in a continuing geophysical and geological investigation of an active sinkhole area in Dry Valley, Shelby County, Ala. (fig. 2). The overall objectives of the study are (1) to examine the thickness and strength of residuum and the thicknesses and spans of soil arches, (2) to examine the rugosity of the buried bedrock surface, including any cavities, and (3) to monitor rates of subsidence.

The preliminary studies described in this report are based on a study grid measuring approximately 300 X 350 ft in extent. Geophysical surveys included total magnetic intensity and seismic refraction. Residuum and carbonate bedrock were cored for later testing, and a velocity survey was run down the drill hole. Additional control was provided by three holes, which had been drilled to bedrock a number of years ago. Rebar pins were driven at the corners of the geophysical study grid as well as along lines in an adjacent grid. Level measurements were taken in both grids in anticipation of periodic relevelling to ascertain if subsidence had occurred.

The data are reported in English and metric units. Consequently, conversion factors are presented in table 1 along with frequently used symbols, equations, and their definitions.

ACKNOWLEDGMENTS

We thank the staffs at the Vulcan Materials Corporation, P.O. Box 7497, Birmingham, Ala., 35253, both at the offices and quarry for access to the land and for their enthusiastic support in drilling, surveying, furnishing information, and providing logistics. In particular, we wish to thank William Kitchens, Peter V. Wiese, and S. J. Stakowski for their written and spoken technical information; J. T. Clark, quarry superintendent for site support; Ray Dennis for his surveying; and Jim Verdon, and Kenny Robinson for their drilling support.

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GEOLOGY

An excellent discussion of the geology of the area by P. E. LaMoreaux and Associates, 1977 (p. 10-25, pt. I) is excerpted below:

The Dry Valley area of Shelby County is located within the Valley and Ridge physiographic province. The bedrock has been extensively folded and faulted and the province is characterized by northeast-southwest-trending valleys and ridges. Dry Valley was formed by differential erosion of folded and faulted rock formations that are composed chiefly of limestone and dolomite. Erosion and solution of carbonate rocks in the area have resulted in ridges underlain by chert and dolomite and valleys underlain by relatively pure limestone.

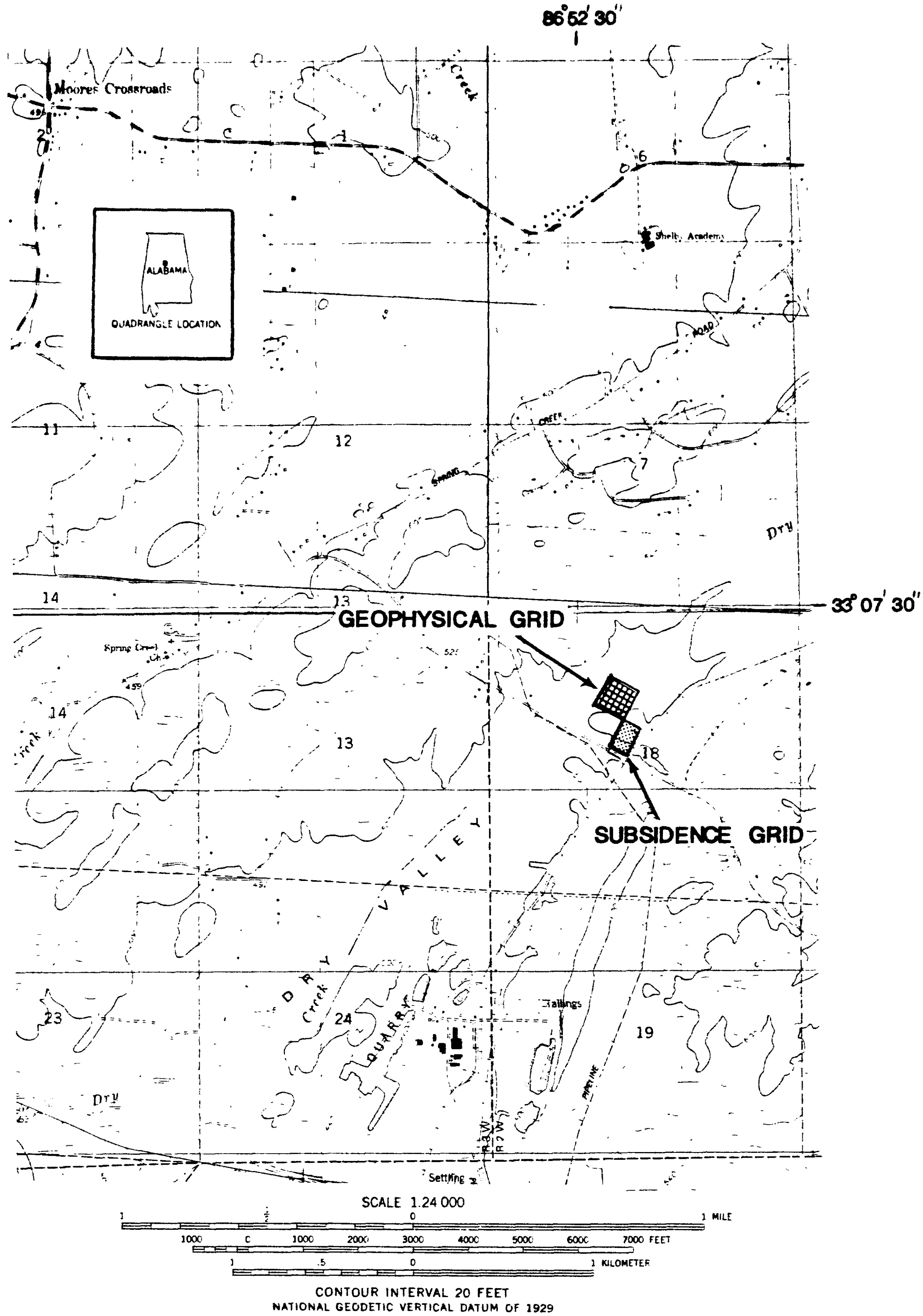


FIGURE 2.--Index map of geophysical and geological test area of subsidence, Dry Valley area, Montevallo, U.S. Geological Survey topographic map (1982), Shelby County, Ala.

TABLE 1.--Summary of frequently used conversion factors, symbols, and equations and their definitions

Feet X 0.3048 = meters

Gammas X 1 = nanoteslas

lb/in^2 X 6,894.7 = Pa

V_p	compressional-wave velocity
V_s	shear-wave velocity
D_b	bulk density
σ	Poisson's ratio
G	shear modulus
E	Young's modulus
B	bulk modulus
K	coefficient of lateral earth pressure

Poisson's ratio $$\sigma = \frac{0.5\ (V_p{}^2/V_s{}^2) - 1}{(V_p{}^2/V_s{}^2) - 1}$$

Shear modulus $$G = V_s{}^2 D_b$$

Young's modulus $$E = 2G(1 + \sigma)$$

Bulk modulus $$B = \frac{E}{3(1 - 2_{\sigma})}$$

Coefficient of lateral earth pressure $$K = \frac{\sigma}{1 - \sigma}$$

Geologic formations underlying the Dry Valley area crop out in northeast-southwest-trending parallel bands and dip to the southeast at 20°-40°. The formation rocks range in age from Cambrian to Mississippian. The Copper Ridge and Chepultepec dolomites form the western boundary of Dry Valley, a stream-dissected ridge that is locally more than 100 ft above Dry Creek (fig. 2). Dry Valley is underlain for the most part by the Longview and Newala Limestone. The Newala Limestone is mined from recessed quarries and underground mines in the valley as a source of raw material for the manufacture of cement. The Athens Shale and Fort Payne Chert form a sinuous narrow ridge that forms the eastern boundary of the valley (fig. 2).

The solution of carbonate rocks is due to acidic water that circulates along small openings in the rocks. The enlargement of openings along fractures, faults and bedding planes forms interconnected solution cavities.

A mantle of unconsolidated material that consists mainly of residual clay covers the carbonate bedrock and obscures geologic contacts and faults. This unconsolidated material or residuum is the residue resulting from the solution of underlying carbonate rocks and it commonly contains varying amounts of insoluble chert. Some of this unconsolidated material is carried by water into openings in the bedrock where it may fill fractures and solution cavities. The buried contact between the residuum and the underlying bedrock is highly irregular because of differential solution. Pinnacles of bedrock extend upward into the residuum and outcrop locally. Boulders also "float" within the residuum and may be easily mistaken for the buried bedrock surface in boreholes. Ground water in the Dry Valley area occurs in the unconsolidated material and in openings in the underlying bedrock. The openings are very small in shaley rocks, such as the Athens Shale, where only small amounts of ground water can percolate through solution-cavity systems in the rocks.

Sinkholes are the result of the collapse of voids in the residuum and may be induced by changing hydrogeologic conditions. Voids in the underlying carbonate bedrock may receive material from above, however, though bedrock does not normally take part in the collapse. The voids in the residuum will grow as material collapses and is transported by water through the underlying solution cavities. A sinkhole is formed when the roof (residuum arch) of the void totally collapses.

The thickness and physical characteristics of the unconsolidated material controls the size and shape of sinkholes. Larger sinkholes form in areas of thick residuum where the developing void space can attain larger dimensions. The ability of various materials to form voids and maintain roof stability also determines the size of sinkholes. For example, thick clay deposits allow the development of larger voids and, subsequently, larger sinkholes. If the residuum does not lend itself to the formation of voids, the result may be compaction and subsidence of the land surface rather than sinkhole development.

Four processes are generally recognized that induce sinkhole occurrence following a decline of the water table. These are:

1. The loss of bouyant support exerted by ground-water saturation on the unconsolidated materials overlying bedrock. Bouyant support may amount to 40 percent of total support.

2. An increase in the velocity of ground water caused by an increased hydraulic gradient such as a cone of depression in the ground-water surface. This may result in the flushing of sediments from the cavity system into bedrock openings below.

3. The weakening of residuum caused by alternate wetting and drying from water-level fluctuations.

4. The erosion of residuum by surface water during periods of heavy or prolonged rainfall.

GEOPHYSICS

Figure 3 shows a topographic map of the geophysical test area. Seismic measurements were done along lines C, D, and E and in the USGS-2 drill hole. Magnetic measurements were taken at 25-ft intervals along the gridlines. Steel pins were driven at 50-ft intervals after the magnetic survey was done and precise levelling measurements were done on the pins for the purpose of monitoring any long-term subsidence. The topography was mapped by plane table and alidade.

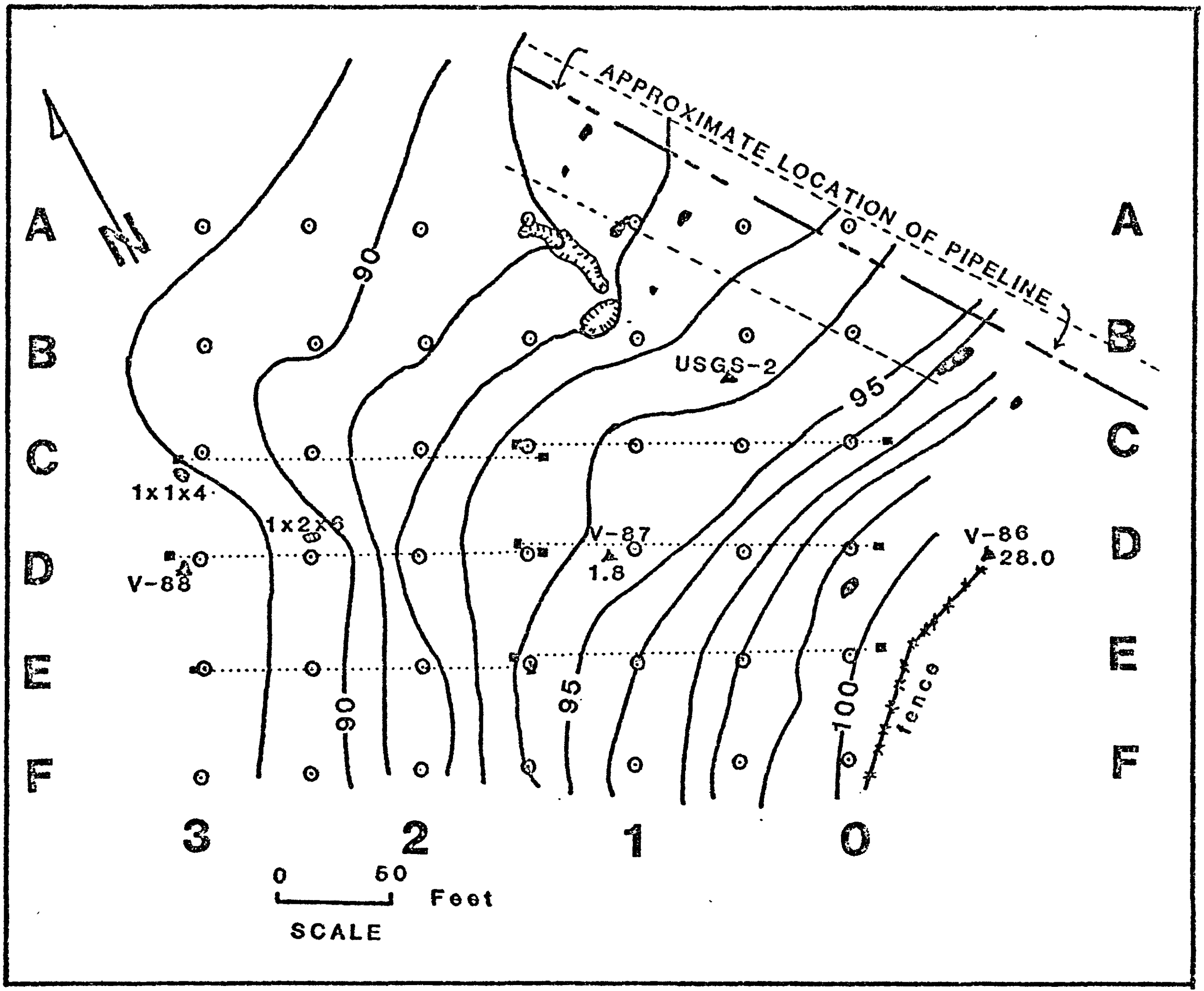
Refraction and Velocity Surveys

Seismic-refraction lines were run along lines C, D, and E of the grid shown in figure 3. Each of these seismic lines included two end-to-end seismic spreads. Each spread was 165 ft in length with 12 geophones at 15-ft spacings. The total length of two end-to-end spreads was, thus, 330 ft with a total of 24 geophones (redundant geophones occupied stations at 165 ft in the center of a spread). Energy sources were set at each end of the 330-ft lines and measurements were taken along each 165-ft spread, first from the energy source at one end of the line and then with the source at the other end.

Both compressional- (P-) and shear- (S-) wave measurements were taken along each seismic spread. The energy source for the P waves were explosive charges that were placed in shotholes that were hand-augered to about 3 or 4 ft. Charges in the shotholes were equivalent to about one-half stick of dynamite (one-quarter pound) for gridline C and part of line D. Charges for line E and the rest of line D were increased to the equivalent of about one stick of dynamite. The resulting P waves were detected with vertically oriented seismometers.

The energy source for the S-wave measurements was originated at a weighted-down wooden timber, and oriented perpendicular to the seismic line. Horizontally oriented geophones were planted for the S-wave surveys, and the ends of the timber were struck with a sledge hammer. The blows were alternated for each seismogram, so that reversed particle motion could be observed on the seismogram.

The P and S waves were measured with a signal-enhancement seismograph with electronic filters. While the P waves were recorded without filters, experimentation showed that the S waves could be optimized by filtering above a corner frequency of about 50 Hz. Although considerable effort was expended in producing quality S-wave refraction seismograms, none could be completely interpreted. The downhole S-wave seismograms, likewise, could not be



⊙	Surveyed location
▲ V-88 28.0'	Drill hole with number and depth
⊙ 1x1x3	Sinkhole showing length by width by depth, in feet. Hachured areas without numerals are topographic lows
	Outcrop of carbonate rock
▪ ······ ▪	Seismic-refraction line

FIGURE 3. Map of the geophysical test area. Seismic measurements were taken along lines C, D, and E and in the USGS-2 drill hole. Magnetic measurements were taken at 25-ft intervals along the gridlines.

interpreted, although the same equipment and procedures for obtaining high-quality S-wave seismograms in most other soils and rocks was used (Miller and others, in prep.). While reversely polarized S waves were obtained for any one station whether along the ground or downhole, phase shifts between the stations rendered whole suites of S-wave seismograms unusable.

The P-wave seismograms obtained from the refraction lines also exhibited more than one "first arrival." Only seismograms obtained from line E could be deciphered, probably because the energy sources at either end of the seismic line were increased from one-half stick of explosive to one stick.

The cause of all the low-quality S-wave seismograms and some of the P-wave seismograms is unknown but seems to be due to the very irregular surface of buried carbonate bedrock as well as due to the carbonate boulders and cobbles that may be scattered through the residuum. The angle of incidence of seismic waves at these interfaces may vary considerably and, hence, produce many waves that arrive nearly simultaneously at the detectors. Apparently, the S-wave arrival times are complex and interpretation is virtually impossible. Although additional explosives may override some of the spurious P-wave signals, no amount of hammering improved the S-wave seismograms.

Figure 4 shows the time-distance curves with velocities along line C (A) and D (B) and the interpreted geology along line E (C) of the grid. Two velocity layers are clearly defined by the time-distance curves of line E: a V_1 (low-velocity) layer, which overlies another layer of higher velocity, V_2. The seismic lines run at the grid were designed so that most of the seismometers would receive signals from the V_2 layer. The first-arriving waves at the two or three seismometers, closest to the energy source, travel directly through the V_1 layer. Consequently, the traveltimes for the V_1 layer can be corrected for slant distance and the true velocity calculated. The first-arriving waves for the V_2 layer have been refracted through that layer and the V_2 velocities may depend on the rugosity of the buried V_1-V_2 interface.

Table 2 shows the P-wave velocities of the V_1 layer, which represent the residuum overlying the carbonate bedrock. The representative value for the V_1 layer is 1,400 ft/s, which is an arithmetic average for all seismic lines whereas the representative value for the V_2 layer is 15,550 ft/s, which has been determined by mathematical formula from the apparent velocities calculated for line E. Table 2 also shows V_2 velocities for seismic lines C and D. All V_2 velocities were calculated by a method of least squares after corrections were made for shothole depth.

Thickness and configuration of the V_1 layer (residuum) were interpreted from the seismic-refraction data by using the method of differences (Redpath, 1973). The advantage of the method is that it accounts for variations in thickness of the low-velocity layer wherever two V_2 data points from the forward and reverse shots coincide. Figure 4 indicates that most of the 24 seismometers along a seismic line were placed so that they received first-signals from the V_2 layer, whereas only 2-4 seismometers received primary signals from the V_1 layer. While this arrangement is desirable, more closely spaced seismometers and shorter spreads might have provided more detailed data on the configuration of buried bedrock as well as required less energy. The geologic interpretation under line E shows depths to bedrock that vary from 3 to 14 ft. However, the interpreted highs and lows in the carbonate rock may

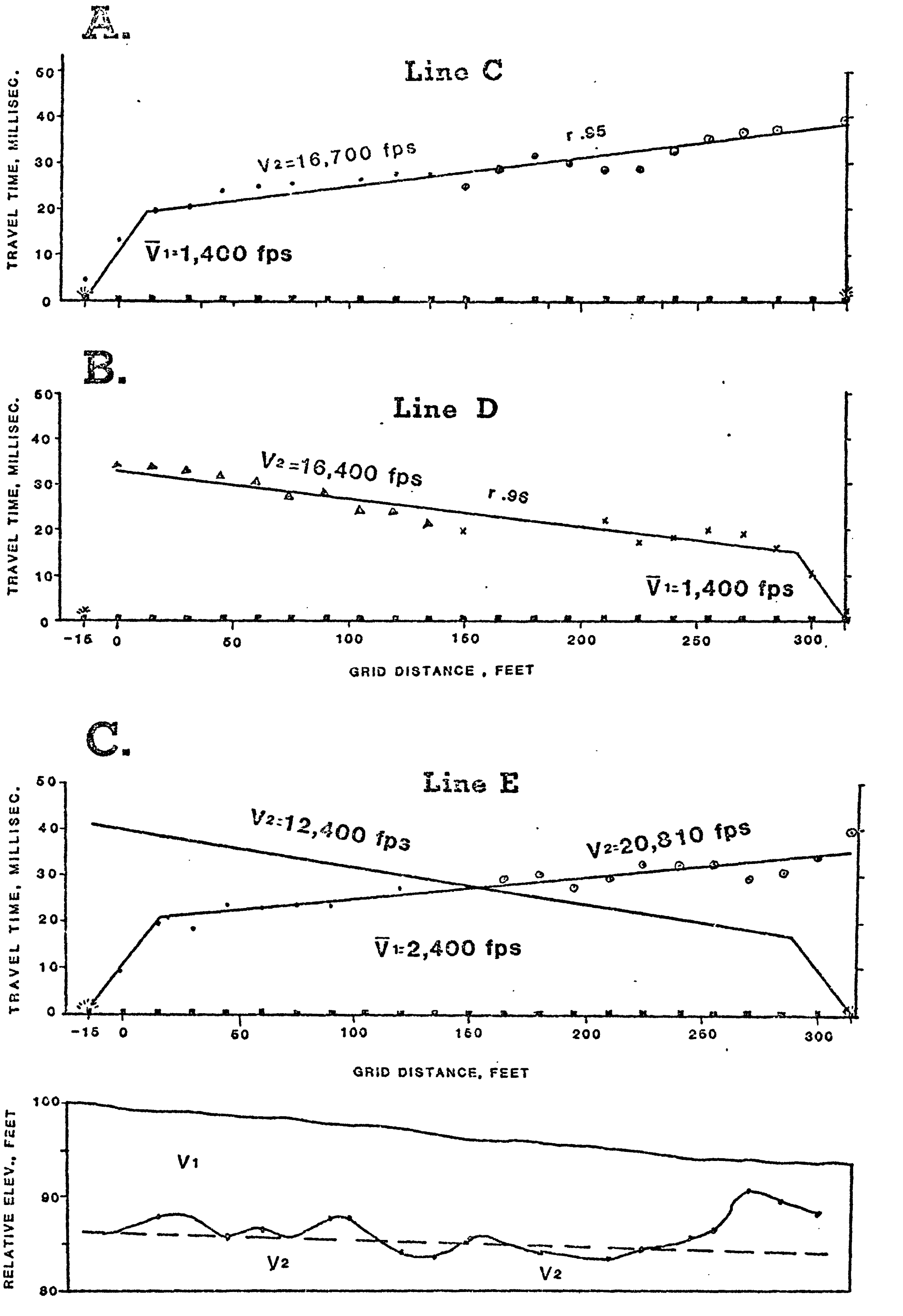


FIGURE 4.--Time-distance curves for seismic lines: A, showing seismic line C; B, showing seismic line D; C, showing seismic line E, with a geologic interpretation for E.

EXPLANATION

V_1 or V_2 = 15,550 — Compressional-wave velocity, in feet per second. The subscript indicates velocity layering. The coefficient, r, indicates the degree of correlation of a linear regression line with data-point trends

● ⊙ × △ — Traveltimes corrected for uphole travel

■ — Seismometer

[shot point symbol] — Shot point

Interface between velocity layers for the geologic interpretation of line E, the undulating solid line (inferred bedrock surface) was computed by the method of differences and the straight dashed line by the time-intercept method.

Figure 4--Continued

TABLE 2.--Compressional-wave velocities of the low-velocity layer (residuum) and high-velocity layer (carbonate bedrock)

[Representative value for the low-velocity layer is an arithmetic average of all seismic lines, whereas that for the high-velocity layer has been determined by mathematical formula from the least-squared apparent velocities of line E. Leaders (----) indicate no data]

Location of measurement[1]	Compressional-wave velocity (ft/s): Low-velocity layer	Compressional-wave velocity (ft/s): High-velocity layer (least-squared apparent velocity; correlation coefficient)
Line C		
Forward--------	1,140	16,700; 0.95
Reverse--------	-----	------------
Line D		
Forward--------	1,360	------------
Reverse--------	1,430	16,400; 0.96
Line E		
Forward--------	2,520	21,700; 0.98
Reverse--------	1,580	12,400; 0.88
USGS hole-2------	2,770	------------
Representative value----------	1,400	15,550

[1]See figure 2.

have been inadvertently "smoothed" as a result of the relatively great seismometer spacing compared to the relief at the surface of buried bedrock--even by the method of differences. The time-intercept method (fig. 4) calculates the thickness of residuum only approximately under each shot point. Undulations in the V_1-V_2 interface cannot, therefore, be accounted for.

Strength and Other Properties of Residuum and Carbonate Rocks

Calculations of some of the dynamic-elastic properties of soils and rocks required three measured parameters: P-wave velocity (V_p), S-wave velocity (V_s), and bulk density (D_b). Table 3 summarizes some approximations of elastic moduli, shear strength, and coefficients of lateral earth pressure calculated from measured V_p and from estimated V_s and D_b (table 3). While V_p has been measured and a preliminary D_b can be estimated with reasonable confidence from experience and the literature, 2.1 g/cm^3 for residuum and 2.7 g/cm^3 for the carbonate rocks, an estimate of V_s and, therefore, certain elastic properties, is made by inference.

Figure 5 (C. H. Miller and others, written commun., 1984) shows Poisson's ratio as a function of V_s/V_p for rocks and soil units of the San Francisco Bay area. The data points are averages of values for each unit defined by Fumal (1978) on the basis of downhole measurements of V_s and other criteria. Although these lithologic units range from relatively hard rocks to soft soils, Poisson's ratio for rocks ranges from about 0.35 to 0.45, and soils is from about 0.39 to 0.50. Using these values for Poisson's ratio along with the measured values for V_p produces a value for V_s from the graph of figure 5 of 420 ft/s for residuum and 7,150 ft/s for carbonate rocks.

Shearing strength is defined by the Coulomb equation as shear strength at failure. For small structures, on cohesive soils that are not drained when tested, shearing strength is proportional to one-half the unconfined compressive strength (Terzaghi and Peck, 1967, p. 103). Imai and Yoshimura (1975) have empirically related V_s for soils and relatively soft rocks to unconfined compressive strength. Substituting a value of twice the shear strength for unconfined compressive strength yields a mathematical relation between V_s and shearing strength at failure (Miller, 1979). The V_s declines more or less uniformally as shearing strength declines until the range of about 300 to 400 m/s (soft soils) where it declines much more rapidly. For a V_s of about 128 m/s (table 3) for residuum, the corresponding value for shearing strength is about 5 lb/in^2. The original empirical relation for V_s and shear strength did not include relatively strong rocks. An approximate projection of the curve for soils, however, suggests that the strength for carbonate rock may be about 5,000 lb/in^2--approximately 1,000 times stronger at failure than residuum.

The elastic moduli (table 3) include Young's, shear, and bulk parameters, as well as Poisson's ratio. While the moduli are frequently used in the design of structures, they are also indicators of relative earth strength. The data of table 3 also show a striking disparity between the moduli for the carbonate rocks and residuum of several hundred to one.

The relation between lateral and vertical strain is described by Poisson's ratio. The relation between overburden pressure and lateral pressure is found from Poisson's ratio by the formula in table 1, and it is

TABLE 3.--Some approximations of elastic moduli, shear strength, and coefficients of lateral earth pressure calculated from measured compressional-wave velocities and from estimated shear-wave velocities and bulk densities

Lithology	Velocity; ft/s (m/s)		Density (g/cm^3)	Poisson's ratio	Elastic modulus lb/in^2 (Pa)			Shear strength at failure (lbs/in^2)	Coefficient of lateral earth pressure
	Compressional	Shear			Young's	Shear	Bulk		
Residuum---	1,400 (427)	420 (128)	2.1	0.45	$.01 \times 10^6$ (0.1×10^9)	0.005×10^6 (0.3×10^9)	0.05×10^6 (0.3×10^9)	5 (35×10^3)	0.82
Carbonate bedrock.	15,550 (4,740)	7,150 (2,180)	2.7	0.37	(5×10^6) (35×10^9)	2×10^6 (13×10^9)	6×10^6 44×10^9	5×10^3 (31×10^6)	0.59

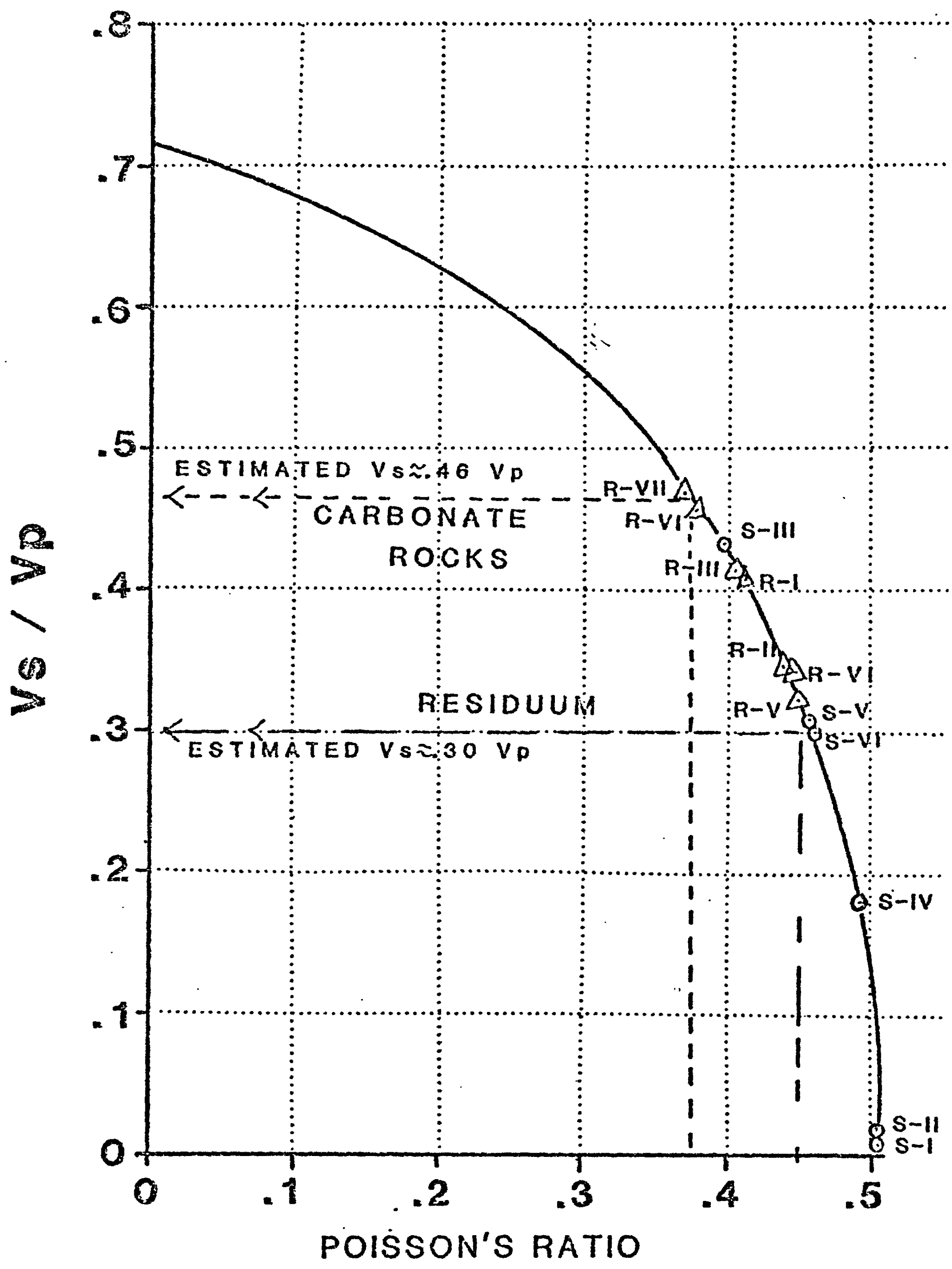


FIGURE 5.--Shear-wave velocity, V_s, estimated for residuum and carbonate rock for Poisson's ratio as a function of the ratio of V_s to V_p for some lithologic units in the San Francisco Bay area. Six units of soil (s-labeled circles) and seven of rocks (R-labeled triangles) are defined by V_s and V_p measurements (Fumal, 1978; C. H. Miller and others, written commun., 1984).

described by the coefficient of earth pressure in elastic equilibrium (Sowers, 1979). Table 3 shows that the residuum has a coefficient of about 0.82 and carbonate rocks are about 0.59. The relatively weak and deformable residuum shows about 40 percent more lateral stress per unit of depth than the carbonate rocks. The greater deformability of the residuum was demonstrated during the downhole tests when clayey residuum at about 20 ft repeatedly "squeezed off" the hole.

Magnetic Survey

Magnetic surveys of sinkholes have been done by McDowell (1975) in southern England where chalk deposits have undergone solution and weathering to produce a highly irregular surface of pipes and sinks that may be infilled with gravel, sand, or clay. He points out that clay-filled sinks can be expected to produce high-magnetic anomalies relative to the chalk, because the clay is more magnetic. McDowell (1975) ran a grid of magnetic measurements where the distance between stations was planned to be less than about half the lateral extent of a sink. One buried sink was delineated by about a 20-gamma magnetic anomaly and substantiated by drilling. The margins of the delineated sink were expected to occur at the half-width of the anomaly.

The preliminary interpretation of the present magnetic survey performed for this study is based on the following assumptions: (1) the clayey residuum in sinks produces considerably stronger magnetic anomalies than do carbonate bedrock, and (2) any caverns in the bedrock may reduce the total magnetic field.

A total magnetic-intensity survey was run over the geophysical grid of figure 3 with a portable proton magnetometer. Readings were taken at about 25-ft intervals with the sensor at a constant height of about 7 ft above ground. Individual readings of total magnetic intensity were adjusted to a base-station value of 52,660 gammas. Two-thirds of the adjusted readings were within an accuracy of 4 gammas and more than 90 percent were within 8 gammas (fig. 6). Base readings were repeated within 20 min of the initial reading and the base drift was linearly distributed over the station readings. The results are shown in figure 7, which is a map of the contoured magnetic field, and figure 8, a cross section showing magnetic anomalies and ground surface.

Figure 7 shows a very strong high at the extreme northeast part of the map that is associated with the buried pipeline. At the extreme southeast corner near coordinates F-0, is a magnetic low of less than 52,580 gammas (a negative anomaly of about 20-40 gammas), which may be associated with near-surface carbonate rocks. Northeast of the F-0 low, two highs of 52,650 gammas (a positive anomaly of about 50-70 gammas) at E-0 and 52,660 gammas (about 60-80 gammas) at D-0 alternate with lows associated with carbonate-bedrock outcrops. These lows between E-0 and D-0 and another at about B-0 are about 52,600 gammas and 52,500 gammas, respectively.

Three other magnetic highs are worthy of mention: one is elongate with two centers at B-1 and C-1, but with outcrops (which may be steep-sided pinnacles) at its northeastern extremeties; another high is broad and trends east-west for more than 100 ft with a center between about E-1 and E-2; a third high also trends east-west with a center at about 2.5 between C and D lines; this latter anomaly shows a depth to bedrock of 27 ft at drill hole V-88.

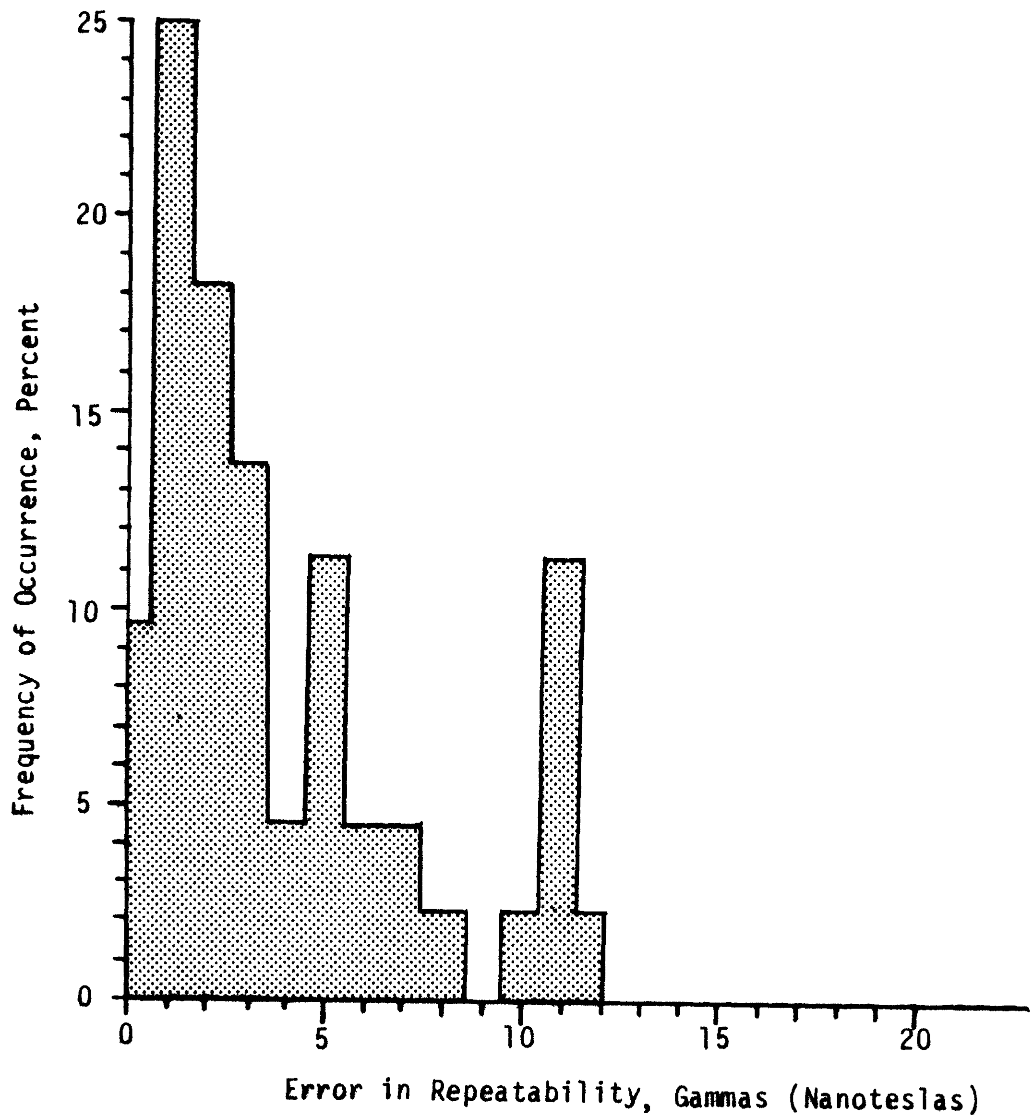


FIGURE 6.--Repeatability of 44 magnetic-data points at the geophysical-test grid of figure 3. Ninety percent of the data can be repeated within 8 gammas and two-thirds of the data within 4 gammas.

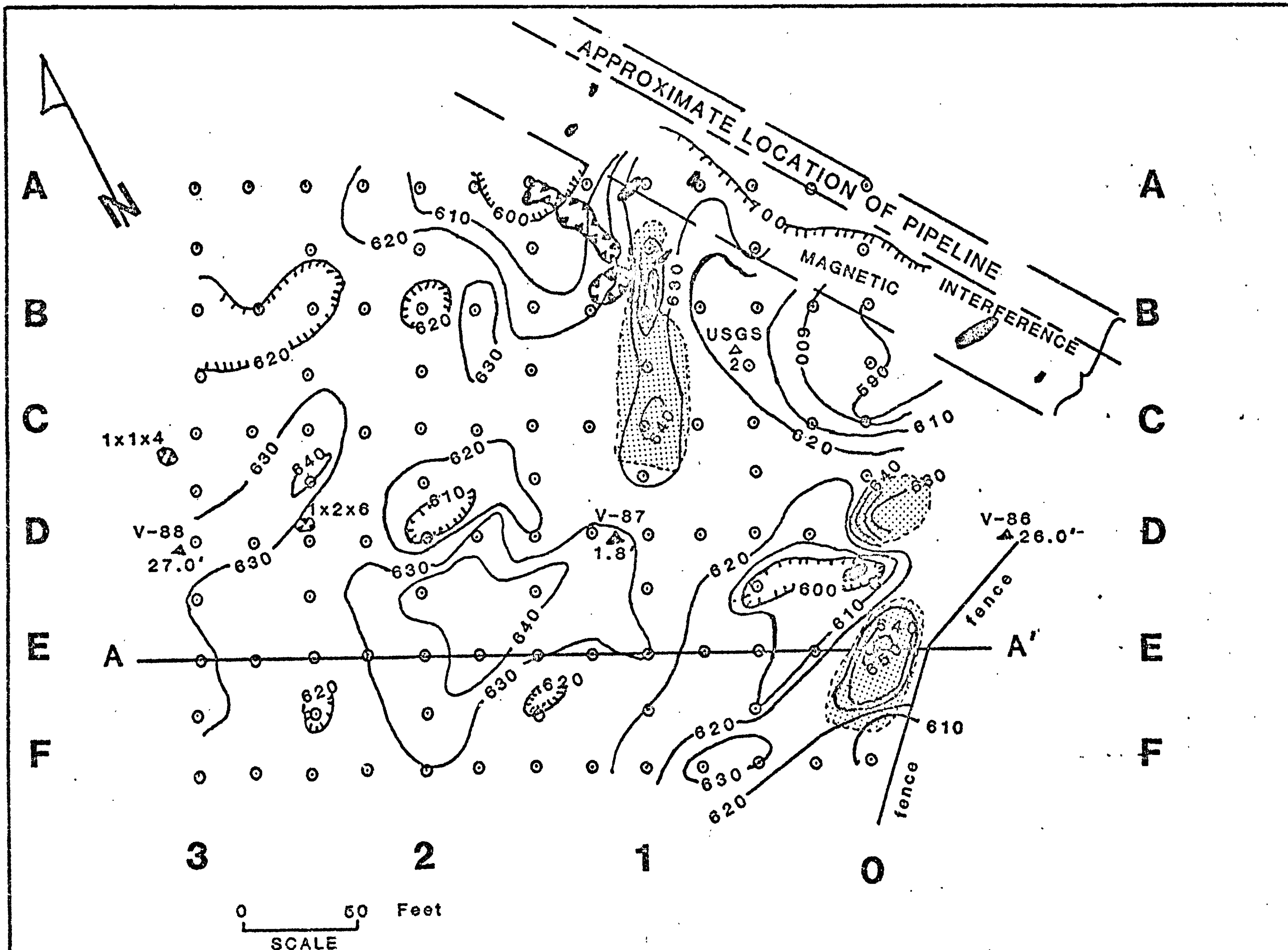
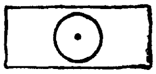
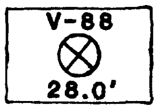


FIGURE 7.--Magnetic map of geophysical grid (fig. 2) in a carbonate-rock sinkhole area, Shelby County, Alabama. Contours are in gammas (nanoteslaus) and indicate values above 52,000 gammas.

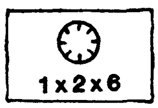
EXPLANATION



Data location

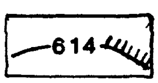


Drill hole showing hole number and depth, in feet, to carbonate bedrock



Sinkhole showing dimensions of length, width, and depth, in feet. Hachured areas without numerals are topographic lows

Outcrop of carbonate rock



Contour of Earth's total magnetic field in gammas (nanoteslas)--add 52,000 to the contour numerals. Base reference is 52,660 gammas. Contour interval is variable in the northeast section of the map but 10 gammas over the rest of the map. Magnetic depressions are hachured and highs are darkened.

Figure 7.--Continued

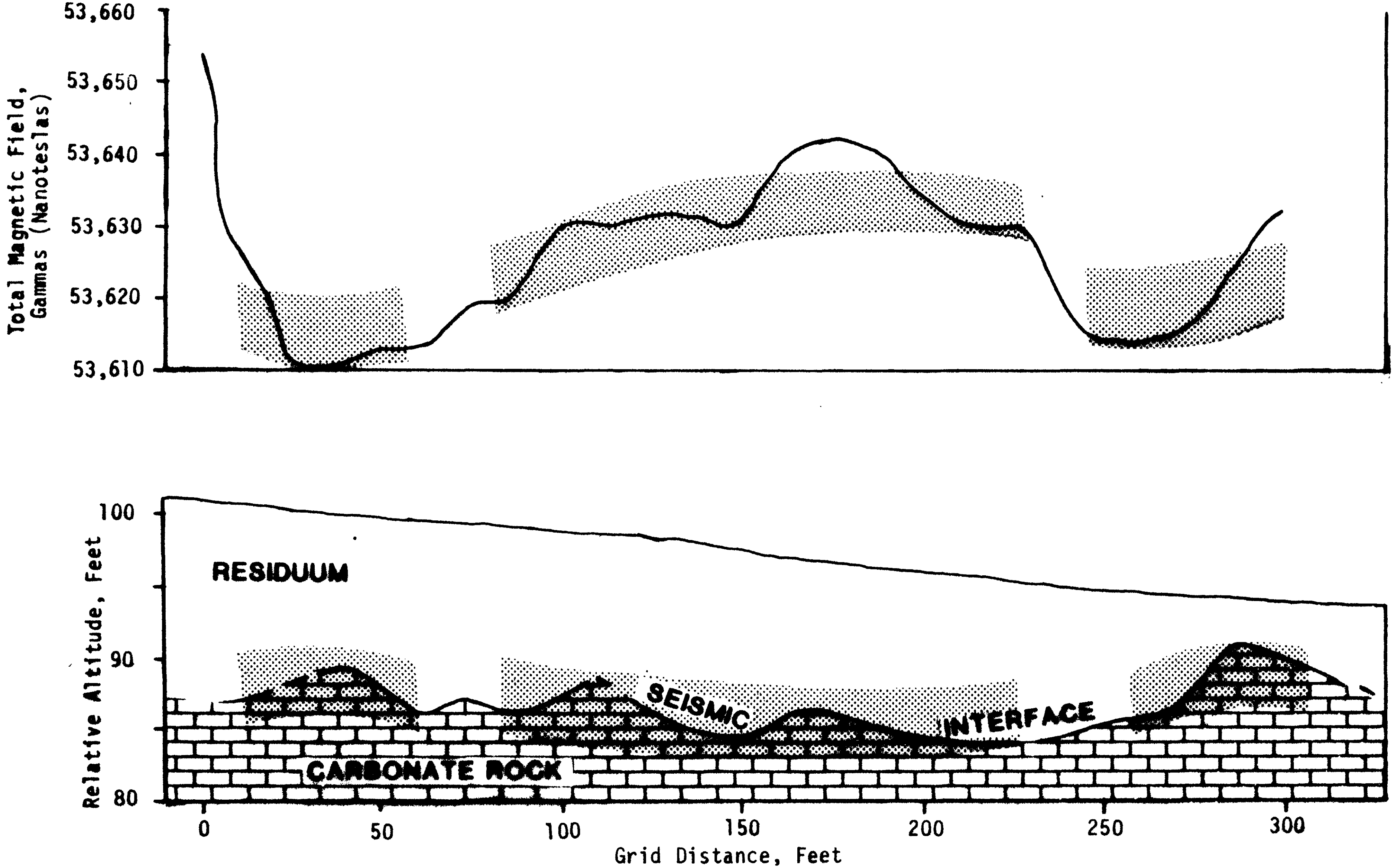


FIGURE 8.--A cross section of total magnetic intensity compared to the interpreted seismic interface along line E. The dark bands suggest that buried topographic lows in the carbonate bedrock (thick residuum) correspond to magnetic highs and visa versa and that the residuum is more magnetic than the carbonate bedrock.

A broad low is situated with its center near A-1.5 at the northern border of the map and is associated with both broad subsidence features and outcrops.

The interpreted highs and lows in either the magnetic-data or seismic-interface profiles may be subdued, however, because buried pinnacles and valleys may have quite steep topographic gradients, whereas the data points along the seismic lines are 15 ft apart and those of the magnetic lines are 25 ft.

The outcrop patterns and drill-hole depths to bedrock shown in figure 7 suggest that magnetic highs may be related to the relatively thicker deposits of residuum and visa versa. This inverse relationship is also suggested by the cross section of total magnetic intensity compared to the interpreted seismic interface between carbonate bedrock and residuum along line E of figure 8. A broad magnetic high dominates the central part of the cross section and seems to correspond somewhat to a broad low in the seismic interface. Similarly, magnetic lows at either end of the profile may correspond approximately to highs in the seismic interface. These preliminary interpretations are subject to further studies.

SUMMARY AND CONCLUSIONS

Sinkholes formed by subsidence and collapse of residual soil and unconsolidated surficial materials in carbonate karst terranes constitute a geologic hazard in areas of the southeastern United States. Underground openings develop along fractures in the carbonate bedrock, resulting in the development of pinnacled and cavernous bedrock surfaces and contemporaneous formation of an overlying, residual soil. A change in water level in the carbonate bedrock may promote cavity growth in the unconsolidated materials overlying the underground openings with subsequent subsidence or collapse. Failure occurs mostly in the overlying residuum and the magnitude of subsidence is a factor of the thickness and strength of the residuum.

The rugosity of the buried surface of carbonate rocks can be indicated by both seismic-refraction and magnetic surveys. Refraction lines were run along three gridlines, but reverse measurements for compressional-wave velocity were obtainable along only one of the lines. Seismograms of shear waves from a drill hole as well as from the surface spreads could not be interpreted. Evidently the relatively low-quality seismograms resulted from interference of many refracted- and reflected-wave modes caused by a very rough, buried bedrock surface. The rather poor seismograms of both compressional and shear waves may conversely indicate rugose carbonate rocks. The seismograms of compressional waves of one line were interpreted by the method of differences and the interpretation showed considerable buried relief.

The contoured magnetic map shows anomalies with amplitudes of several tens of gammas. A preliminary comparison of depth to bedrock inferred from seismic and drill-hole data and outcrop patterns to magnetic anomalies suggests a correlation: the relatively iron-rich residuum causes relatively high-magnetic anomalies and, conversely, low-magnetic anomalies are associated carbonate rocks.

The extent of sinkhole collapse is dependent upon the strength of residuum, and its thickness, as well as other parameters. Estimates of V_s indicate that the shear strength and elastic moduli are several hundred times greater for carbonate rocks than for residuum and that the residuum is much more amenable to deformation and failure. This supports the geologic observations that cavities in carbonate bedrock are created mainly by solution, whereas sinkhole failure is primarily confined to the much weaker residuum.

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