FINAL REPORT TO THE CITY OF EVANSVILLE:
Shear-wave and earthquake hazard mapping of Evansville, Indiana

---

INDIANA UNIVERSITY
INDIANA GEOLOGICAL SURVEY
OPEN FILE REPORT 94-19

FINAL REPORT TO THE CITY OP EVANSVILLE: Shear-wave and earthquake hazard mapping of Evansville, Indiana

D.L. Eggert,[1] A. C. Samuelson,[2] D. Bray,[3] S.W. Chang,[3] W.R. Eckhoff,[4] K. Kayabali,[5] E. J. McClees,[3] T. R. West,[6] M.C. Woodfield,[1] B. Zheng,[1]

[1] Indiana Geological Survey, Bloomington, IN 47405, [2] Ball State University, Dept. of Geology, Muncie, IN 47306, [3] University of California, Dept. Civil Engineering, Berkeley, CA 94720, [4] Dames and Moore, Cincinnati, OH 45203, [5] University Ankara, Geological Engineering Dept. Tandogan, Ankara, 06100, Turkey, [6] Purdue University, Dept. of Earth and Atmospheric Sciences, West Lafayette, IN 47907

INTRODUCTION

Evansville has been the focus of our most intense study of soil velocity measurements because of its vulnerability to earthquakes that originate in the New Madrid and Wabash Valley seismic zones. Thickness and particle size variations in the nonlithified unconsolidated sediments (soils) beneath the city determine the geographic distribution of damage from future major earthquakes. Knowledge of shear—wave velocity, standard penetration testing (SPT), and cone penetrometer testing (CPT) of the unconsolidated sediment column is essential to determine soil period, amplification potential, liquefaction risk, and other site responses to earthquake shaking. Forty—four monitoring wells were installed to bedrock, penetrating from 23 to 140 ft of unconsolidated sediments, so that seismic velocities of soils could be measured in situ. Soil velocity testing was also completed on 21 private and public water monitoring wells. Sixty—four gamma ray logs were made on monitoring wells used in our study. More than 50 SPT’s were made within Evansville and over six hundred SPT’s records from public and private sources were collected. CPT’s were conducted at 27 sites.

This information was processed to evaluate how the cities “soils” will respond to earthquake shaking. From our downhole velocity measurements we were able to determine the dominant period at which soils would shake in response to an earthquake and the potential for the soil to amplify earthquake shaking. The data, particularly the SPT and CPT, were reviewed and evaluated to measure the risk of soil liquefaction within Evansville.

Gamma logging is a technique that uses the natural radiation given off by sediments that surround a well to identify the particle size of the sediments. We applied this method to each well used in this report. Finer sediments, such as clay, generally emit more gamma radiation thus they shift the line to the right (higher gamma ray counts/sec.) and coarser sediments, sand and gravel, generally shift the line to the left (lower gamma ray counts/sec.). Soils in Evansville were deposited in a continuum of depositional settings from wind–blown bess (clayey silt), to lake deposits of clay and silt, and to stream deposits of silt, sand, and gravel.

Using the gamma logs of the monitoring wells, cross sections were made that show the lateral variations of soils within the city (figs. 1–5). These sectional views can be interpreted to show the underlying geological processes that determined the distribution of soils within the city, and they provide a framework for mapping seismic hazards within Evansville.

Hopper (1985) prepared maps that suggested that some areas of Evansville would shake more severely than others and that some parts of the city are more vulnerable to soil liquefaction than others (figs. 6 and 7). Using the soil data we have collected in the Evansville region since 1989, we have made several new seismic hazard maps (figs. 8 and 9). These maps suggest that areas vulnerable to amplification of shaking or liquefaction are significantly different from those reported by Hopper. In response to our work, the United States Geological Survey has awarded two research contracts to build upon the information collected. These new studies will facilitate the development of the next generation of seismic hazard maps and maps that will help protect ground water.

Results

Soil Velocity

A downhole technique similar to that of Fumal and Tinsley (1985) was used to measure the in situ shear–wave velocity. The shear–wave velocities were measured in Evansville by positioning a downhole geophone at various depths in the cased holes. A seismic signal was generated at the surface by hitting a timber with a sledgehammer equipped with a switch that activated a data recorder. The impact of the hammer generated primary waves and shear waves. The time required for these waves to travel through the sediment column was measured using a portable seismograph. The data were processed by Indiana Geological Survey (IGS) or Ball State University (BSU) staff to determine the average shear wave velocity for the “soil” column tested at each location. The variability of the wave velocities within each hole was determined. A log sheet was prepared for each well showing lithology, shear–wave velocity, average shear– wave velocity, and soil period (Appendix A).

Downhole velocity measurements to bedrock have been made in forty–four wells, and the near-surface soil velocities were measured in nineteen shallow monitoring wells. Several hundred STP borings were checked, and soil velocities were calculated from the particle–size descriptions and the number of hammer blows required to obtain the SPT samples for these borings. Average shear wave velocities vary from 529 to 871 ft/s.

Soil Period

The soil period-- the length of time between the arrival of two shear waves–– is an important factor in the relationship between building failure and soils during earthquakes. The soil period for a site was calculated by using the average shear–wave velocity of the soil and the following equation.

4 X soil thickness / average shear wave velocity = soil period.

Thick fluvial, transitional, and lake soils in this area have long natural periods (up to 0.7 s) in contrast to the short periods (less than 0.1 s) for thin upland soils (fig. 8). From the soil–period map for Evansville several basic conclusions can be made. Damage from a future earthquake will not be uniform. Minor structural damage in Evansville from the October 31, 1895 earthquake was restricted to the areas near the present downtown district where soil periods range from .4 to .6 s. Much of the present city of Evansville is located on soil having similar to longer–soil periods. This suggests that the damage areas will be more extensive than in the 1895 earthquake. Critical facilities (water, sewage treatment plants, hospitals, fire stations, and schools) and highway bridges are located in areas where these structures have similar natural periods that are very similar to the underlying soil’s period. A lesson from the 1985 Mexico City earthquake was that structures with periods similar to the soil beneath them are more vulnerable to earthquake shaking.

Site–Specific Amplification

The collection of shear wave velocity data for soils in the Evansville, Indiana area provides an exceptional opportunity for evaluating the likelihood of site–specific amplification in that area. The shear wave velocity measurements and idealized soil profiles at two typical sites in the Evansville area are shown in figure 10. SHAXE91, a computer program, was used to calculate seismic response based on the vertical propagation of shear waves through a one–dimensional column of soil.

The development of representative bedrock motions at specified levels of uncertainty is an integral part of the site response studies. Unfortunately, strong motion recordings for moderate to strong earthquake events in the Midwest are scarce resulting in a major source of uncertainty in our study. Ongoing research may solve this problem. For our preliminary site response study, the following two existing earthquake records (which appear to represent the likely characteristics of bedrock motions in the Evansville area) were modified so that the maximum horizontal ground acceleration (MHA) of the records was 0.15 g:

Earthquake	M_w	NHA (g)	T_p (sec)
1988 Saguenay	6.0	0.121	0.16
1940 El Centro	6.9	0.356	0.216

MHA = 0.15 g corresponds to the Uniform Building Code’s (UBC) seismic zone factor for Zone 2A, which encompasses Evansville. It also is intermediate between the MHAs shown in the U.S. Geological Survey maps developed by Algermissen and others (1990) for a 10 percent probability of being exceeded in 50 and 250 years, respectively.

Acceleration response spectra developed from the wave propagation analyses for the two modified earthquake records are shown in figure 11. The computed acceleration response spectra for the input bedrock motions are depicted as solid lines, and the computed response spectra for the ground motions at the two sites are depicted as dotted lines. For comparison, the UBC normalized acceleration response spectrum for soil type 1 (stiff sandy and clay soils in which the soil thickness is less than 61 In (200 ft) is also shown as a heavy solid line. The short period response can be underestimated by a factor of two or more for both input bedrock motions with the UBC design response spectrum at these typical sites. Buildings with fundamental periods in the range of 0.1 to 0.6 seconds (namely one— to six— story buildings), particularly those with fundamental periods close to 0.2 seconds, have the potential to be more strongly shaken and damaged in future Midwest earthquake events. The predominant period of the two input motions is relatively short and that earthquake input motions containing significant energy at longer periods are possible due to large magnitude events traveling over longer distances (for example, the Mexico City 1985 earthquake). The longer period soil deposits in Evansville have the potential for significant amplification of ground motions with input bedrock motions containing energy at longer periods.

The potential hazards resulting from site amplification in Evansville must be evaluated in the context that most older buildings in Evansville have not been designed to the force level specified by the 1991 UBC normalized design spectrum shown in Figure 11. Moreover, a number of these buildings have not been designed in accordance with critical 1991 UBC detail requirements, and therefore, are more susceptible to damage if amplified motions occur at a site. The results of these preliminary seismic risk response studies suggest that a number of facilities in the Evansville area could be damaged as a result of soil-induced amplification effects and that further work is warranted in this area.

Liquefaction Potential

Areas of potential liquefaction have been recognized in Evansville (for example Hopper 1985). Concurrent with making the soil velocity measurements, investigators at Purdue University began a study of soil liquefaction vulnerability in the Evansville region by collecting geotechnical data (SPT and CPT). Kayabali (1993) identified areas with loose silt and sand in the upper 30 feet that are vulnerable to liquefaction. Based on analysis of these data Kayabali prepared a liquefaction microzonation map for the Evansville area (fig. 9) Areas vary from those not at risk to those having a very high liquefaction risk. In a general overview of Kayabali’s study, the area at greatest risk from soil liquefaction is downtown east to 1-164 and south of the Lloyd Expressway.

Soil liquefaction is generally restricted to the upper 30 feet of soil. If this part of the soil is dry, it will not liquefy. Our limited examination of water levels in our monitoring wells suggests that much of the vulnerability to liquefaction is seasonal. The water table seems to fluctuate in response to river stage levels, high in late winter to early spring and below 30 feet during the rest of the year. However, at some sites near the river the water table remains less than 30 feet from the surface throughout the year.

Retrofitting

We have provided the results of our work to Woodward–Clyde Consultants, who have evaluated the seismic vulnerability of Evansville fire stations. They, in turn, have processed the data so that they could make suggestions on reducing the seismic risk for these critical facilities. We have also provided our results to each of Evansville’s hospitals, for their use.

Future Work and Ongoing Research

The seismic geotechnical database for Evansville is now more comprehensive than for most urban regions within the central United States. David Frost, Georgia Institute of Technology, and D.L. Eggert, Indiana Geological Survey, were awarded a two–year contract from the United States Geological Survey (USGS) National Earthquake Hazard Reduction Program to develop computer–drawn Geographic Information System (GIS) seismic hazard maps. This project will be funded for approximately $126,152. The USGS has awarded the Indiana Geological Survey $30,000 to prepare GIS geologic terrain maps that will assist in the protection of the regional ground water and in the development of the seismic– 5 hazard mapping. It is unlikely that these contracts would have been awarded without the previous contributions from the City of Evansville, the Indiana Department of

Fire and Building Services, the Indiana State Emergency Management Agency, the United States Office of Surface Mining, and the Indiana Geological Survey.

A critical question remains to be answered. Silt and sand soil materials vulnerable to liquefaction must be saturated to liquefy during major earthquake shaking. When during the average year are conditions favorable for liquefaction? A study of the annual and geographic variation in water table fluctuations would answer this question. We sought funding for this study from the USGS and it was not approved. Funding for this proposed research will be sought from the USGS in the future. Should the USGS again deny funding the City of Evansville might consider supporting the work.

Publications Resulting from Evansville Seismic Studies

Eckhoff, W.R., Samuelson, A.C., Eggert D.L., and Bleuer, N.K.,l991, Downhole shear—wave velocity studies in unconsolidated sediments in selected Indiana urban areas: *Geological Society of America Abstracts with Programs,* v. 23, p. A42.

_____1991, Shear—wave velocity studies in unconsolidated sediments in selected Indiana Urban Areas: *Indiana Academy of Sciences,* v. 107, p. 60.

_____1992, Downhole shear—wave velocity studies in the unconsolidated sediments in Evansville, Indiana: *Geological Society of America Abstracts with Programs,* v. 24, p. A296.

Eggert, D.L., Bleuer, N.K., Bray, J.D., Chang, S.W., Eckhoff, W.R., Kayabali, K., Munson, C.A., Munson, P.K., Samuelson, A.C., and West, T., 1994, Seismic hazards in Indiana: what we have learned, *Fifth U.S. National Conference on Earthquake Engineering, EERI,* Chicago, Ill.

Eggert, D.L., Bleuer, N.K., Samuelson, A.C., and Eckhoff, W.R., 1994, A sedimentologic interpretation and seismic site response prediction for Evansville, Indiana, based on gamma—ray logs: *Geological Society of America Abstracts with Programs,* v. 26, No.1, p. 6.

Eggert, D.L., Eckhoff, W.R, Samuelson, A.C., and Bleuer, N.K., 1993, Shear—wave velocities and soil periods of unconsolidated fluvial, lacustrine, and eolian Sediments (soils) that underlie Evansville, Indiana: *1993 National Earthquake Conference,* v. 1, p. 317-326.

Kayabali, K., 1993, Earthquake hazard analysis for the City of Evansville, Indiana: unpublished Ph.D. thesis, Purdue University, West Lafayette, IN, 354 p.

Samuelson, A.C., Eggert, D.L., and Eckhoff, W.R, 1994, Downhole shearwave studies enhanced by gamma log lithologic interpretations: *Symposium on* the *Application of Geophysics to Engineering and Environmental Problems, Environmental and Engineering Geophysical Society,* Boston, p. 481-498.

References

Algermissen, S.T., Perkins, D.M., Thenhous, P.C. Hanson, S.L., and Bender, B.L., 1990, Probabilistic earthquake acceleration and velocity maps for the United States and Puerto Rico, *United States Geological Survey Miscell. Field Studies,* Map MF2120.

Fumal, T.E., and Tinsley, J.C., 1985, Mapping shear–wave velocities of near–surface geological materials: *USGS Prof. Paper 1360,* p. 127–149.

Hopper, M.G., ed., 1985, Estimation of earthquake effects associated with large earthquakes in the New Madrid Seismic Zone: *United States Geological Survey Open-File Report* 85-457, 186 p.

Kayabali, K., 1993, Earthquake hazard analysis for the City of Evansville, Indiana: unpublished Ph.D. thesis, Purdue University, West Lafayette, Indiana, 354 p.

Glossary

Blow counts / N number = Part of the data collected from a Standard Penetration Test (SPT). This test is performed to measure the capacity of a soil to support a structure’s foundation by indirectly measuring density and cohesion. Thus, it is useful in calculating soil shear—wave velocity and vulnerability to liquefaction. When the test is performed a standard weight hammer is dropped a specific height to drive the soil sampling tube a fixed distance into the soil. The number of times that this hammer is dropped to drive the tool into the soil is referred to the N value or N number.

Cone-penetrometer test or CPT = Is an engineering soil test in which a cone instrumented with a variety of sensors (these sensors may include friction, pressure, moisture, hydrocarbon, or other instruments) is hydraulically pushed into a unconsolidated material, “soil”, as the resulting resistance as well as the other data collected by the sensors are recorded. This test is most commonly used to help design foundations for structures. The data can also be used to evaluate liquefaction hazards in earthquake prone areas.

Gamma-ray log = A geophysical downhole technique to determine the particle size and/or composition of earth materials present in boreholes. A tool is placed into the borehole and records background gamma ray radiation (a photon from an atomic nucleus) from the materials that surround the borehole. Different earth materials have characteristic gamma ray emissions. Thus, if a record is obtained of the gamma radiation it is possible to interpret the particle size and composition of materials that surround the borehole.

Liquefaction = The transformation of a loose saturated silt or sand soil into a fluid as a result of increased pore pressure and reduced effective stress during severe earthquake shaking. This form of soil failure may result in the damage or destruction of structures built upon these soils.

Nonlithified or unconsolidated materials = Clay, silt, sand, and gravel materials that are not cemented together. These materials are some times described in an engineering sense as “soils”.

One-dimensional-soil-column = A simplified view of an unconsolidated deposit, “soil”, where shear-waves are moving vertically and the horizontal movement is restricted to one dimension.

Particle wave, primary wave, or P wave = A seismic body wave that involves particle motion (altering compression and expansion) in the direction of movement.

Period = The interval in time required for the completion of a cyclic motion such as a shear–wave. The unconsolidated deposits at a location will have a period determined by the thickness of material and its shear–wave velocity. A building will have a period determined by its height and construction method.

SHAKE91 = A computer program developed by I. N. Idriss and J. L. Sun to predict the earthquake motion at a soil surface determined by the vertical propagation of shear–waves through a one– dimensional column of horizontal soil layers and using recorded earthquake bedrock motions that are considered reasonable for the studied location.

Shear–wave or S wave = A seismic body wave that is propagated by a shearing motion that involves oscillation perpendicular to the direction the wave is moving.

Standard Penetration Test or SPT = Is an engineering test used in the design of foundations for structures. A standard diameter sample tube is driven into an unconsolidated material or soft rock by dropping a standard weight hammer a fixed distance. The number of hammer drops required to drive the sample tube a prescribed distance is referred to as the blow counts, usually recorded as the N number. The size of the soil particles is determined by analysis of the samples recovered in the sample tube.

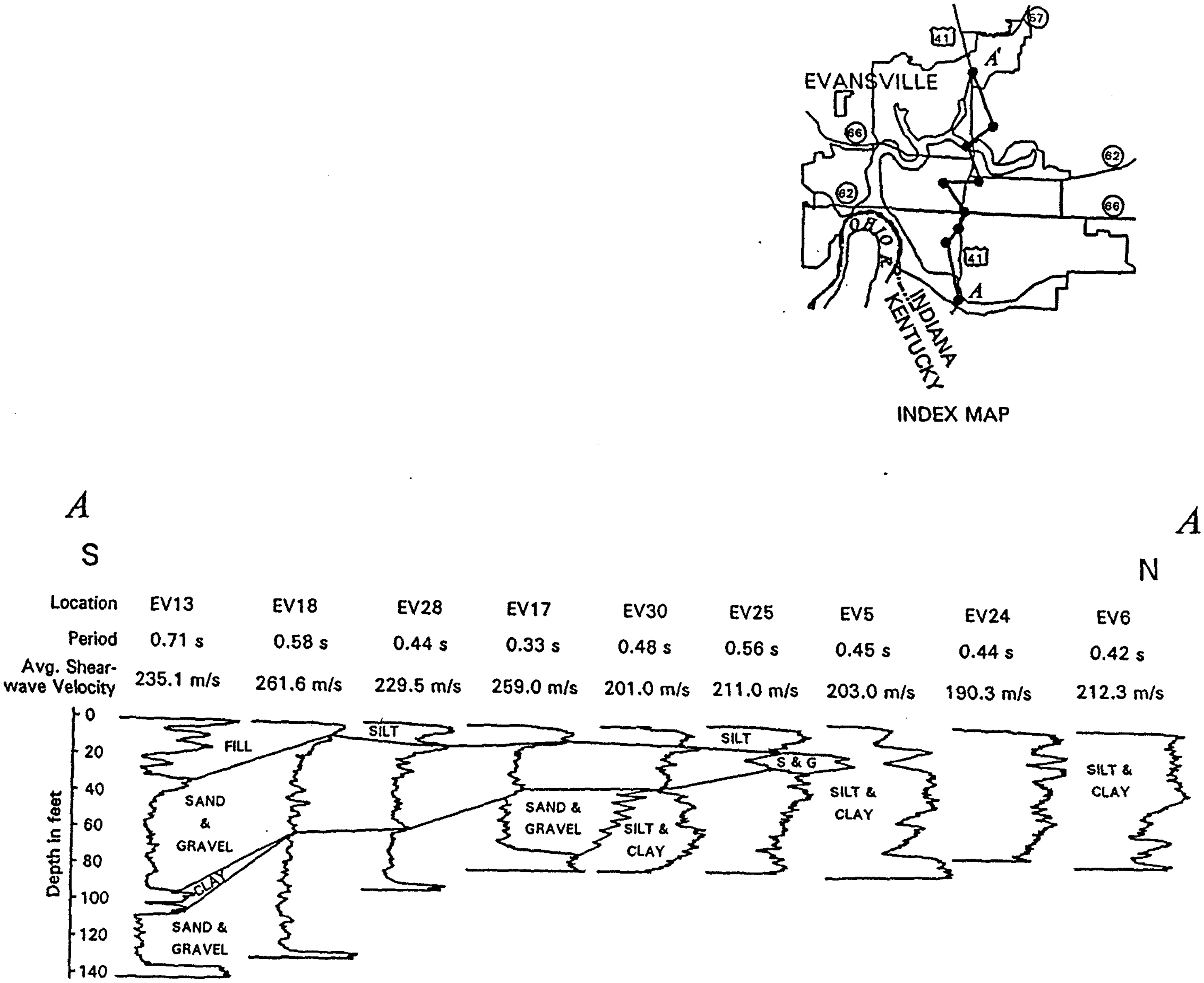


FIGURE 1. A NORTH-SOUTH SECTIONAL VIEW OF SOILS ALONG US 41.

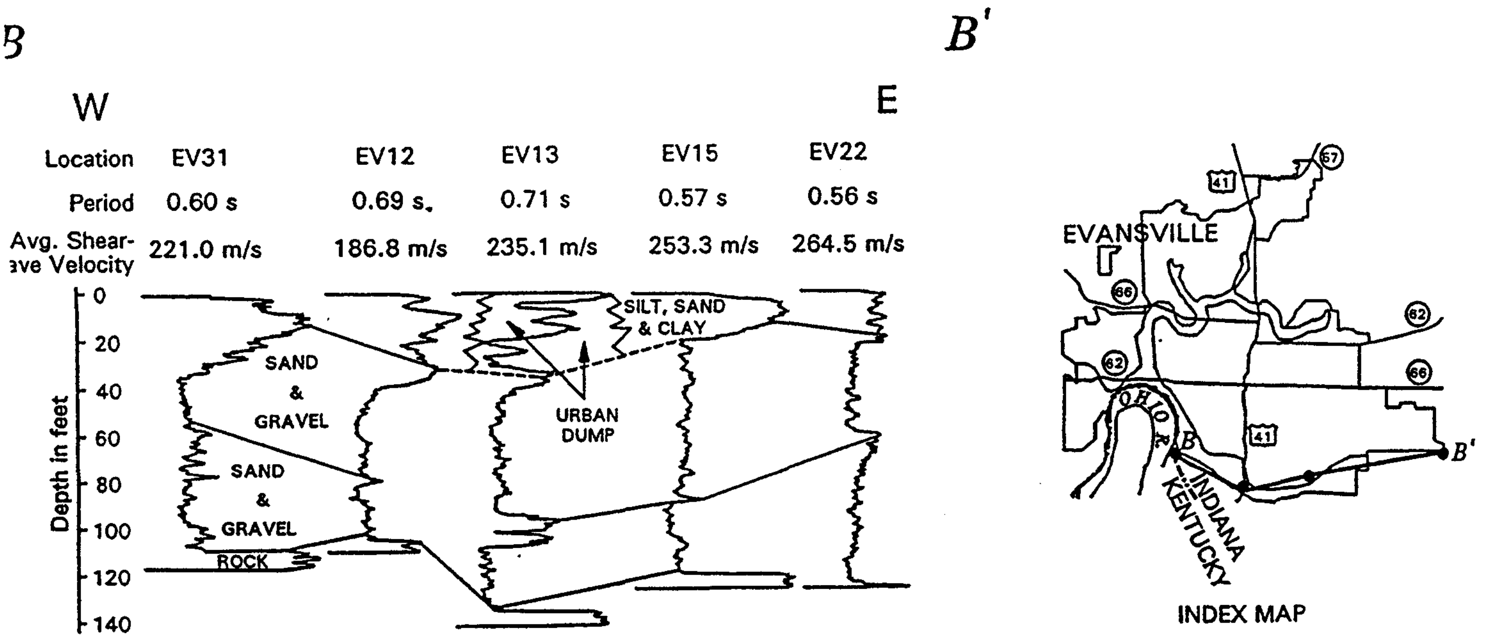


FIGURE 2. AN EAST-WEST SECTIONAL VIEW OF SOILS IN EVANSVILLE'S SOUTH SIDE.

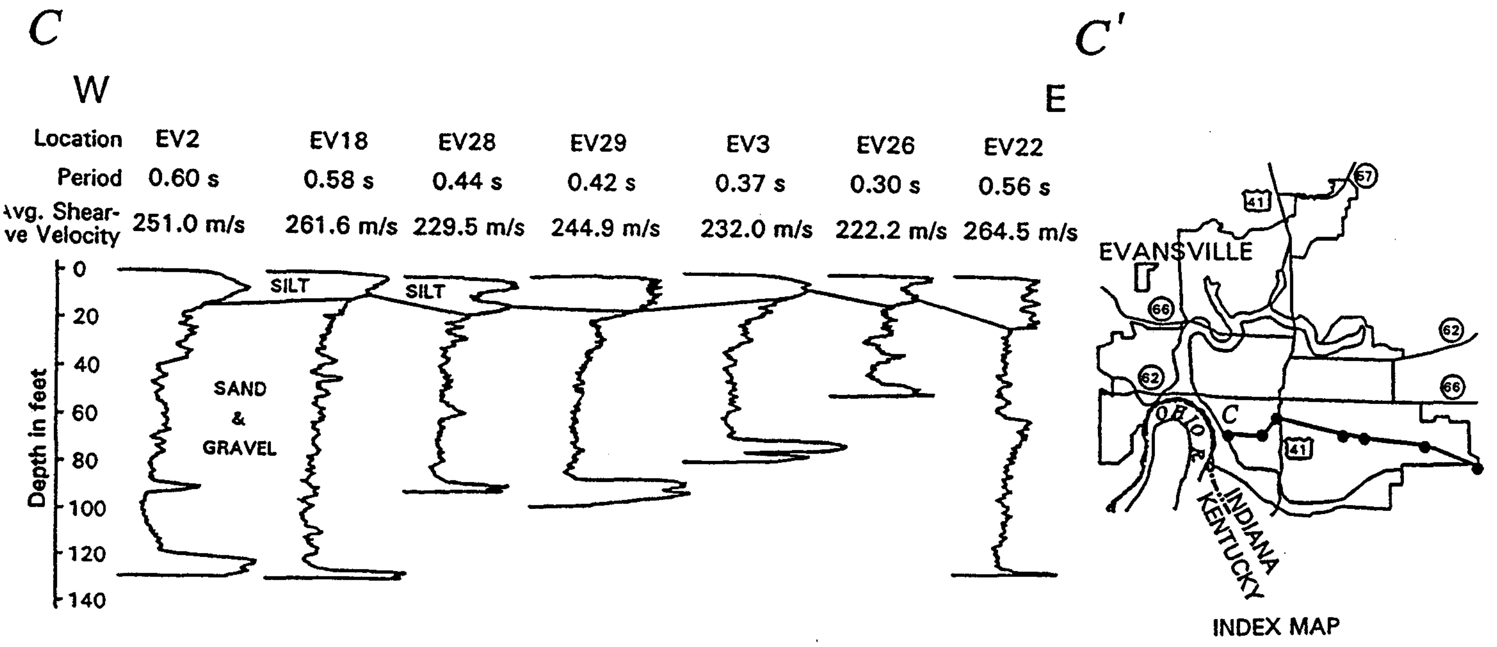


FIGURE 3. A SOIL SECTIONAL VIEW FROM THE CIVIC CENTER TO I-164.

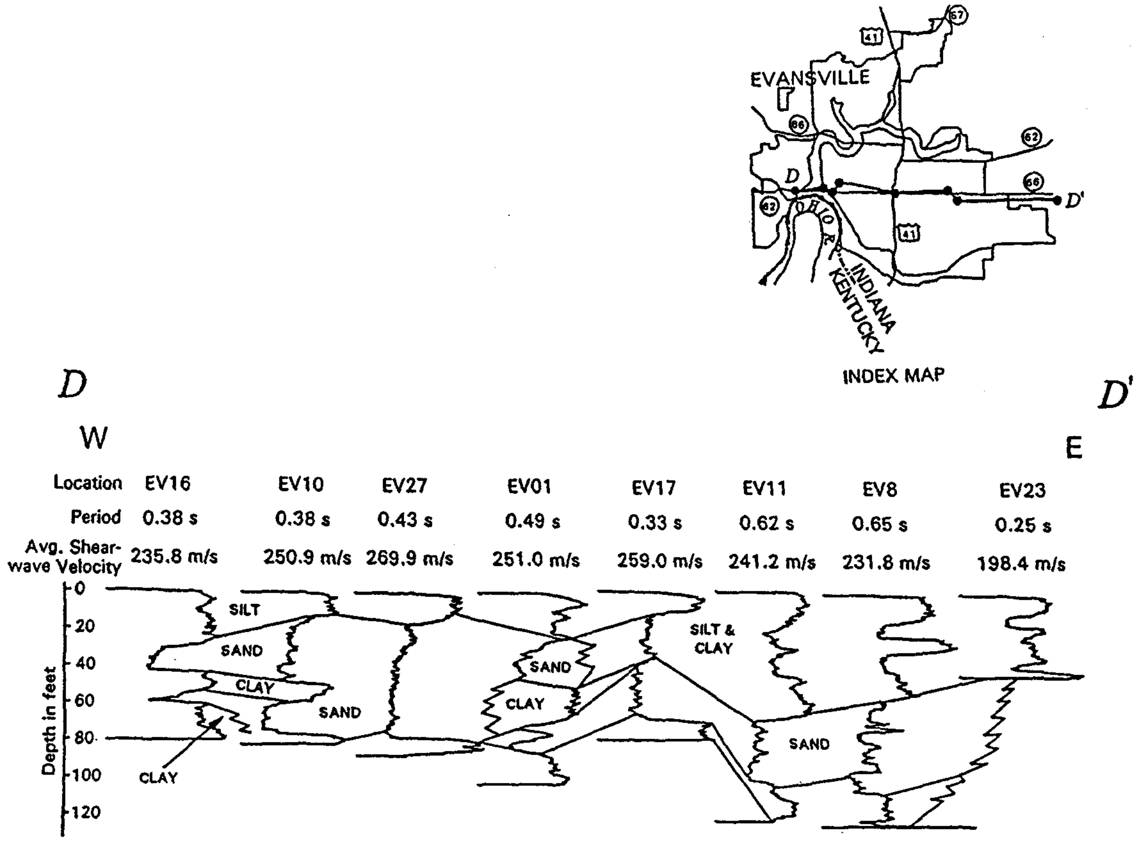


FIGURE 4. A SECTIONAL VIEW OF SOILS ALONG THE LLOYD EXPRESSWAY.

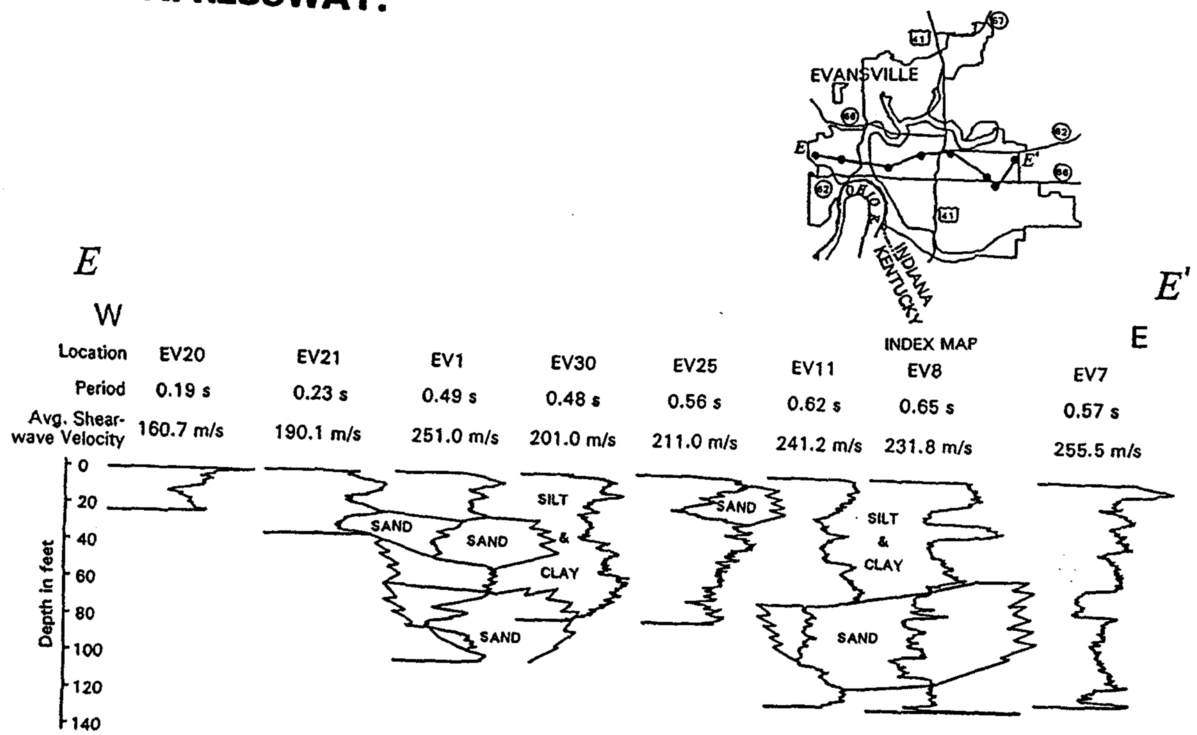


FIGURE 5. A SECTIONAL VIEW OF EVANSVILLES NORTH SIDE SOILS.

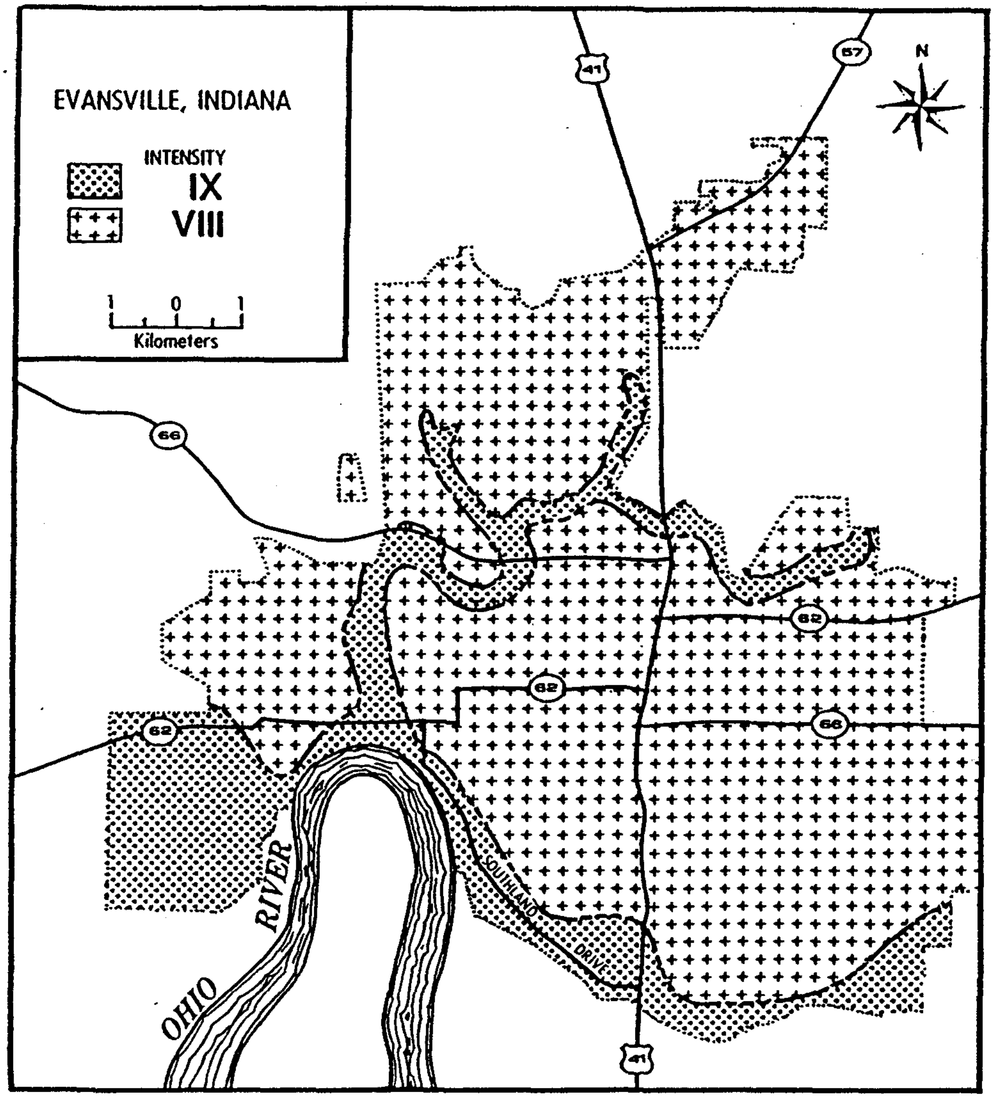


FIGURE 6. A MAP SHOWING INTENSITY OF GROUND SHAKING IN EVANSVILLE DURING A HYPOTHETICAL M 8.6 NEW MADRID EARTHQUAKE. (FROM HOPPER, 1985)

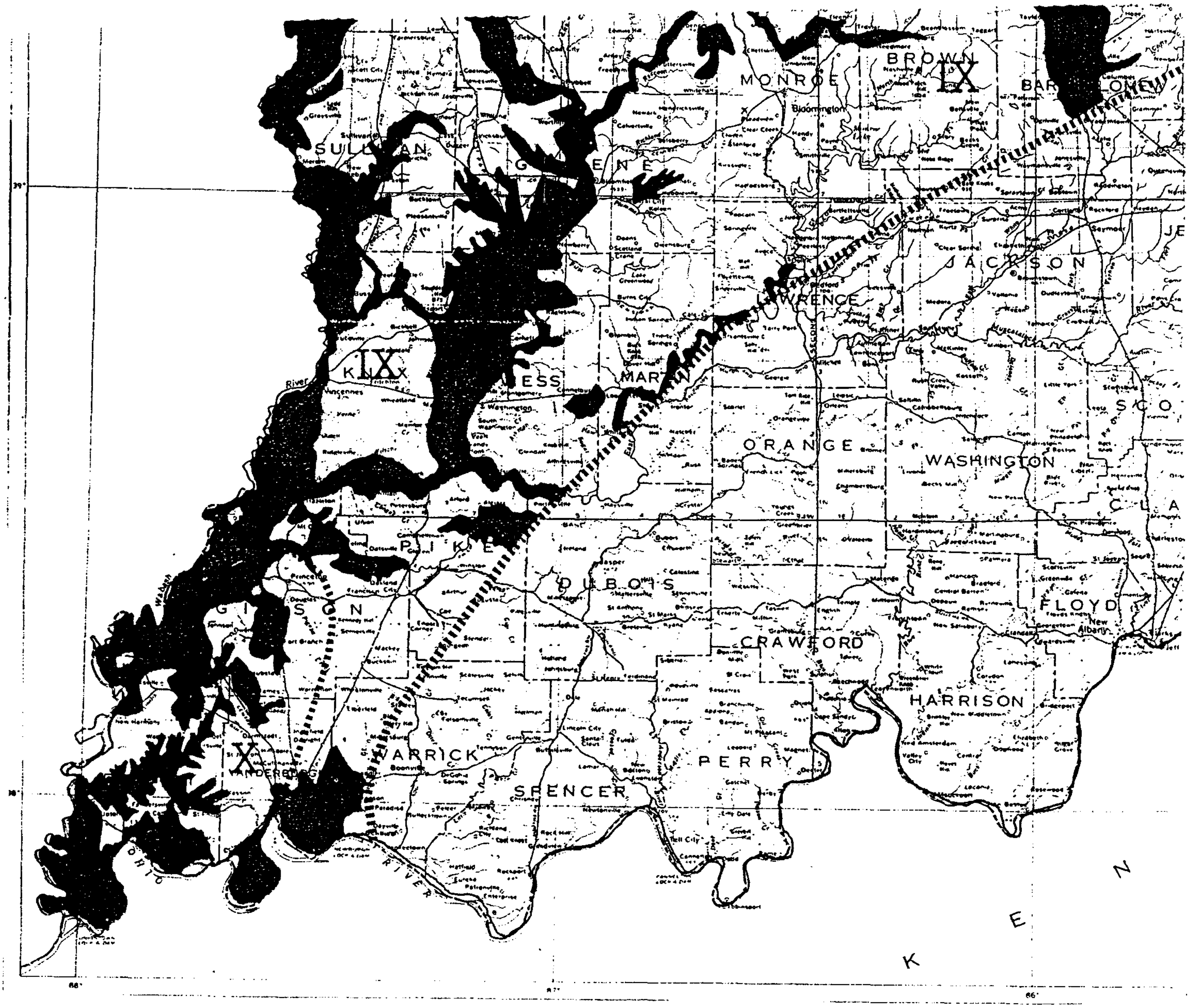


FIGURE 7. A MAP SHOWING AREAS OF SOUTHWESTERN INDIANA VULNERABLE TO SOIL LIQUEFACTION. (FROM HOPPER, 1985.)

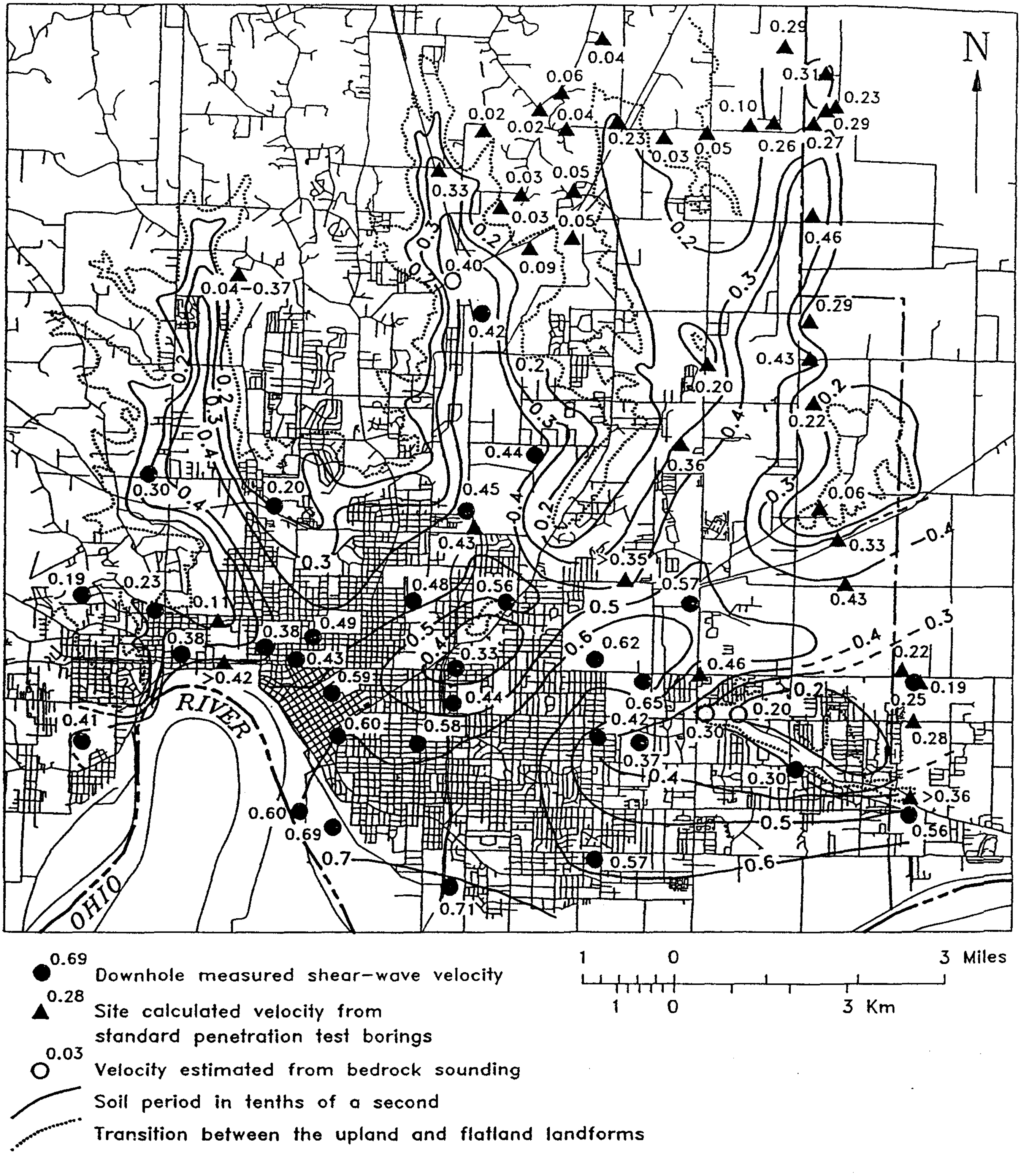


FIGURE 8. A MAP SHOWING THE DISTRIBUTION OF SOIL PERIODS IN EVANSVILLE BASED UPON DOWNHOLE VELOCITY MEASUREMENTS AND ENGINEERING BORINGS.

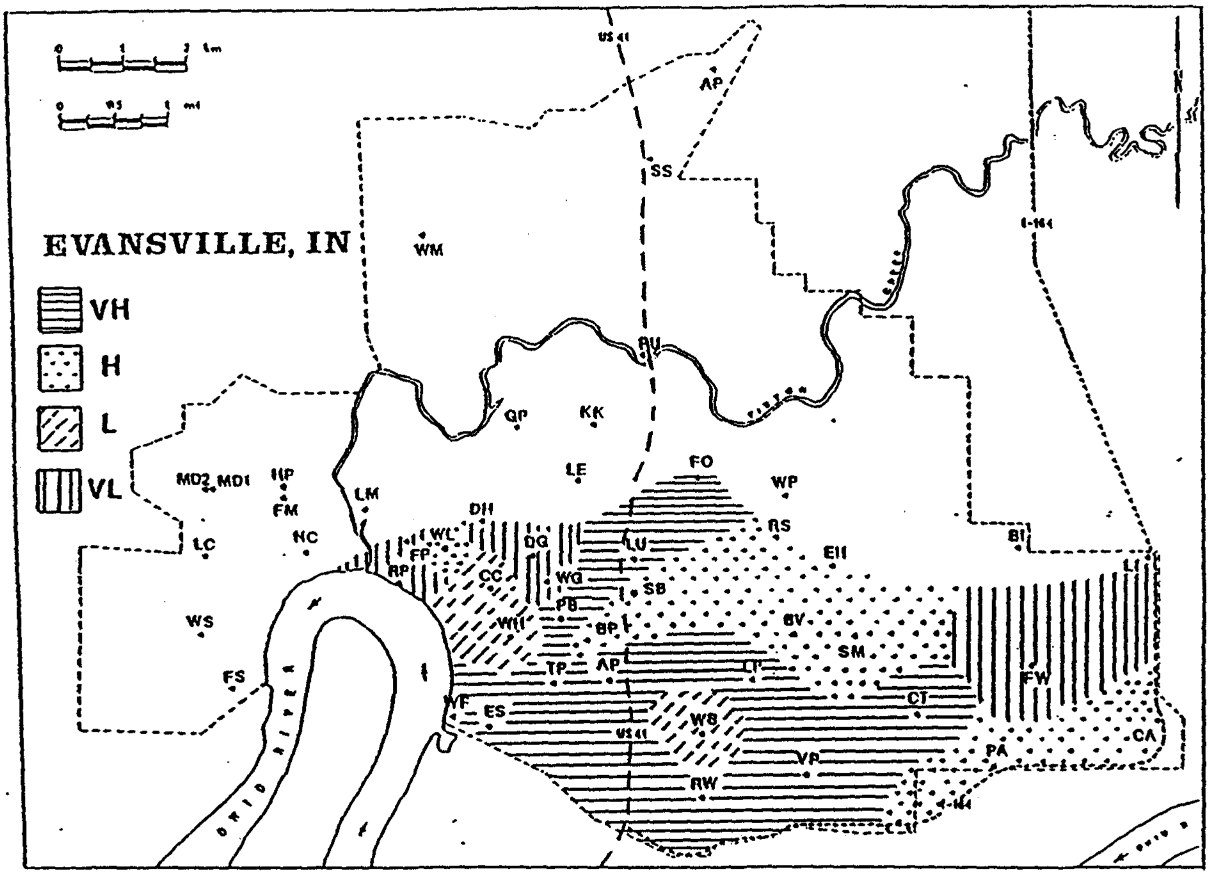
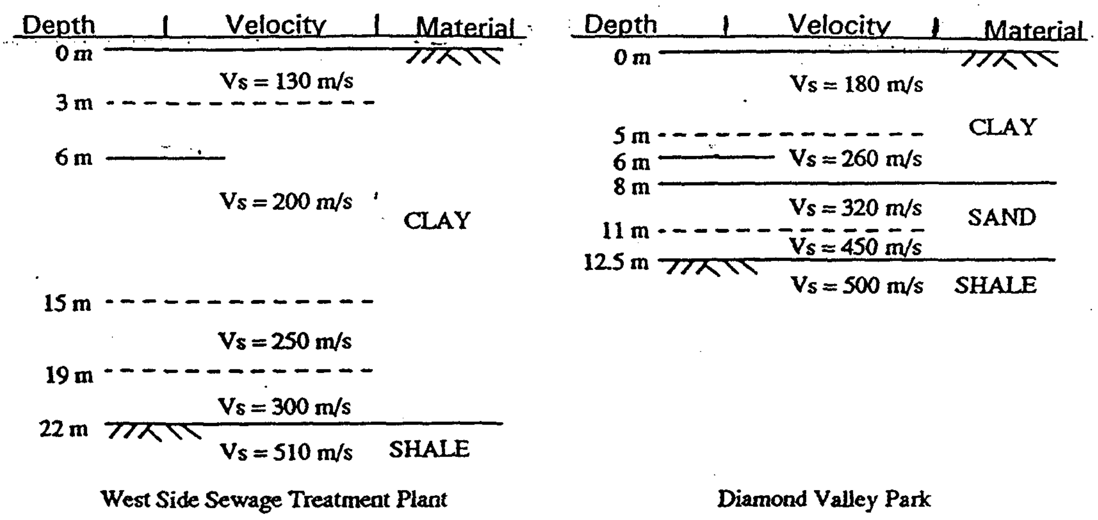


Figure 9. A map showing the vulnerability of Evansville soils to liquefaction. VH) very high, H) high, L) Low, VL) Very Low

ES) Sample location.



West Side Sewage Treatment Plant

Diamond Valley Park

FIGURE 10 IDEALIZED SOIL PROFILES AT TWO SITES IN EVANSVILLE

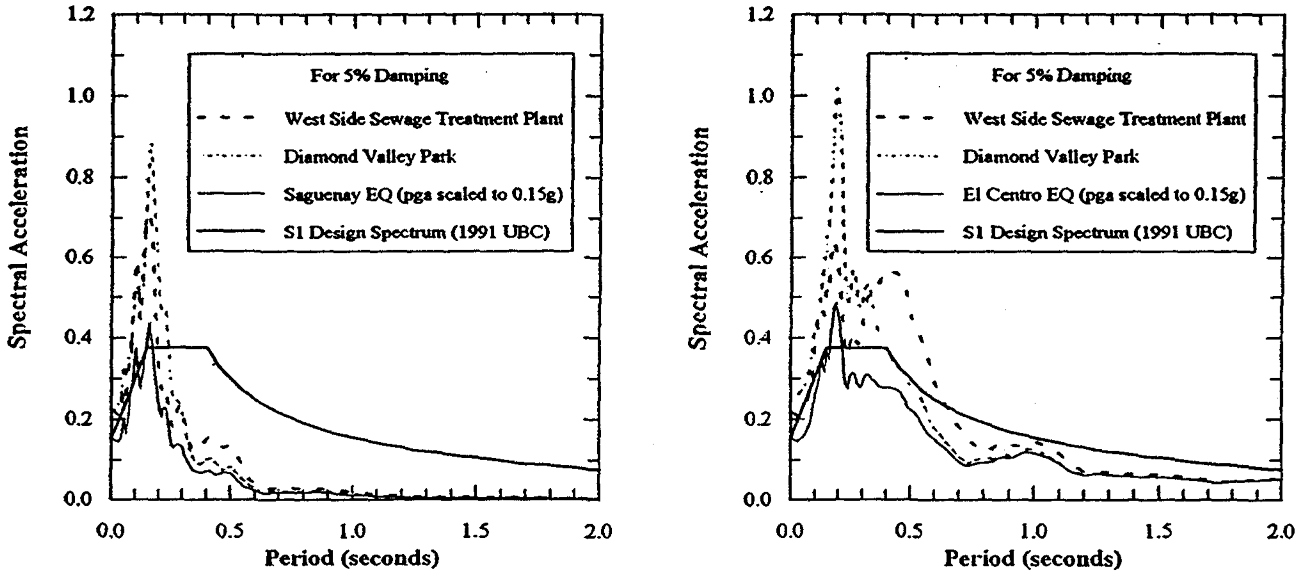
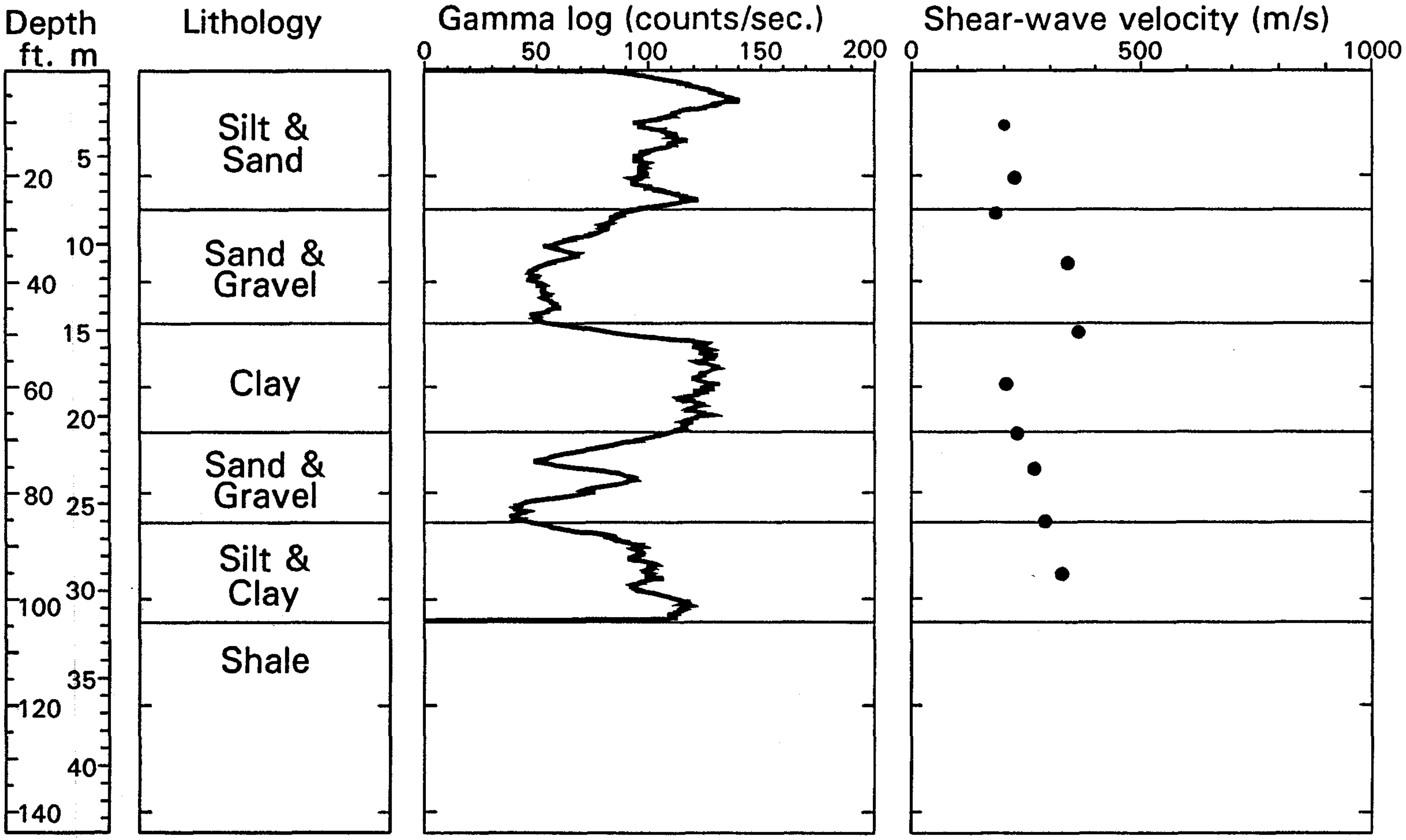


FIGURE 11 COMPUTED ACCELERATION RESPONSE SPECTRA AND THE 1991 UBC S1 SOIL DESIGN SPECTRUM.

APPENDIX A

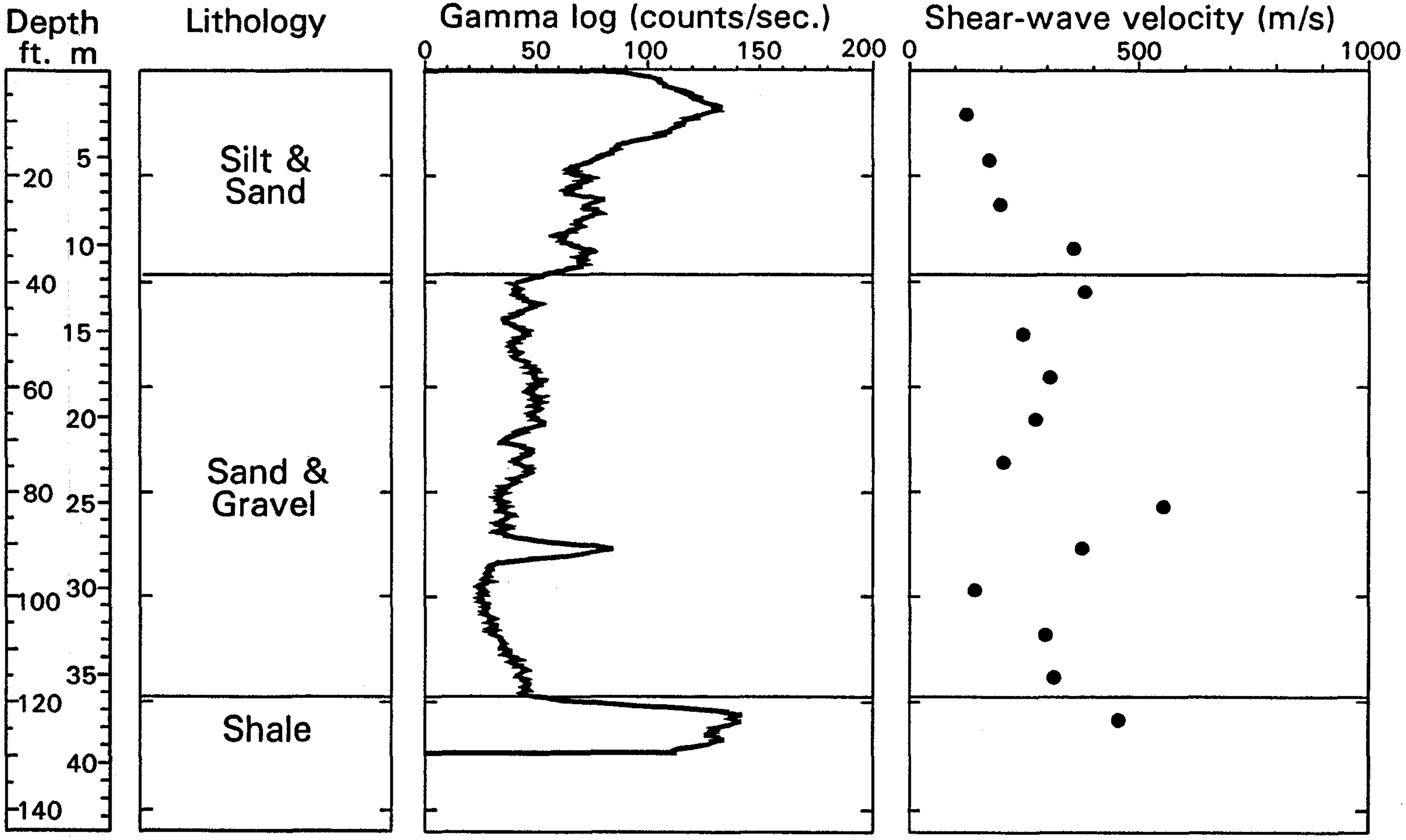
Deaconess Hospital - Evansville #1

Avg. Shear-wave Velocity: 251.0 m/s **Soil Period:** 0.49 s



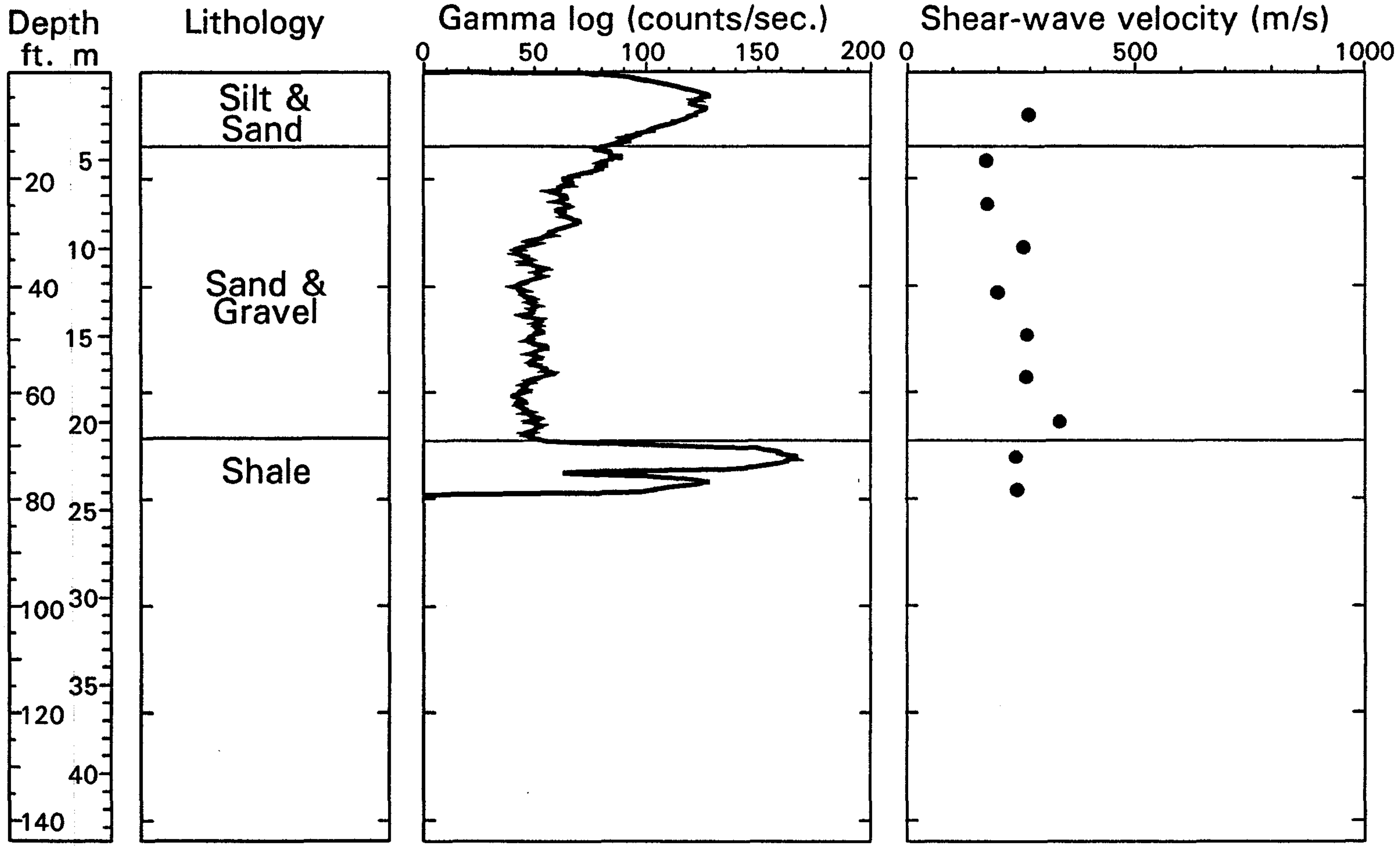
Welborn Hospital - Evansville #2

Avg. Shear-wave Velocity: 251.0 m/s **Soil Period:** 0.60 s



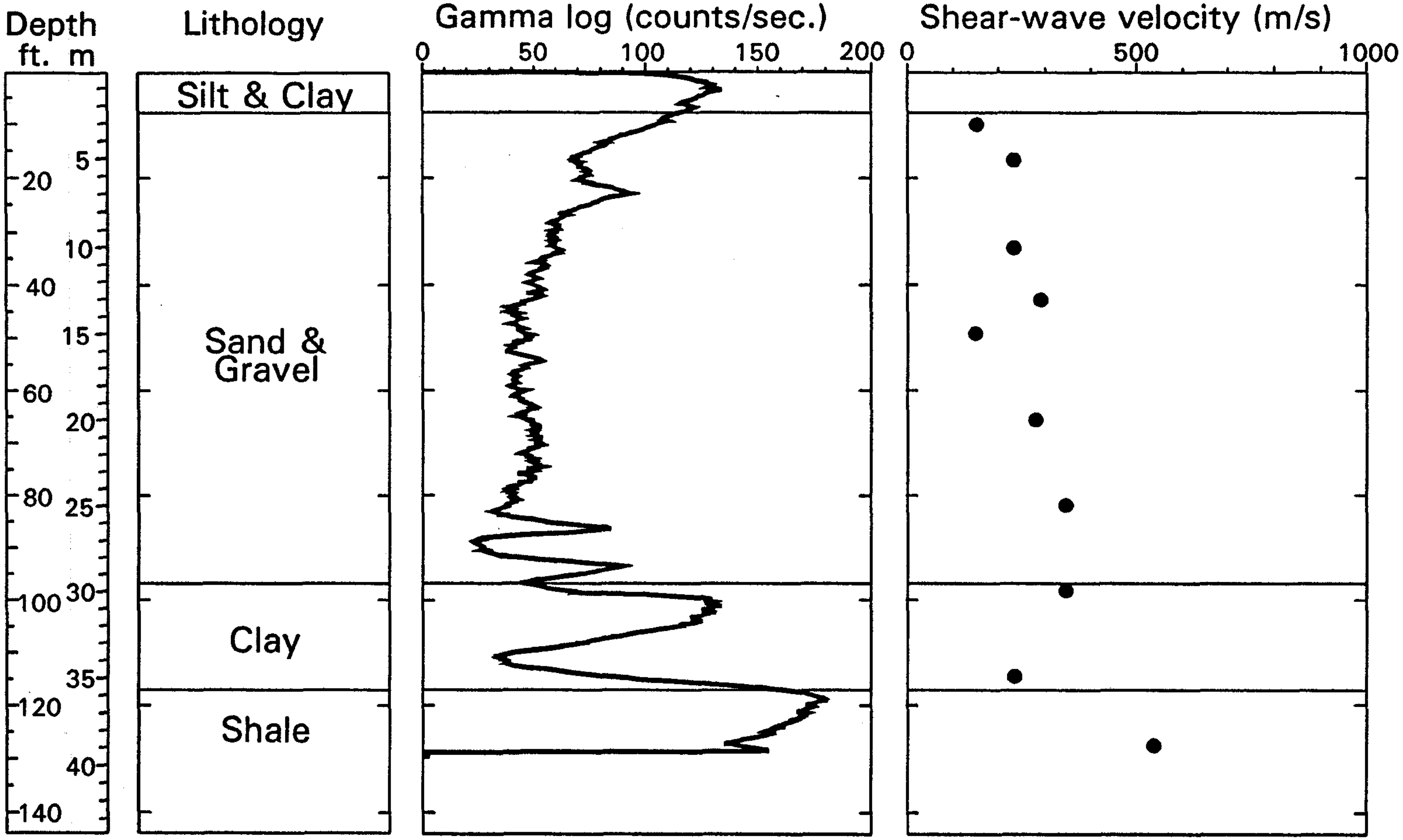
St. Mary's Medical Center - Evansville #3

Avg. Shear-wave Velocity: 232.0 m/s Soil Period: 0.37 s



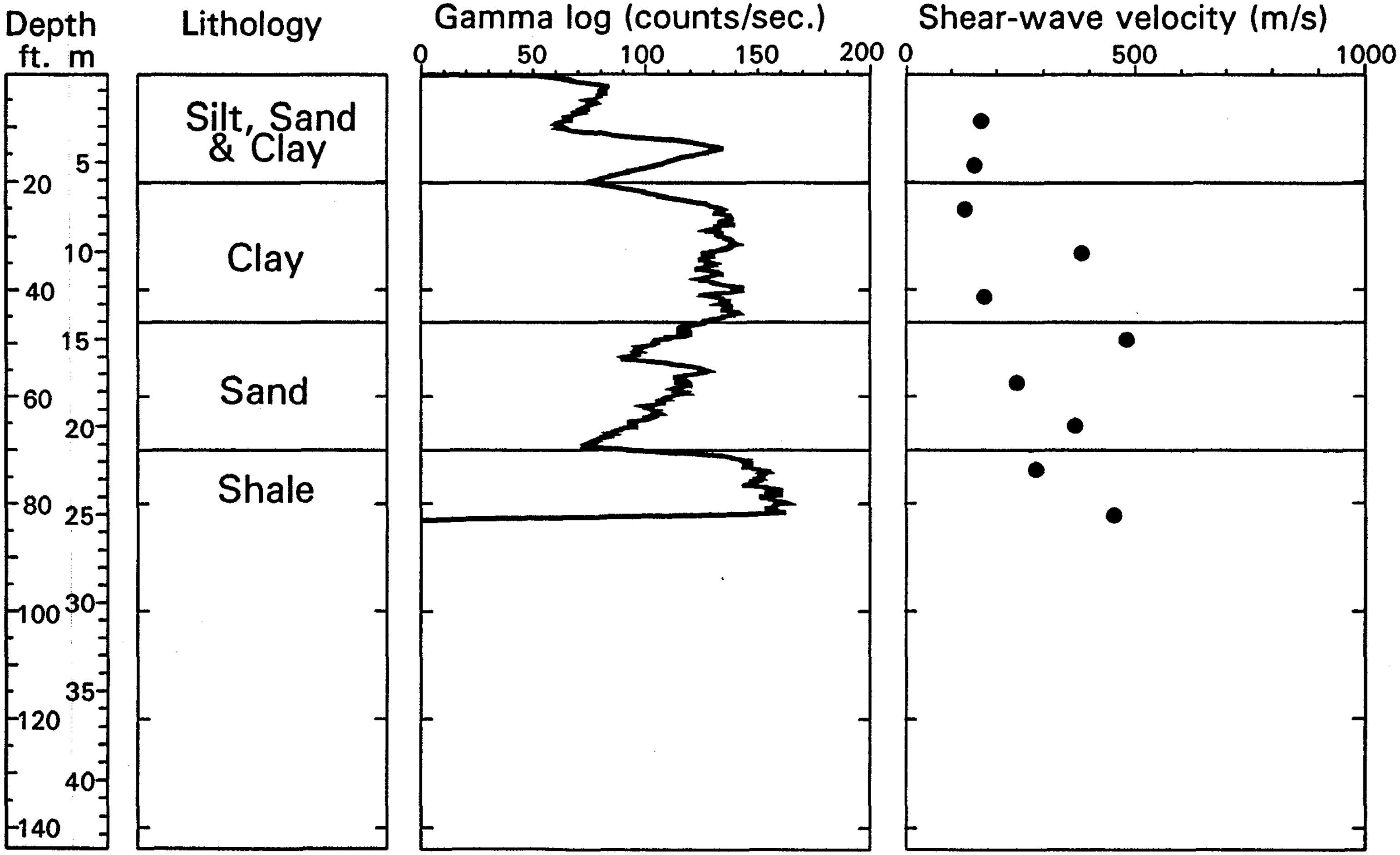
Civic Center - Evansville #4

Avg. Shear-wave Velocity: 248.0 m/s Soil Period: 0.59 s



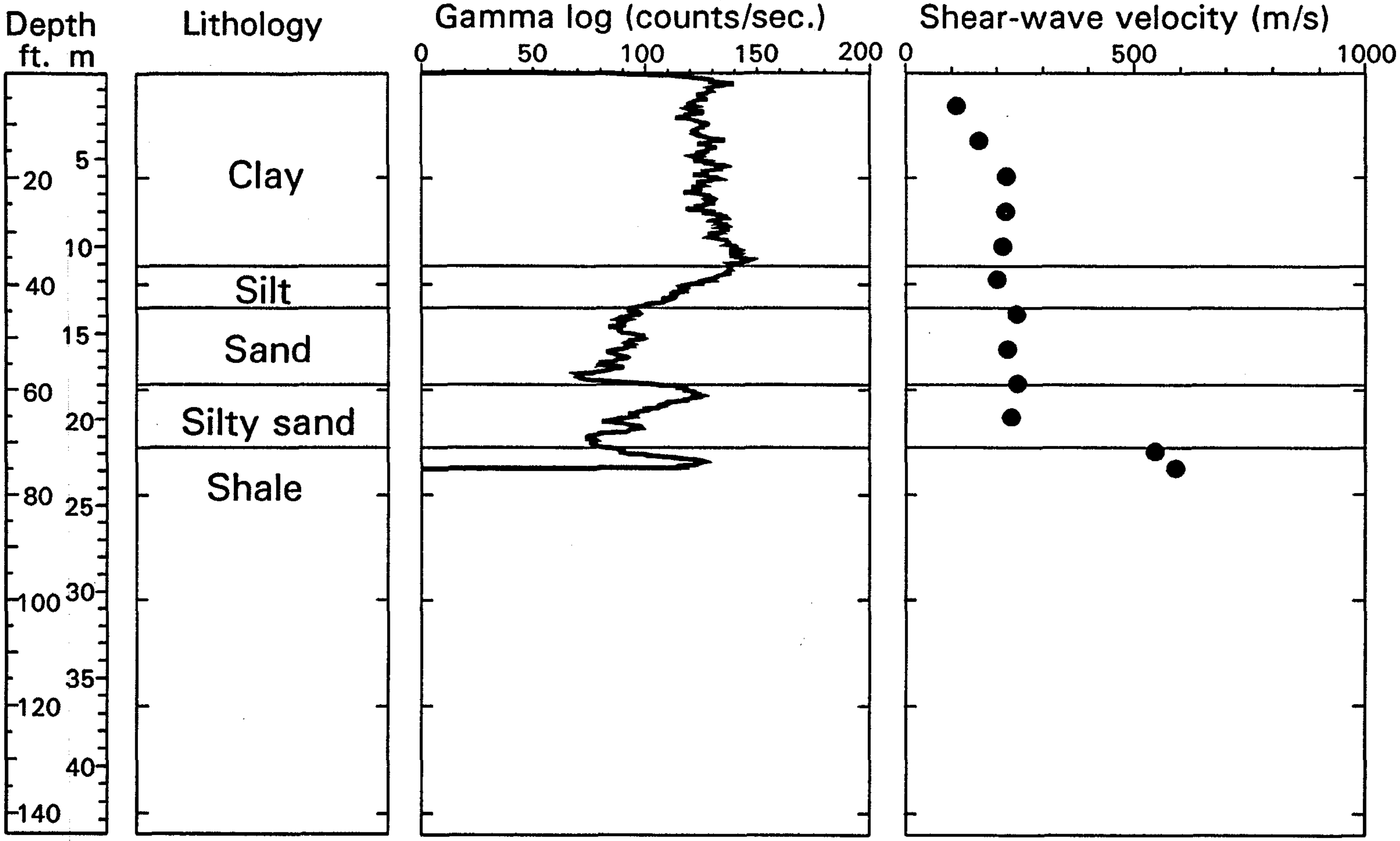
Hwy 41 at Pigeon Creek - Evansville #5

Avg. Shear-wave Velocity: 203.0 m/s **Soil Period:** 0.45 s



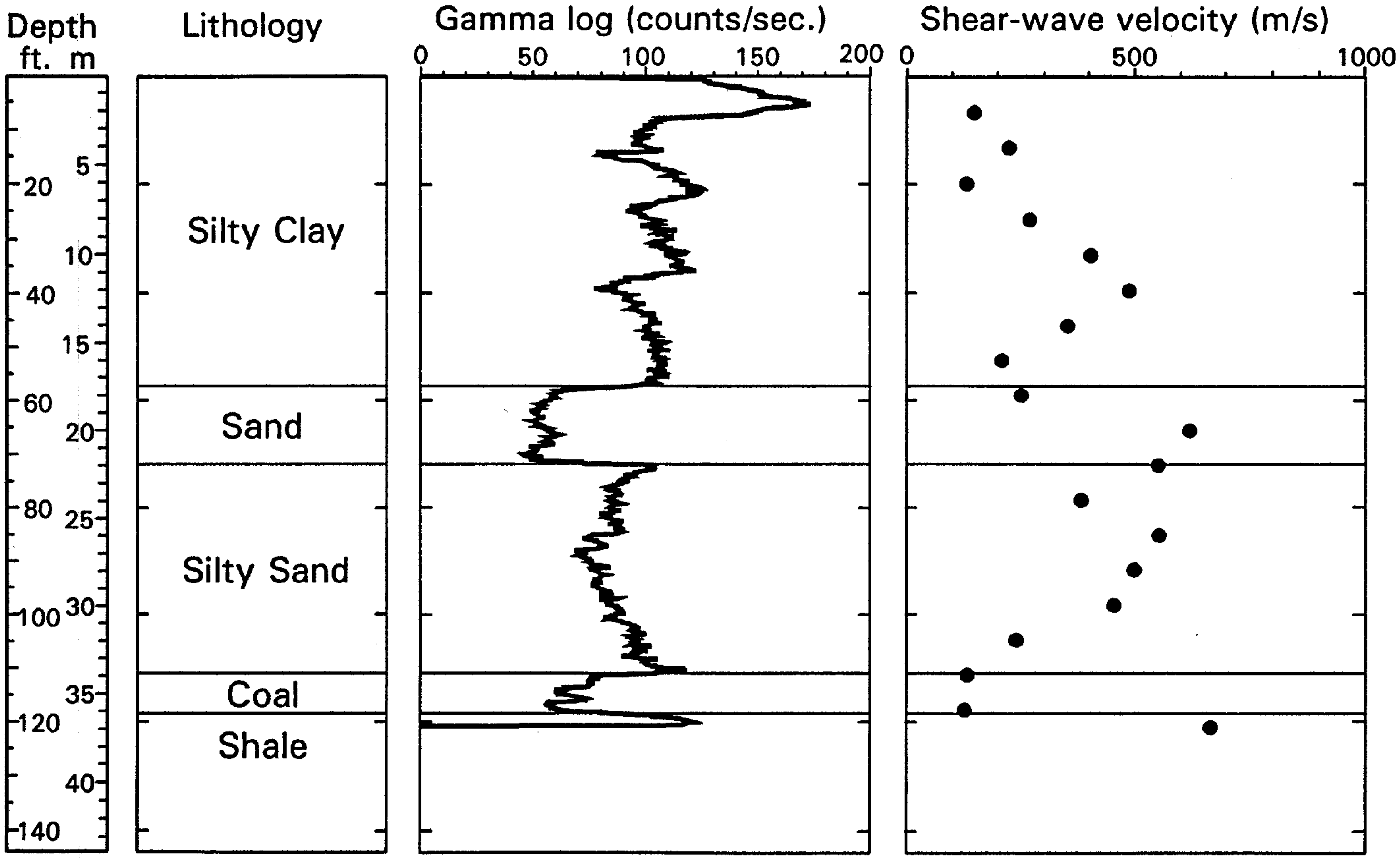
Airport Sheriff Substation - Evansville #6

Avg. Shear-wave Velocity: 212.3 m/s Soil Period: 0.42 s



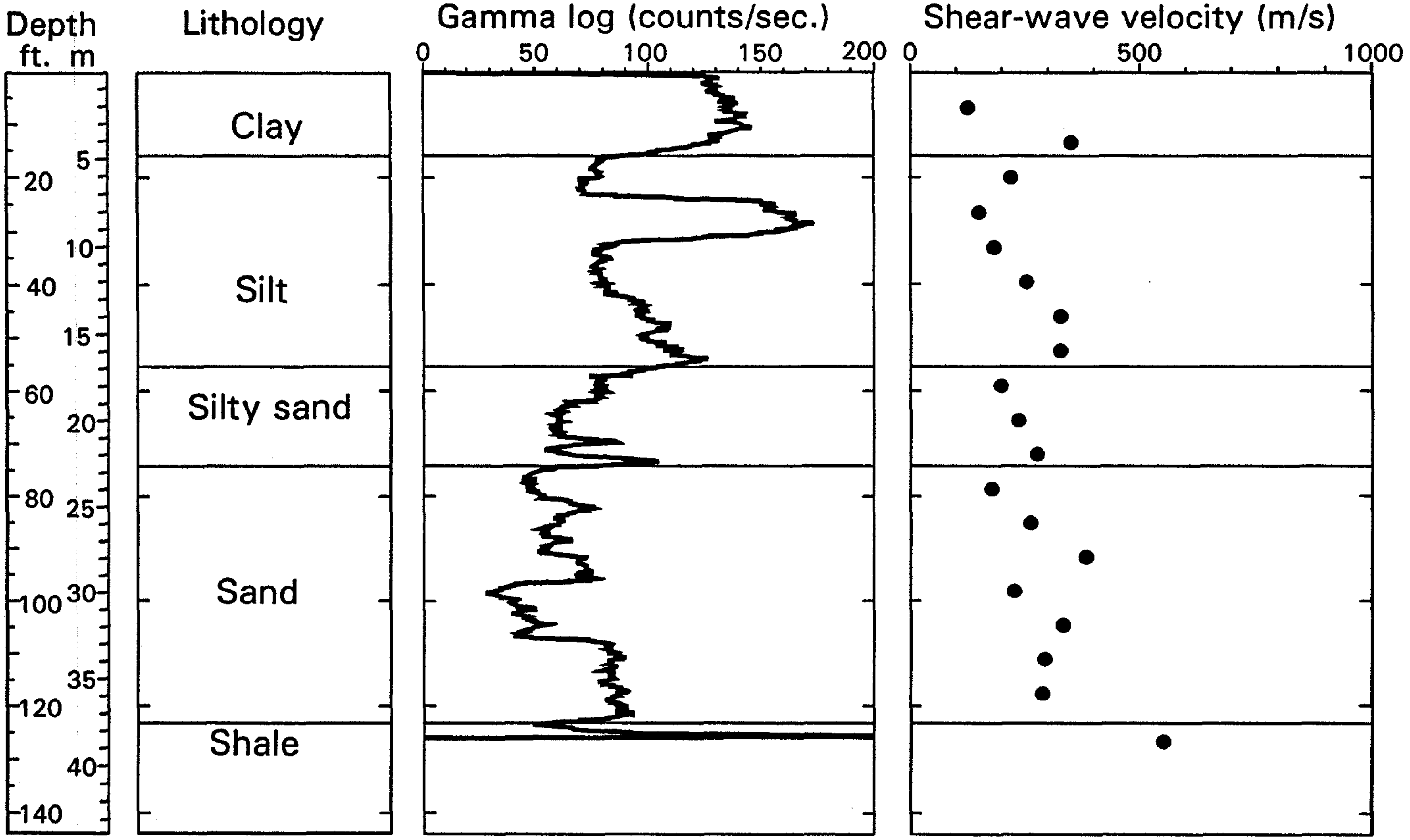
4416 Vogel Road - Evansville #7

Avg. Shear-wave Velocity: 255.5 m/s Soil Period: 0.57 s



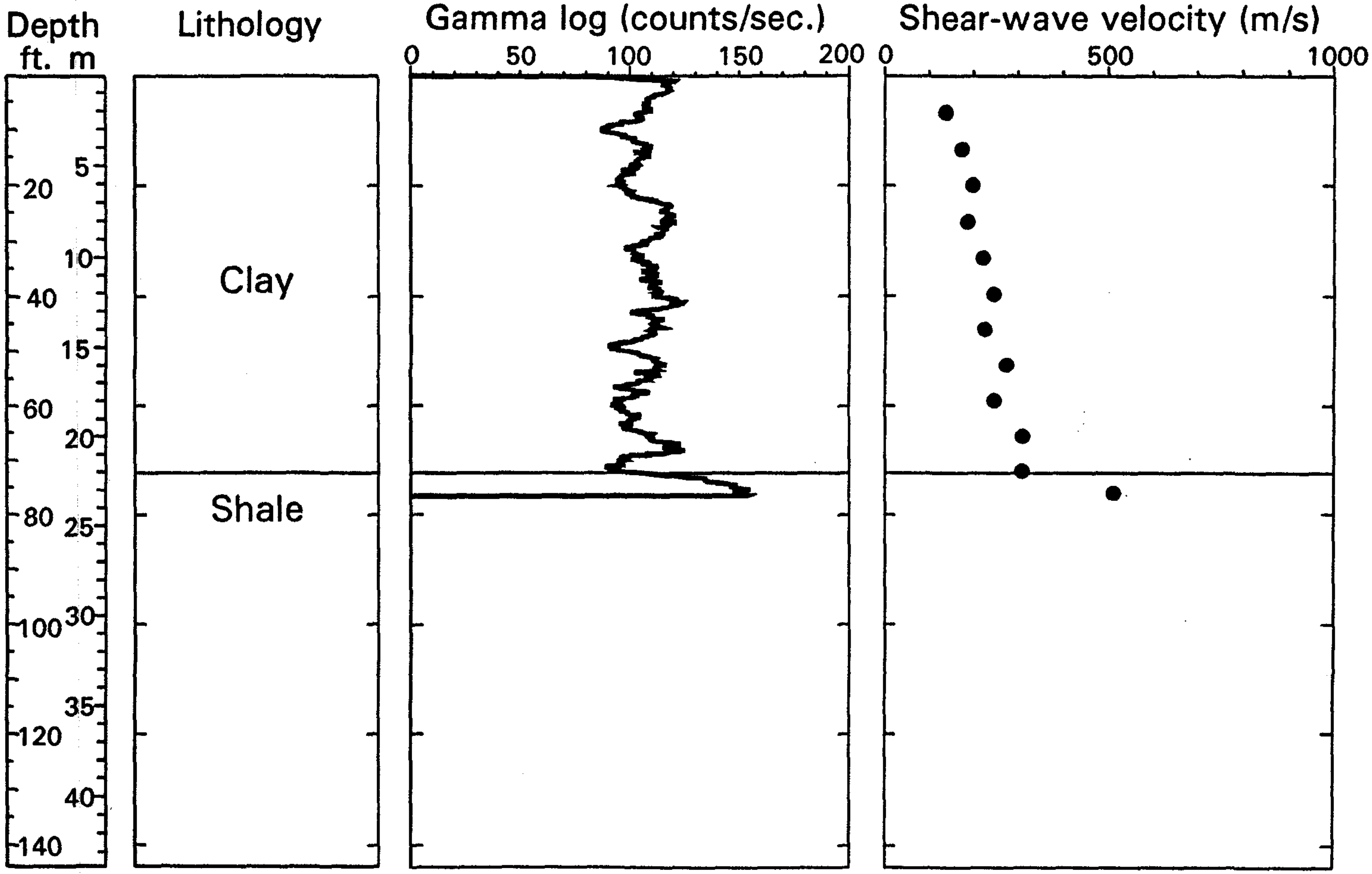
Evansville State Hospital - Evansville #8

Avg. Shear-wave Velocity: 231.8 m/s Soil Period: 0.65 s



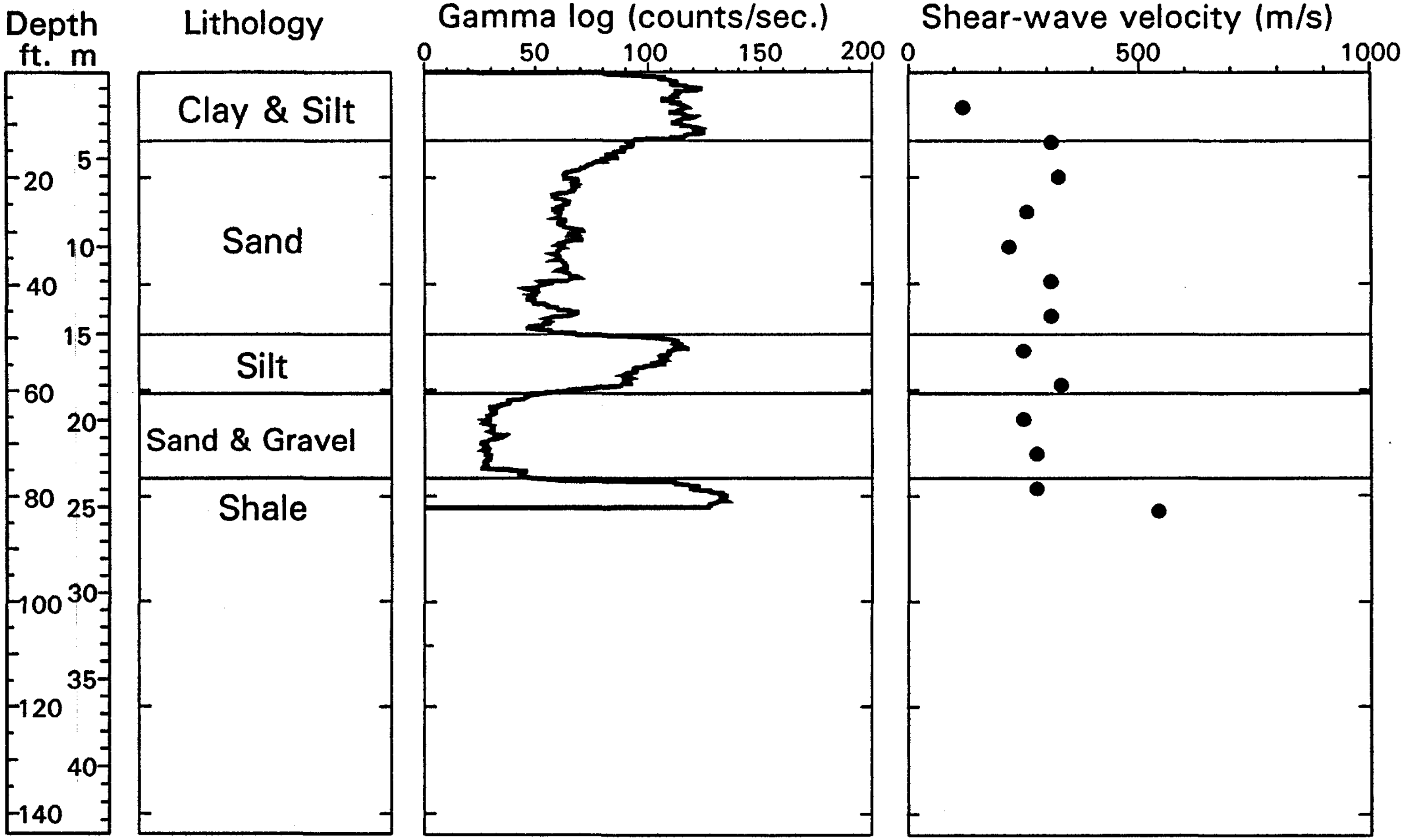
West Side Sewage Treatment Plant - Evansville #9

Avg. Shear-wave Velocity: 217.6 m/s Soil Period: 0.41 s



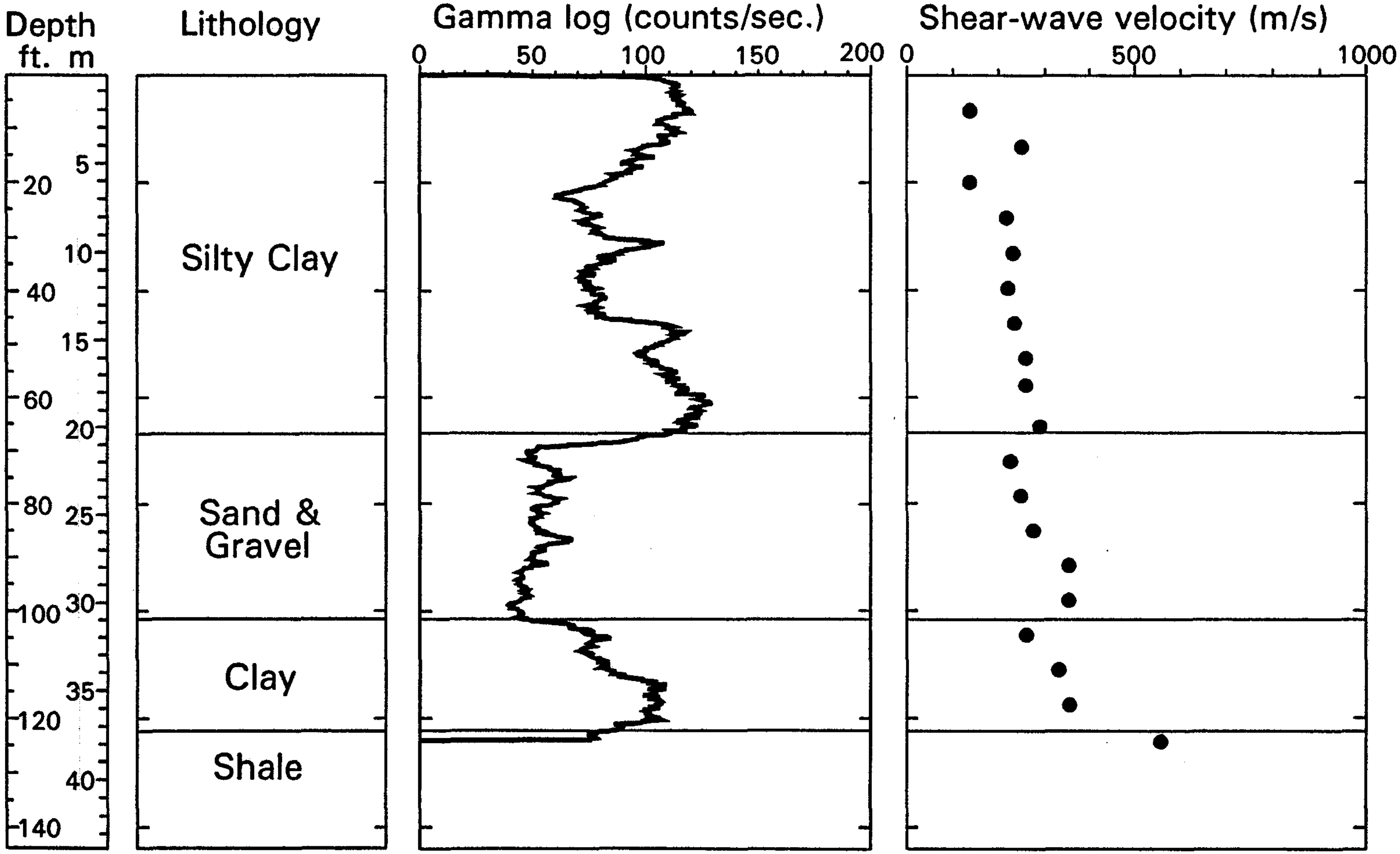
Fulton Park - Evansville #10

Avg. Shear-wave Velocity: 250.9 m/s **Soil Period:** 0.38 s



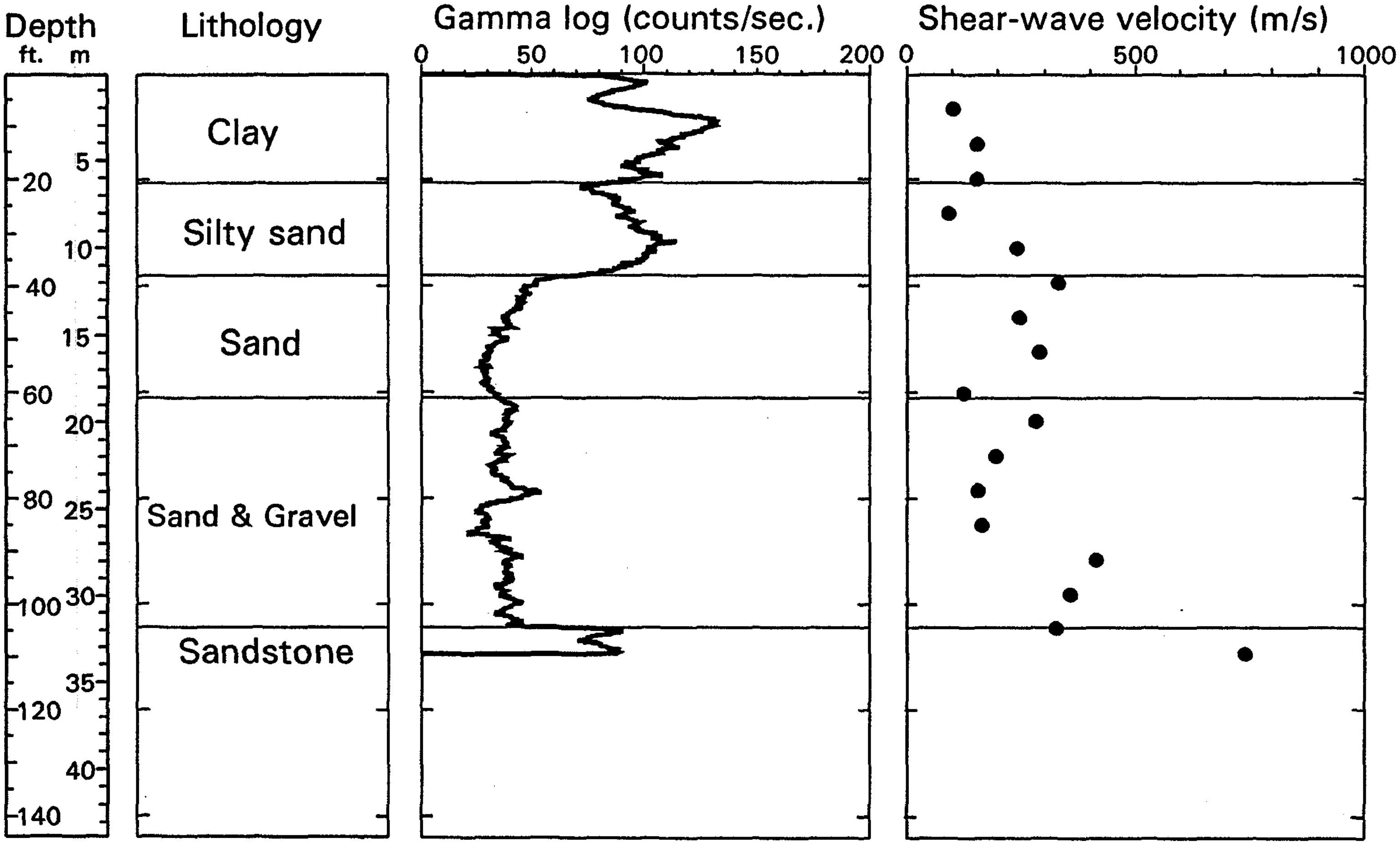
Roberts Stadium - Evansville #11

Avg. Shear-wave Velocity: 241.2 m/s Soil Period: 0.62 s



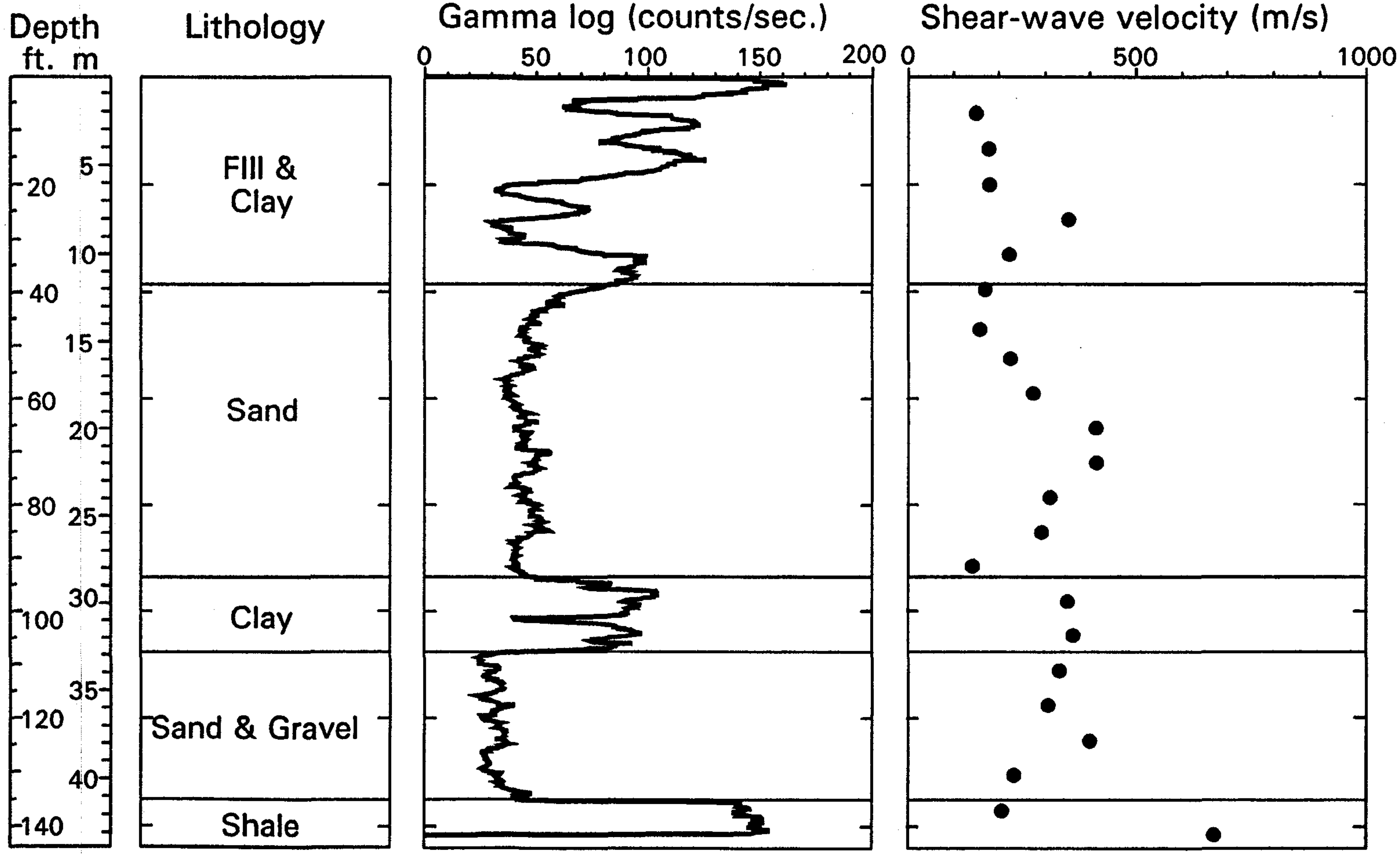
East Side Sewage Treatment Plant - Evansville #12

Avg. Shear-wave Velocity: 186.8 m/s **Soil Period:** 0.69 s



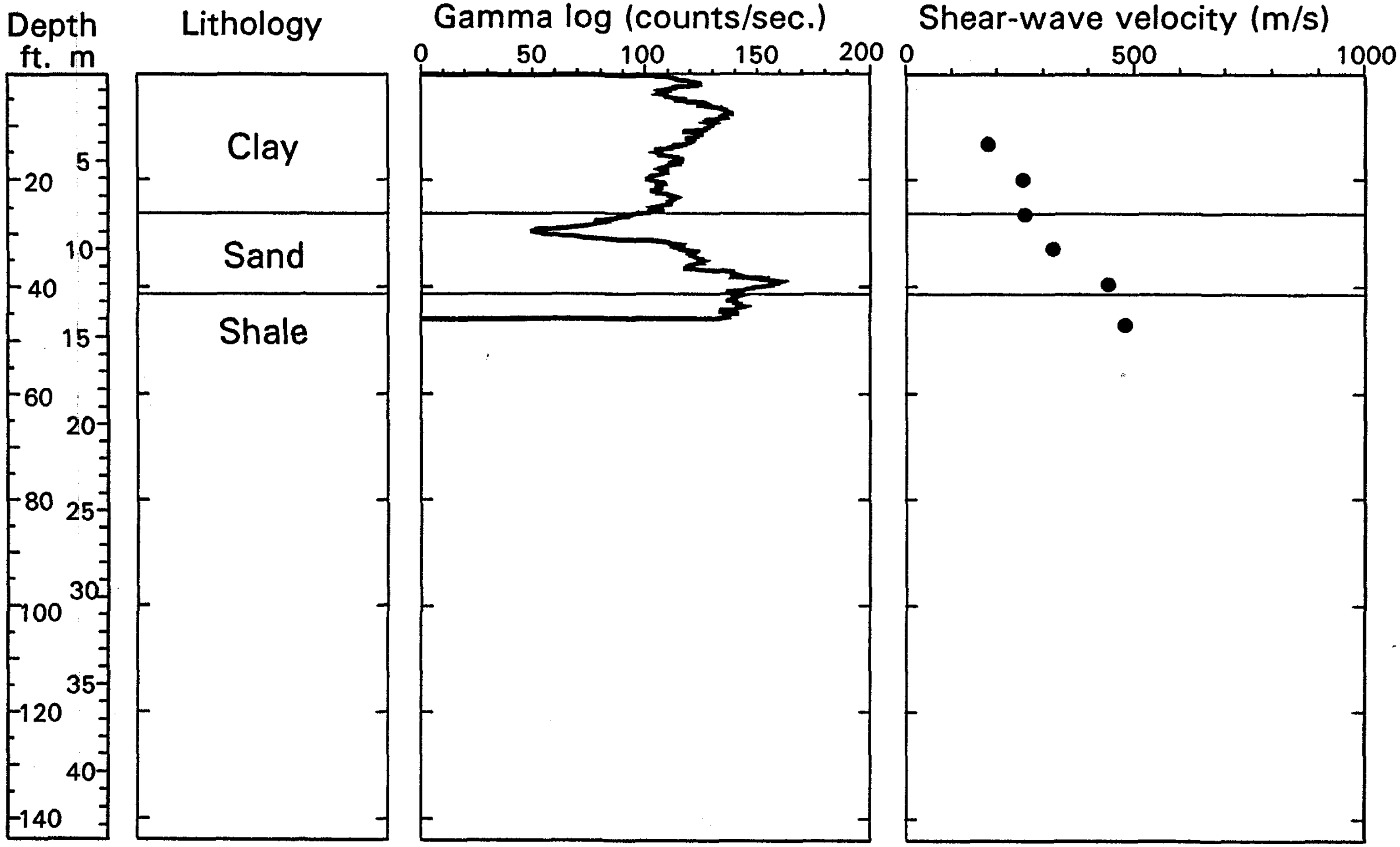
I-164 & US 41 Interchange - Evansville #13

Avg. Shear-wave Velocity: 235.1 m/s **Soil Period:** 0.71 s



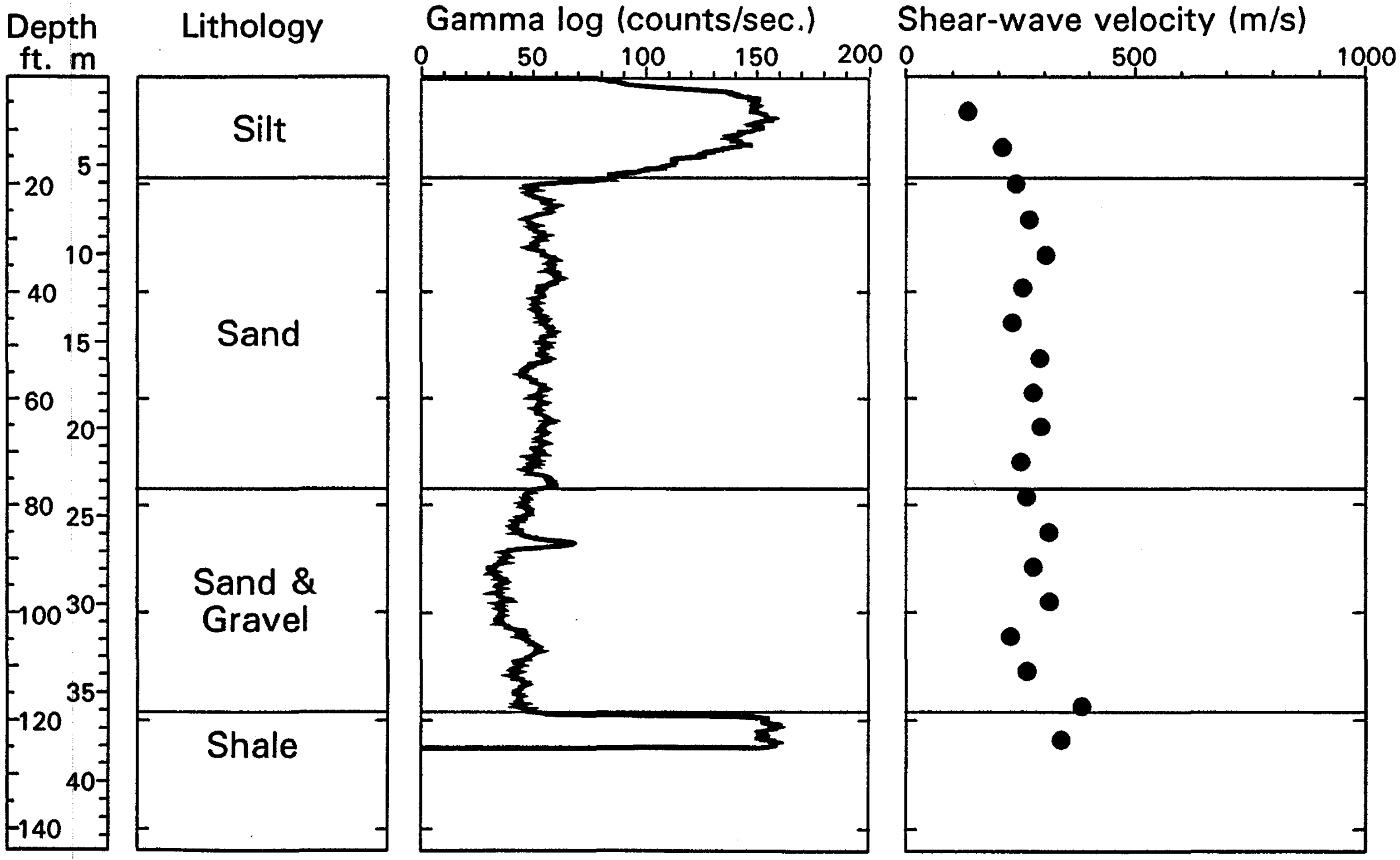
Diamond Valley Park - Evansville #14

Avg. Shear-wave Velocity: 248.4 m/s **Soil Period:** 0.20 s



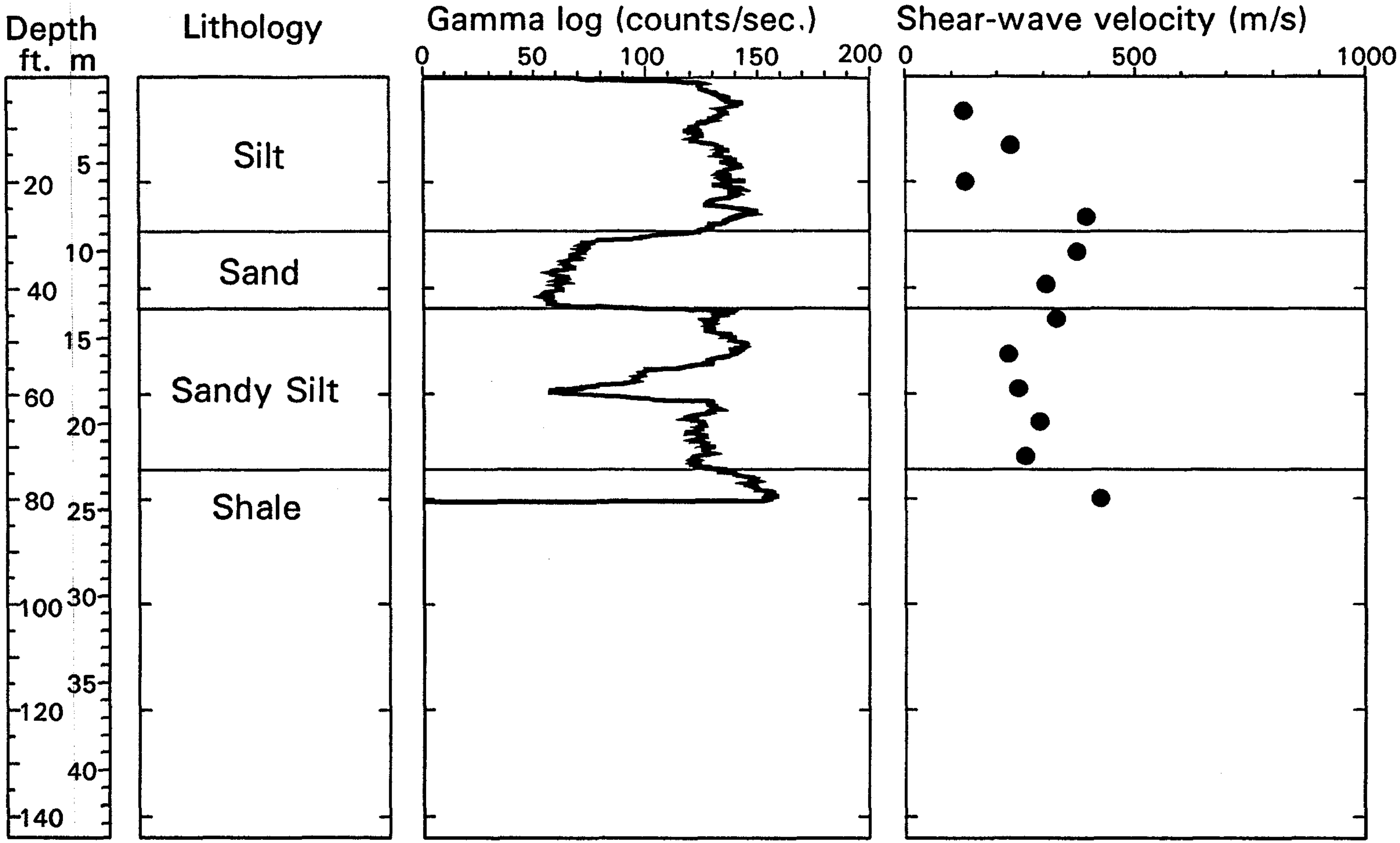
Vann - Pollack Park - Evansville #15

Avg. Shear-wave Velocity: 253.3 m/s Soil Period: 0.57 s



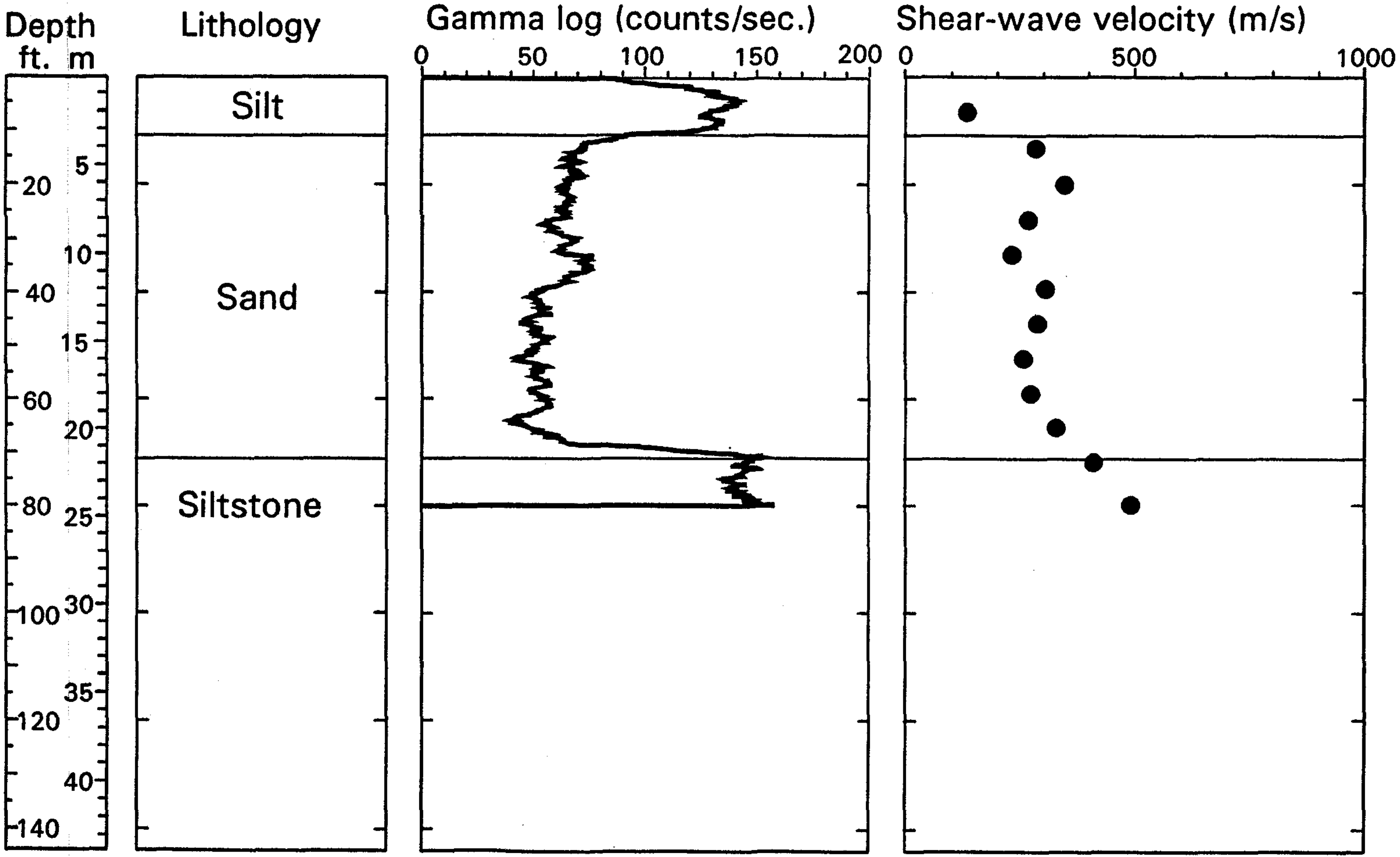
West Side Nut Club Park - Evansville #16

Avg. Shear-wave Velocity: **235.8 m/s** **Soil Period:** **0.38 s**



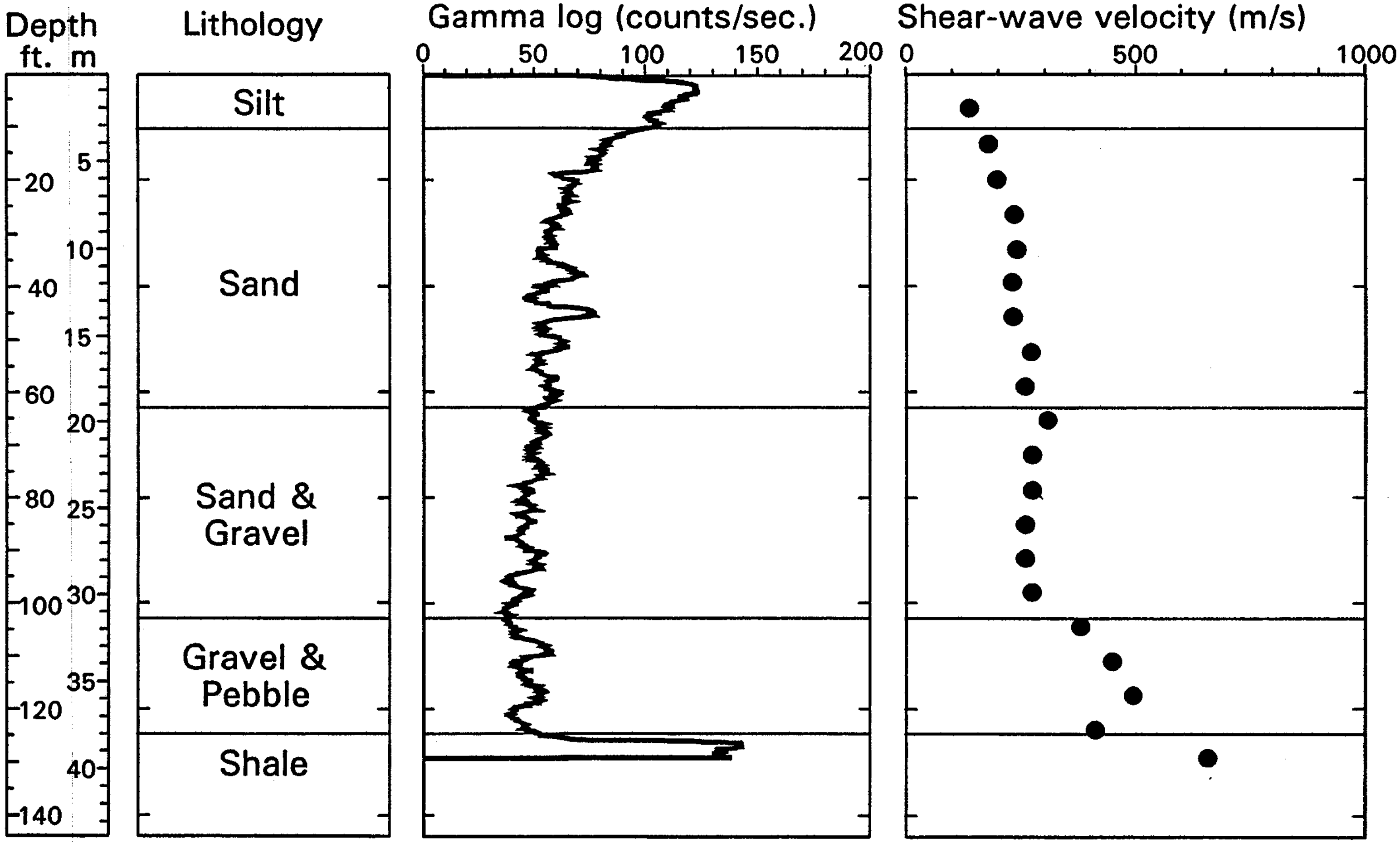
U.S. 41 and Lloyd Expressway - Evansville #17

Avg. Shear-wave Velocity: 259.0 m/s **Soil Period:** 0.33 s



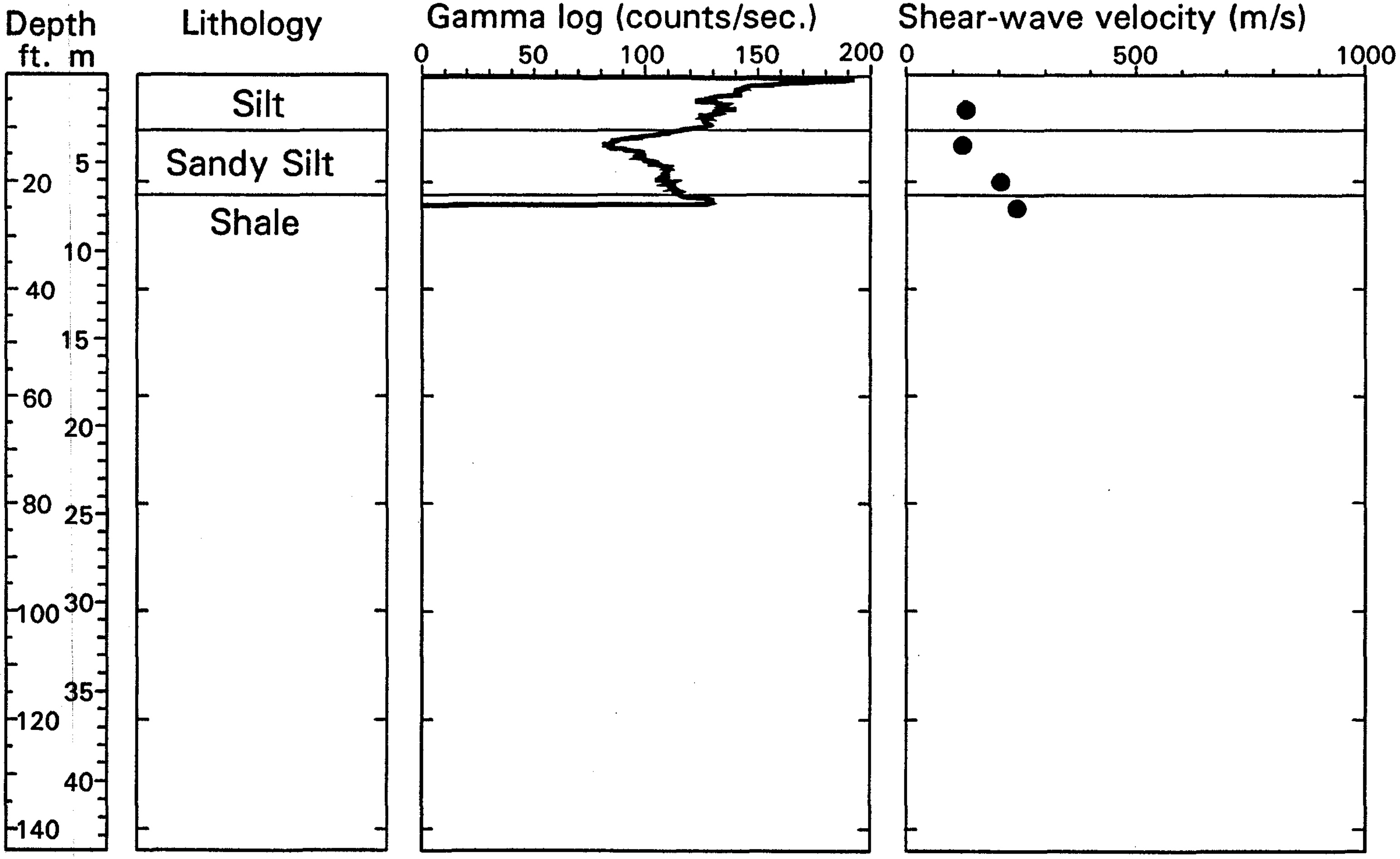
Bayard Park - Evansville #18

Avg. Shear-wave Velocity: 261.6 m/s Soil Period: 0.58 s



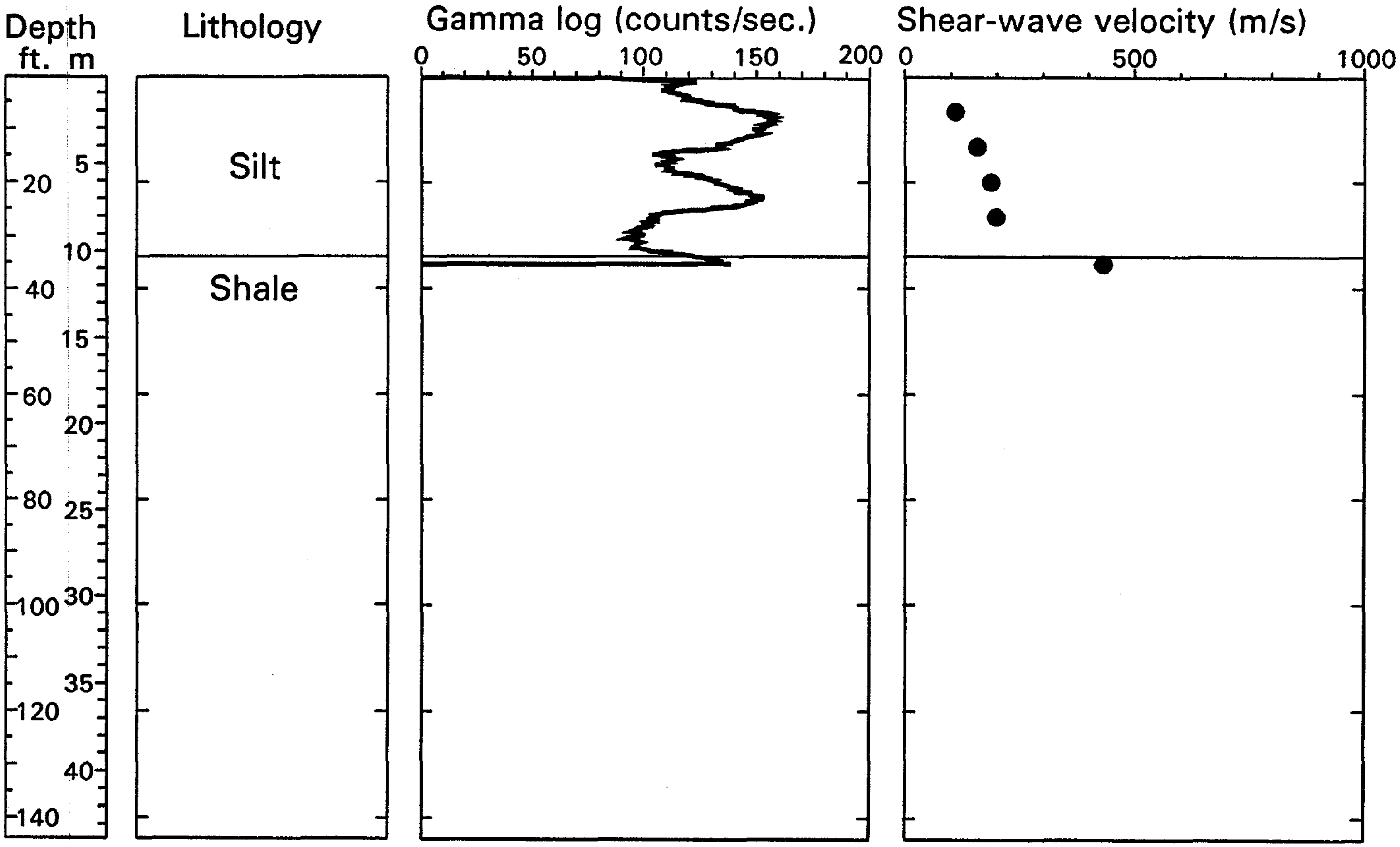
Mater Dei High School - Evansville #20

Avg. Shear-wave Velocity: 160.7 m/s Soil Period: 0.19 s



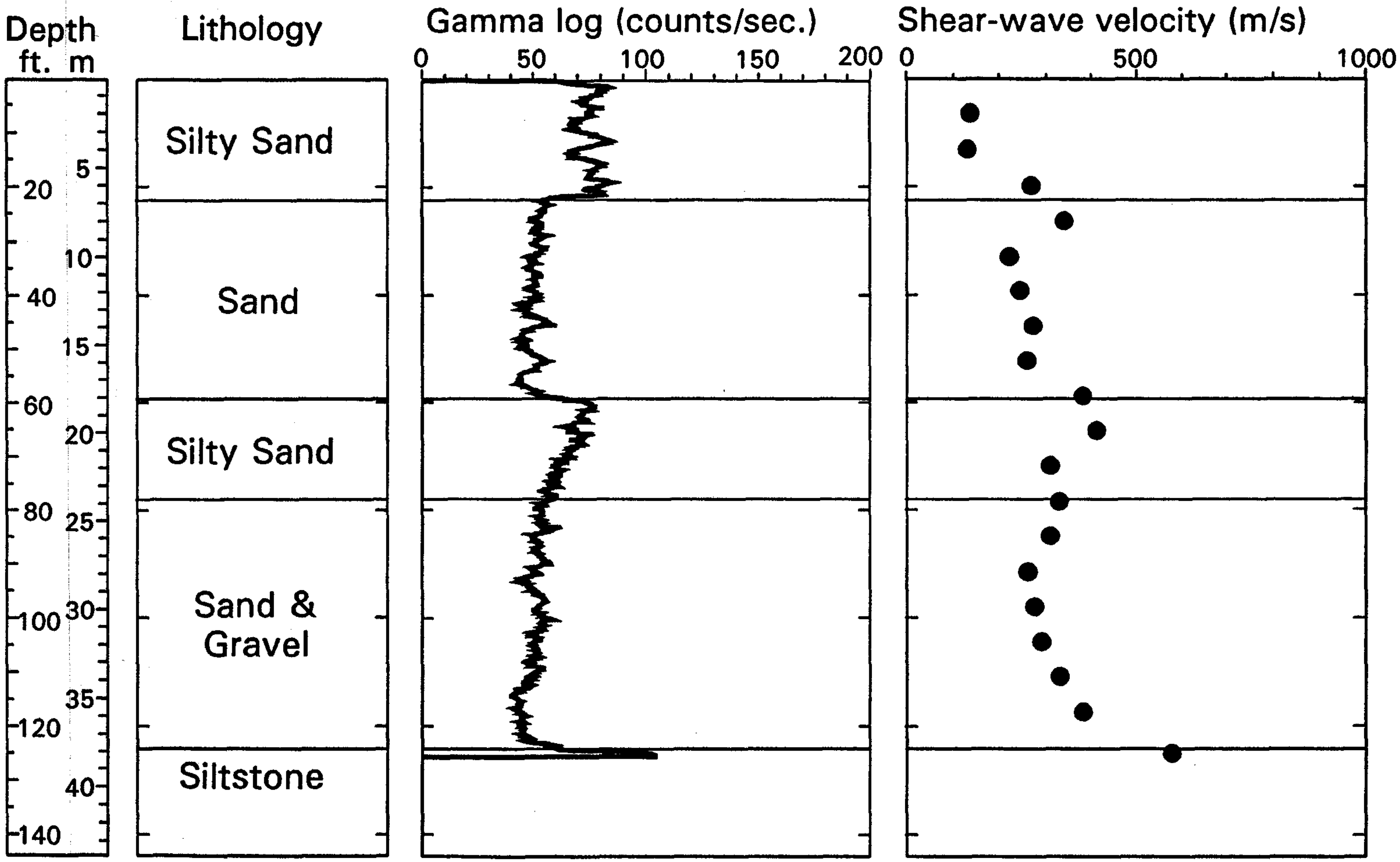
Helfrich Park - Evansville #21

Avg. Shear-wave Velocity: 190.1 m/s Soil Period: 0.23 s



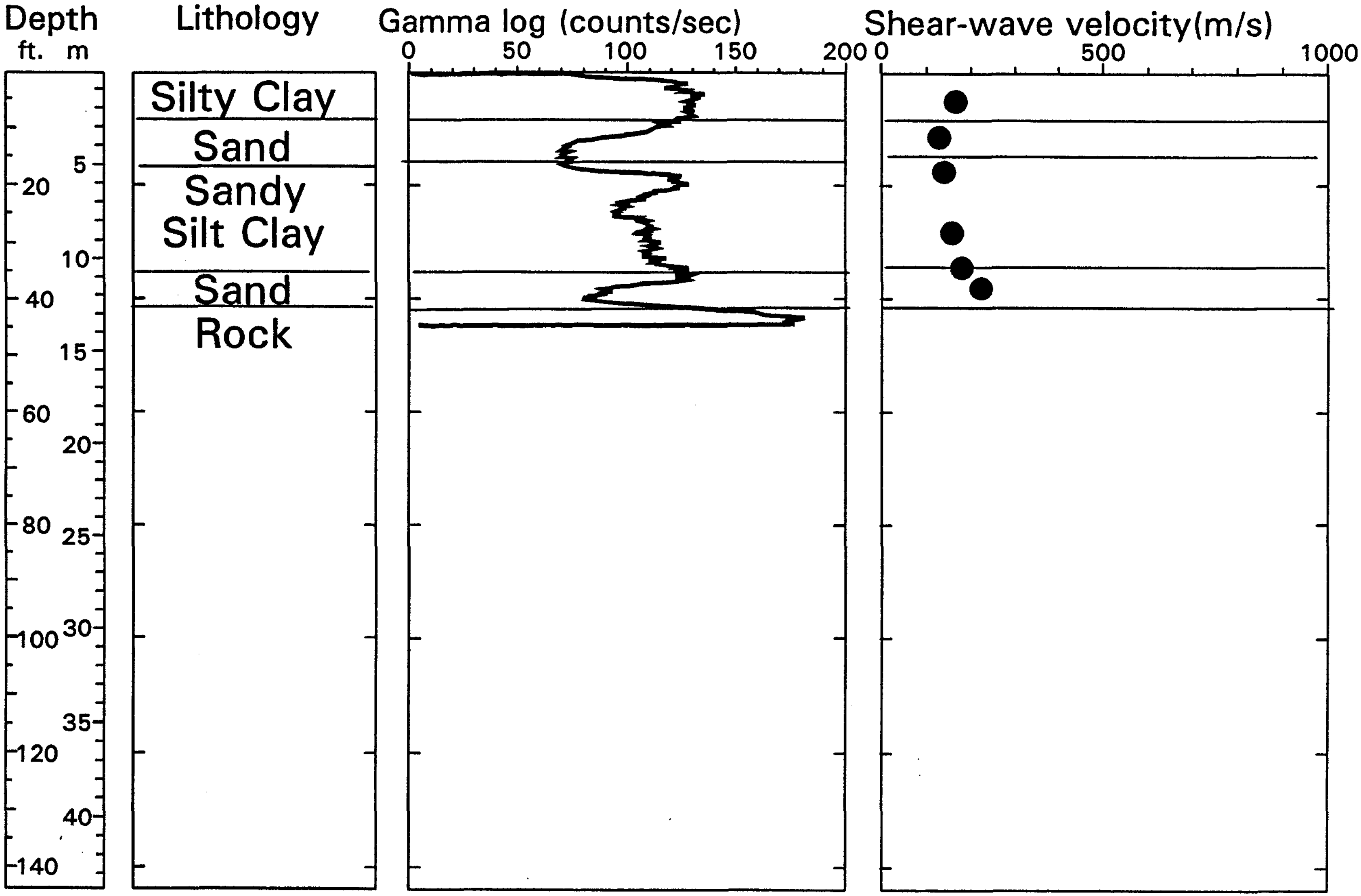
I-164 and Covert Ave. - Evansville #22

Avg. Shear-wave Velocity: **264.5 m/s** **Soil Period:** **0.56 s**



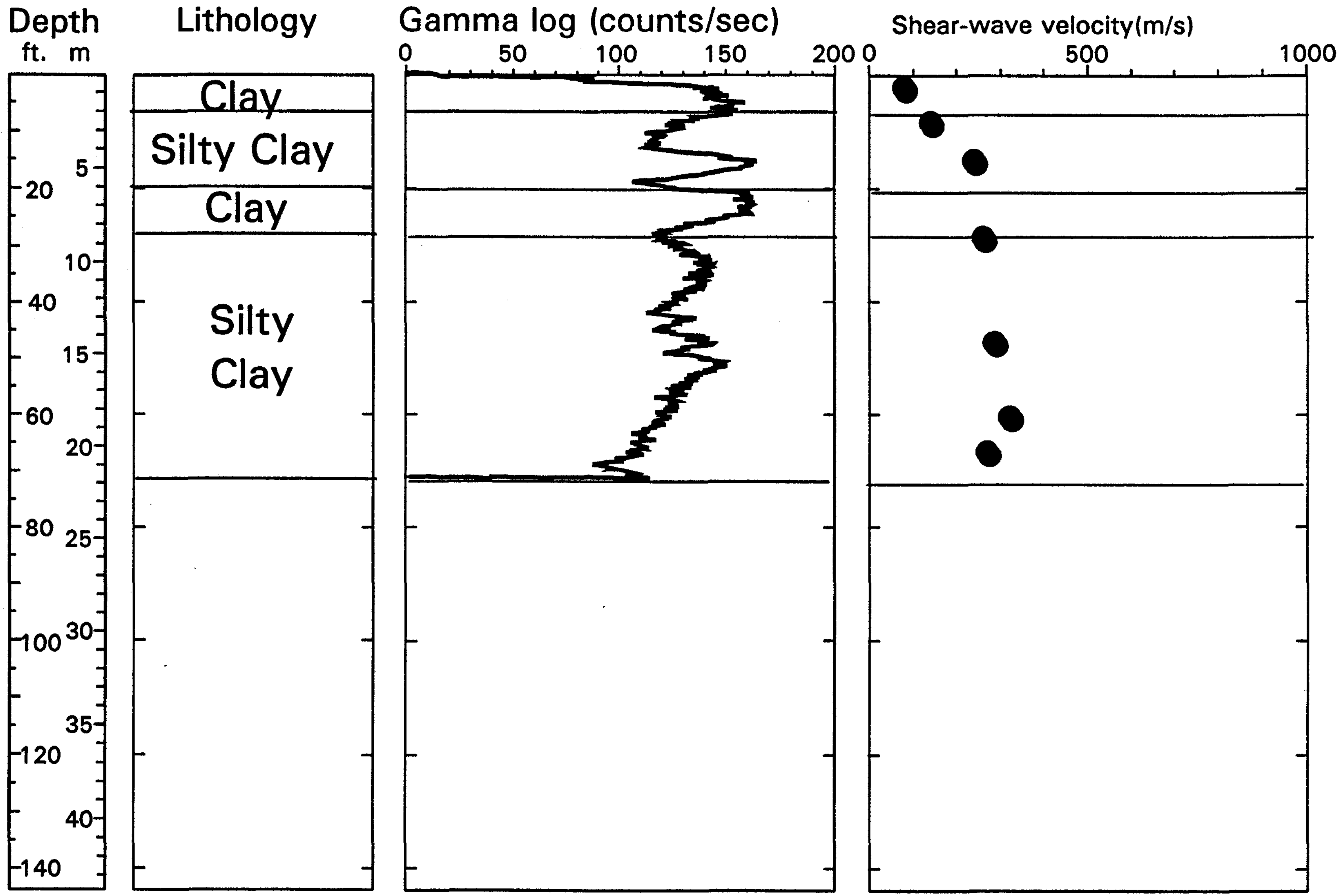
GATEWAY HEALTH CENTER-EV23

Avg. Shear-wave Velocity: 198.4 m/s **Soil Period:** 0.25 s



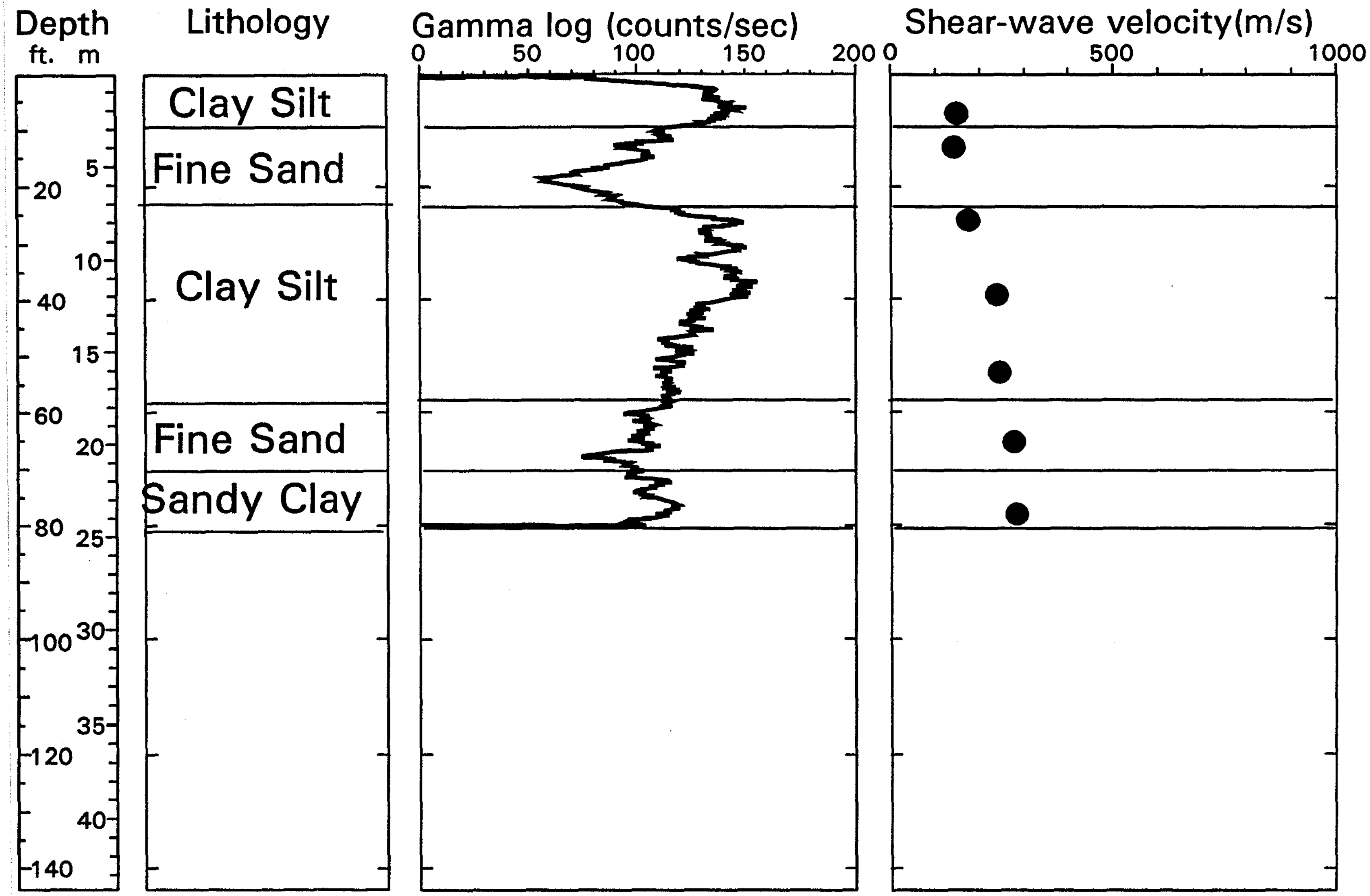
FIRE STATION #2 EV24

Avg. Shear-wave Velocity: 190.3 m/s **Soil Period:** 0.43 s



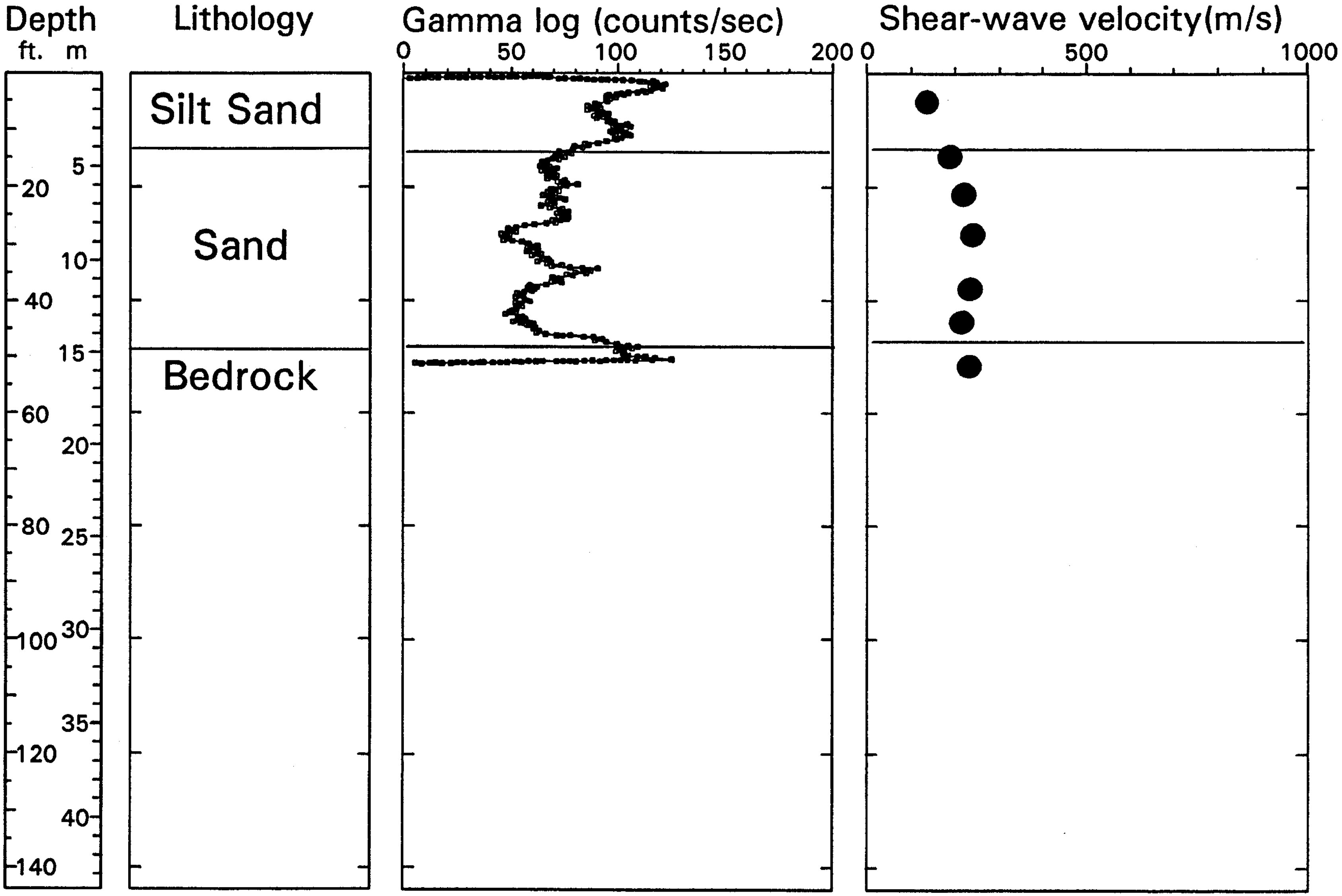
FIRE STATION #4 EV25

Avg. Shear-wave Velocity: 211.0 m/s **Soil Period:** 0.56 s



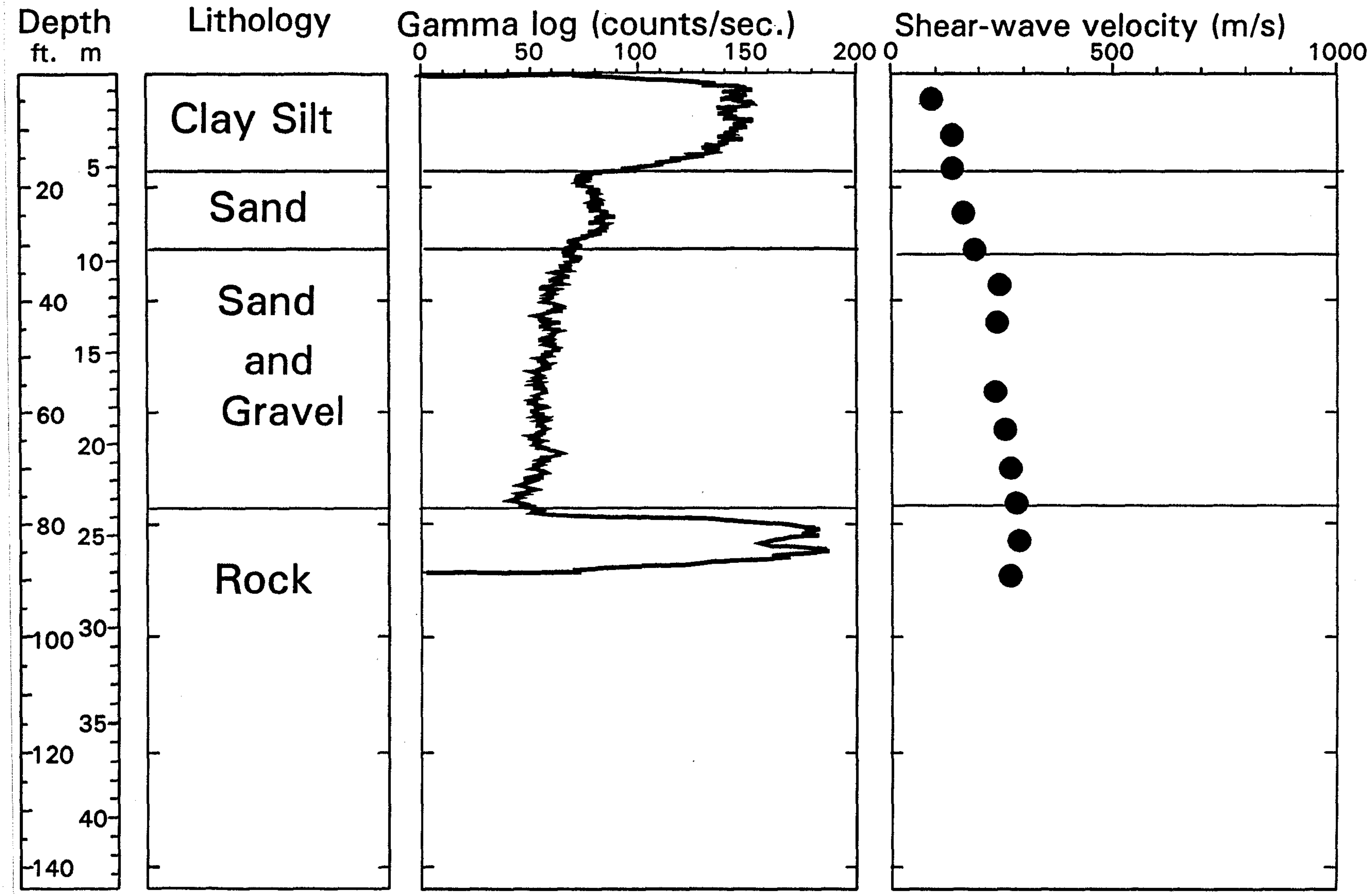
FIRE STATION #6 EV26

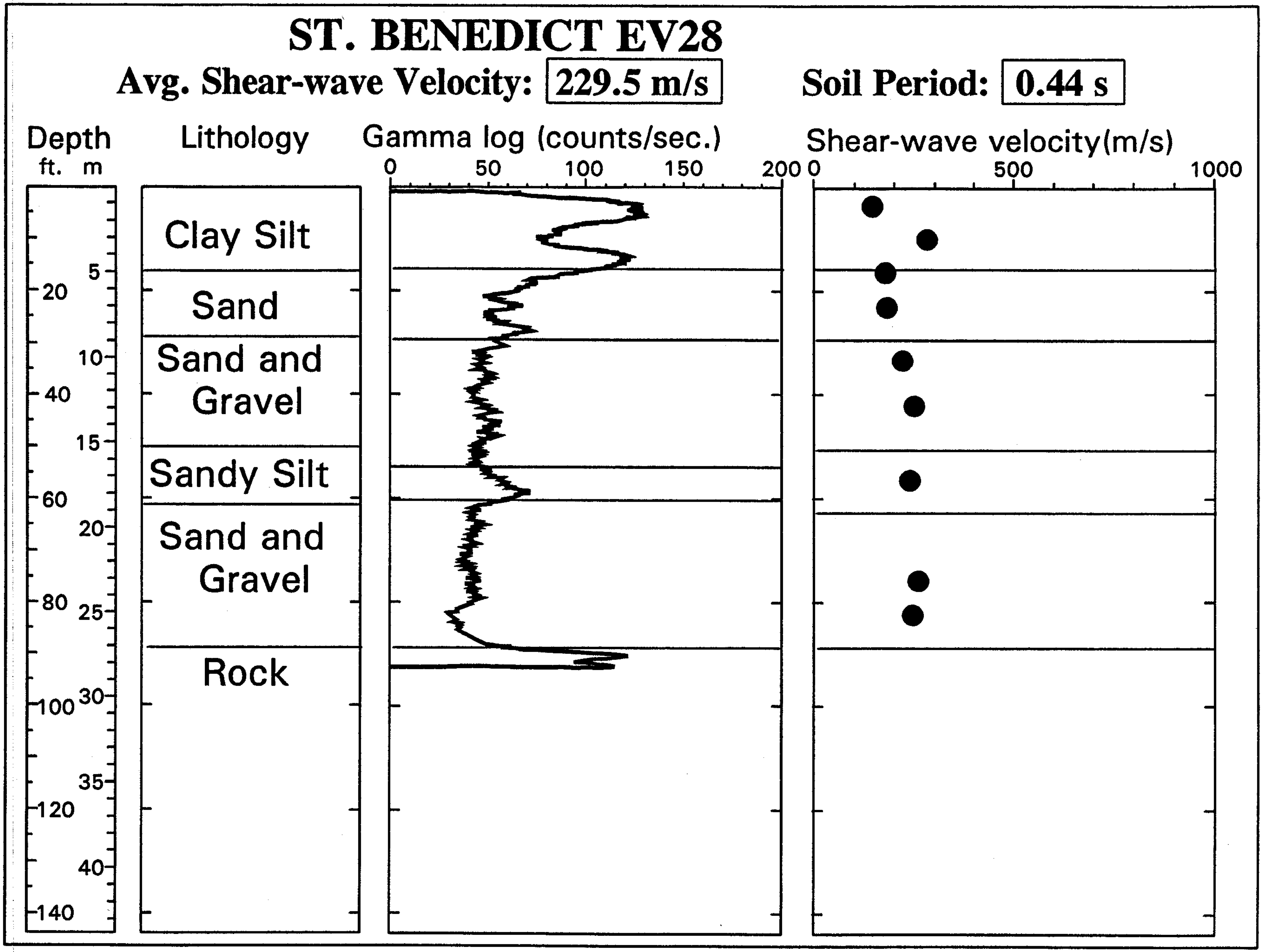
Avg. Shear-wave Velocity: 222.2 m/s **Soil Period:** 0.3 s

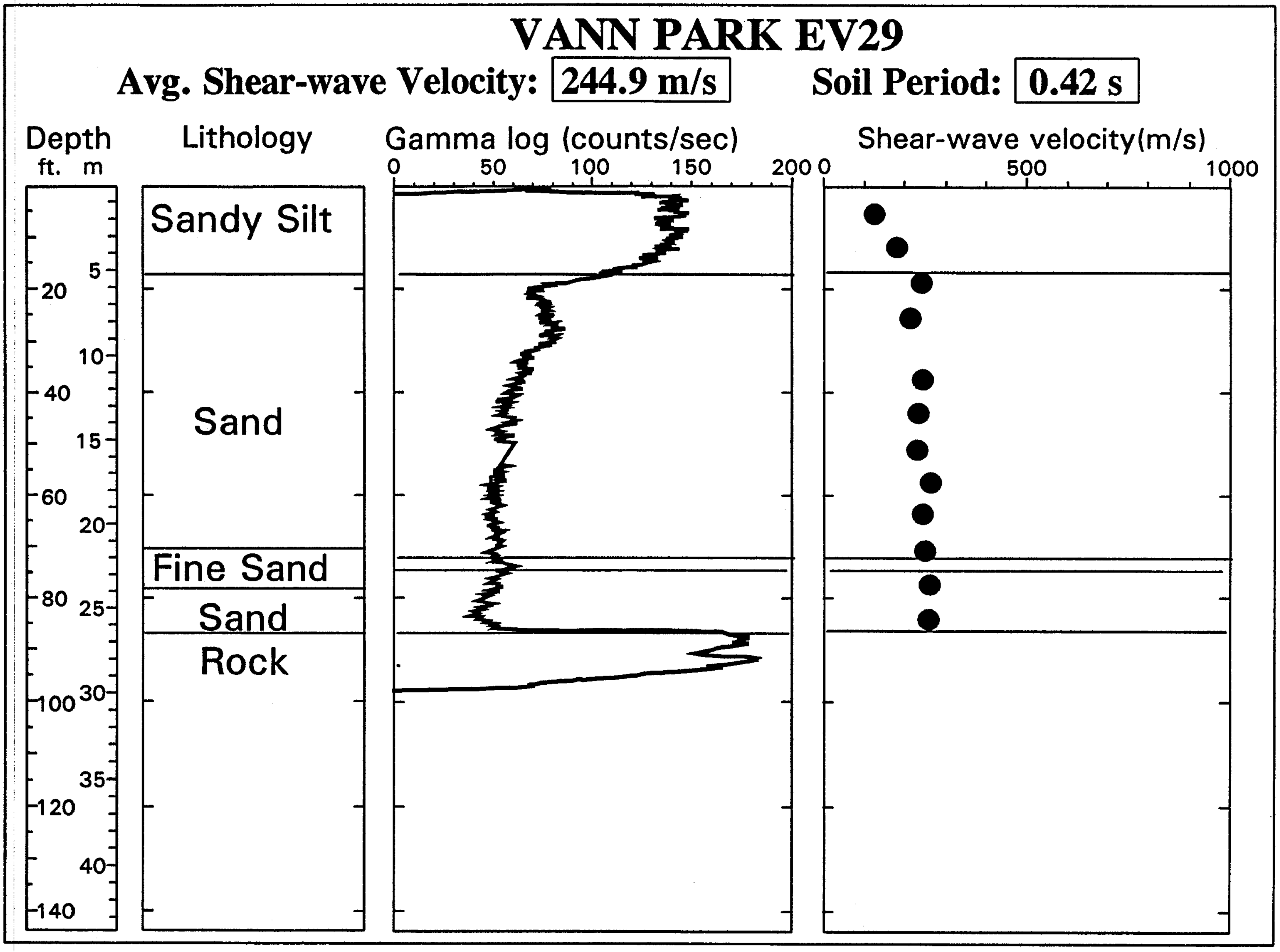


WILLIARD LIBRARY EV27

Avg. Shear-wave Velocity: 269.9 m/s **Soil Period:** 0.43 s




ST. BENEDICT EV28
Avg. Shear-wave Velocity: 229.5 m/s
Soil Period: 0.44 s
Depth
ft.
m
5
20
10
40
15
60
20
80
25
100
30
35
120
40
140
Lithology
Clay Silt
Sand
Sand and Gravel
Sandy Silt
Sand and Gravel
Rock
Gamma log (counts/sec.)
0
50
100
150
200
Shear-wave velocity(m/s)
0
500
1000

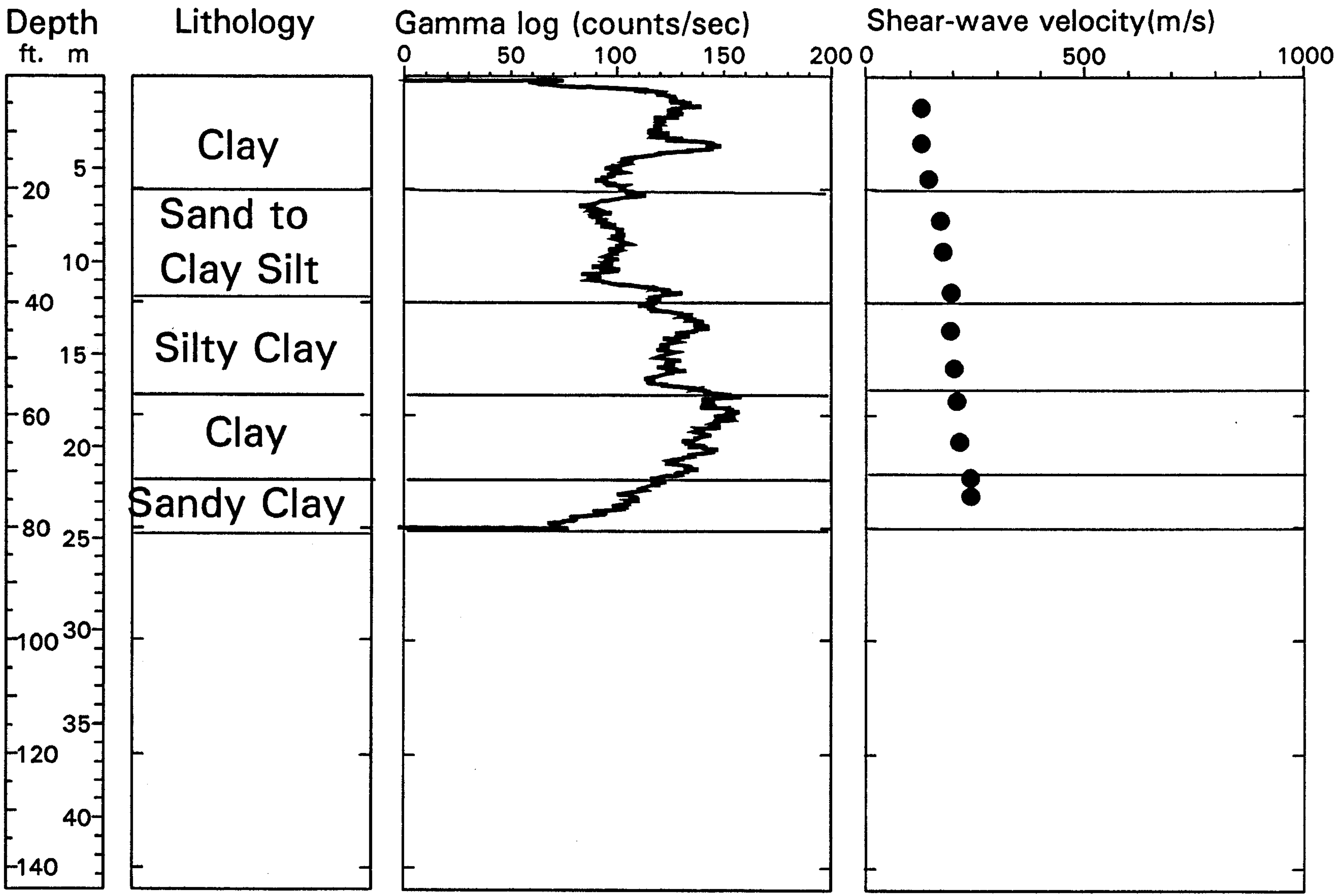


VANN PARK EV29

Avg. Shear-wave Velocity: 244.9 m/s Soil Period: 0.42 s

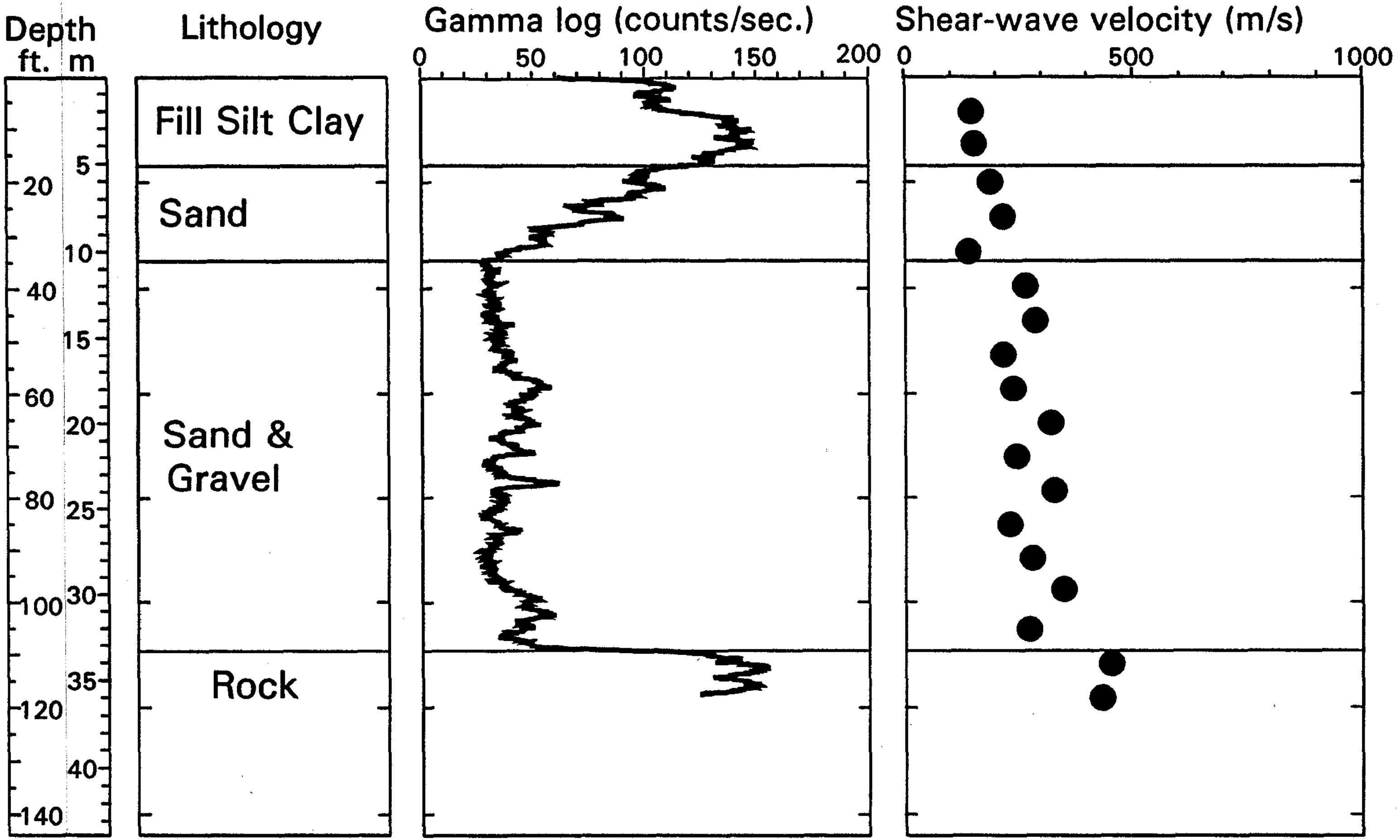
LOUISIANA WAREHOUSE EV30

Avg. Shear-wave Velocity: 201.0 m/s **Soil Period: 0.48 s**



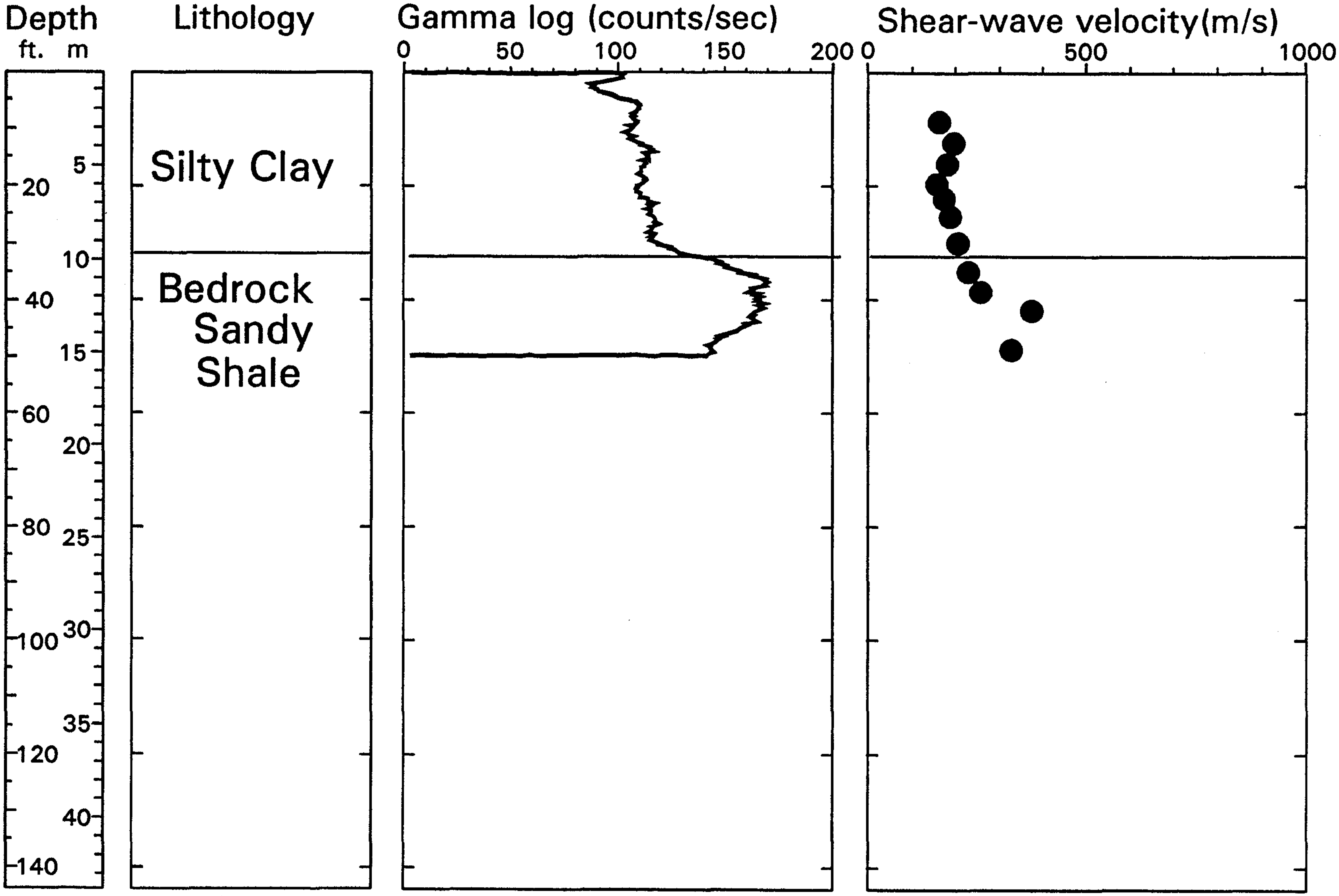
Evansville Water Works Evansille 31

Avg. Shear-wave Velocity: 227.9 m/s Soil Period: 0.6 s



VOLKMAN ROAD EV32

Avg. Shear-wave Velocity: 213.0 m/s **Soil Period:** 0.2 s



Allen Road & Locust Creek EV33

Avg. Shear-wave Velocity: 209.7 **Soil Period:** 0.29s