PART EIGHT

EARTH MODELS

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PART EIGHT

EARTH MODELS

Arthur D. Little, Inc.

I. INTRODUCTION

The question of earth models has repeatedly arisen in our work. An accurate representation of the seismic properties is required for three reasons:

1. To be able to determine from a set of received arrival times, the location of a seismic source in the earth, and secondly the degree of accuracy required in the model used for calculating source location from the set of arrival time differences.
2. To be able to determine the expected arrival times at an array of geophones produced in response to a hypothetical source in the earth.
3. To be able to estimate received signal strengths more accurately.

The work reported here on earth models is based on information from several consultants and from others who expressed an interest in the problem and supplied information to us.

II. COAL MINE GEOLOGY

On one of our earlier assignments for the Bureau of Mines, Earth Science Research Inc. of Cambridge, Massachusetts prepared for us a short description of the lithology to be expected at coal mine sites. This description follows, together with the ranges of compressional seismic velocities (Figure 1*) associated with typical materials comprising the layered structure of a coal mine area.

Coal is primarily associated with fresh water sediments including sandstones, shales, and clays, and occasionally may be metamorphased to varying degrees. In the Appalachian Basin the coal beds occur within cyclical sequences of non-marine shales, sandstones, conglomerates, limestones, and clays. The beds range in thickness from a few inches to 60 feet, averaging between 2 feet and 10 feet. They have generally broad areal extent, occasionally up to 5,000 square miles, and have an overall tabular or lens-like shape. Within a particular lens, local changes in thickness are normal.

* References to Figures, Tables, and Equations apply to those in this Part unless otherwise noted.

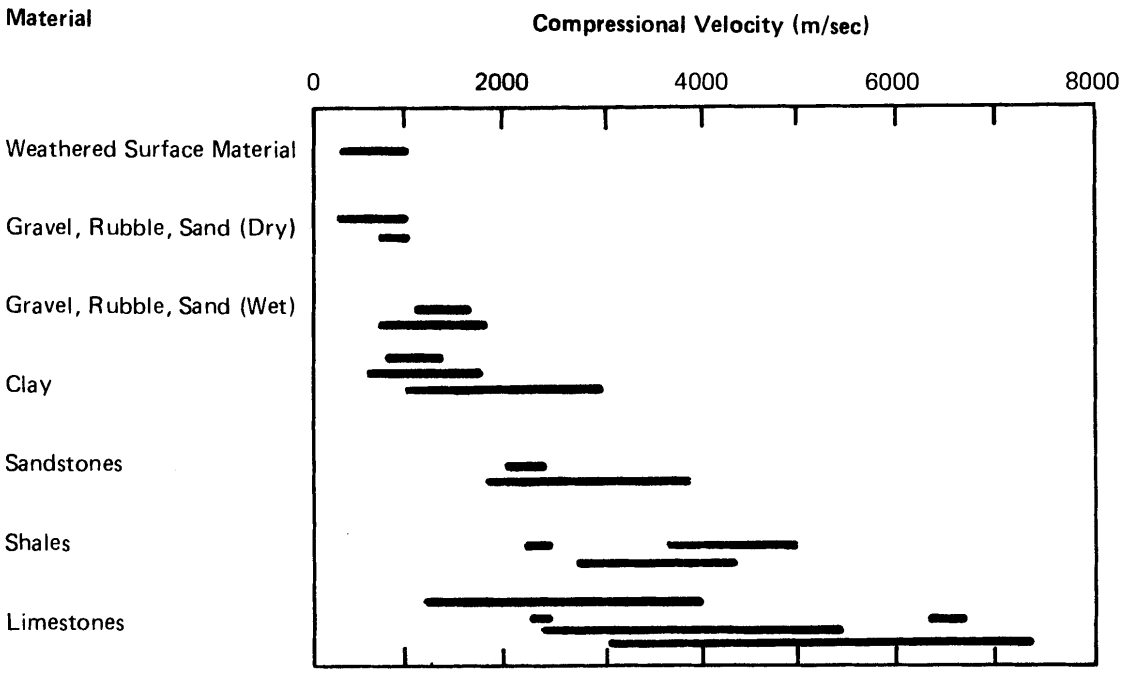


FIGURE 1 COMPRESSIONAL VELOCITIES FOR TYPICAL OVERBURDEN MATERIALS

Coal beds typically contain thin bands of clay, shale, fine grained or nodular pyrite, marcasite, and siderite. Graphite is also prevalent with the content depending on the degree of metamorphism. In the steeply folded rocks of the anthracite region in northern Pennsylvania, which have undergone dynamic metamorphism, the graphite content is above average.

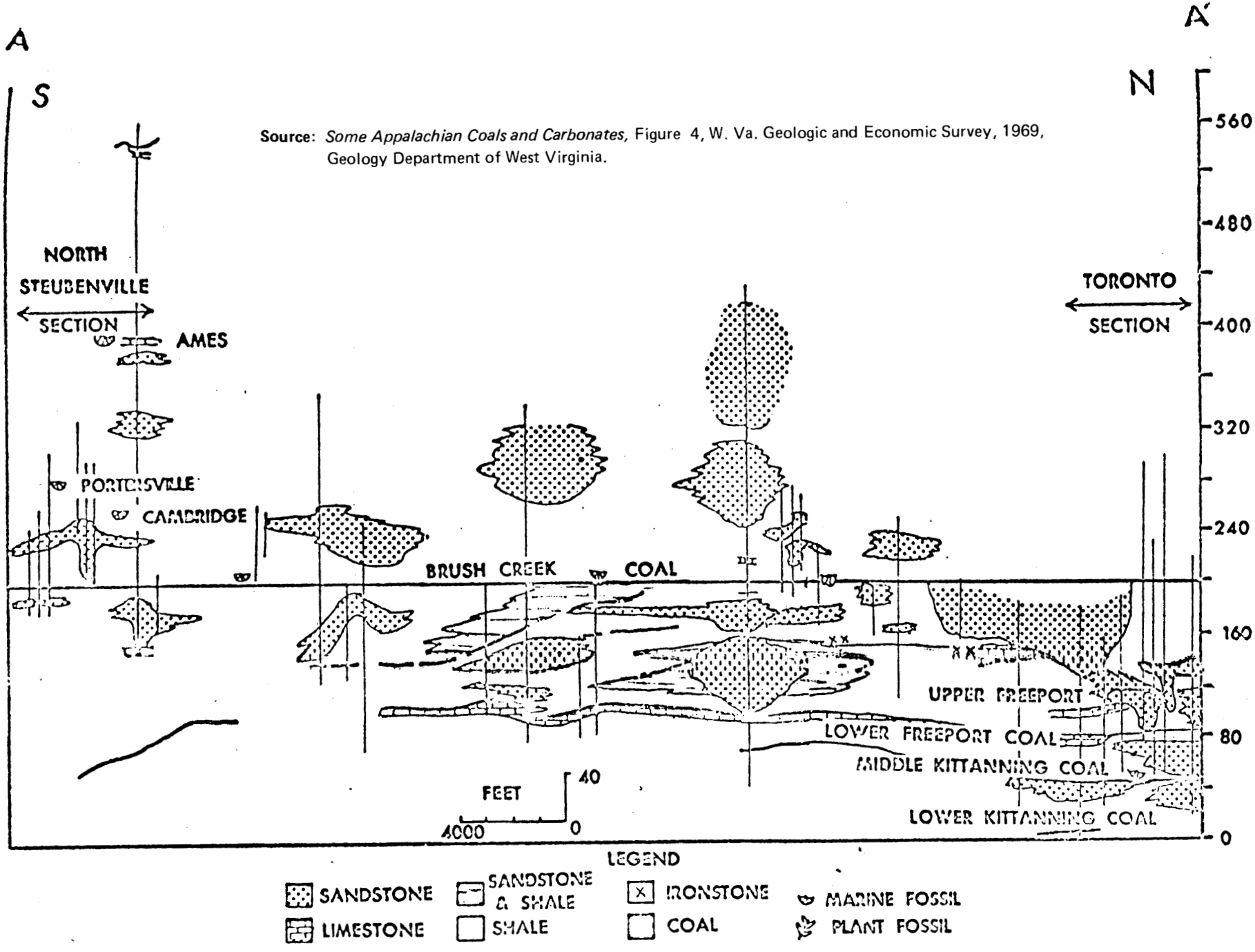
Cyclothems are cyclical sequence deposits which repeat in succession throughout the geologic column of a coal basin. When ideally developed, a typical cyclothem, starting with the oldest beds, is as follows:

1. Fine grained micaceous sandstone and siltstone grading into conglomerate varying from thin to massive bedded, in which occasional plants are found.
2. Grey sandy shale which often contains ironstone concretions.
3. Fresh water limestone occurring as nodules or discontinuous beds.
4. An underclay, medium or light grey in color and somewhat calcareous.
5. Coal seam.
6. Grey shale with pyritic nodules and ironstone concretions towards the base. Fossils are rare.
7. Marine limestone.
8. Black laminated shale with large concretions and often fossiliferous.
9. Marine limestone with fossils.
10. Grey sandy shale or shaly sandstone often grading into conglomerates. The shales may have fossils and sometimes ironstone concretions.

Part or all of this sequence may be repeated many times in the coal series.

J. Powell of the U.S. Bureau of Mines has conducted an investigation of coal mine geology for this present investigation. Utilizing data obtained from References (1), (2), and (3) and information supplied by Mr. George Smith, a geologist with U.S. Steel, Powell concludes:

1. Geologic strata are usually horizontal, a slope of 100 feet per mile would be unusually large.
2. Although the strata are horizontal, they often pinch out or grade into different rock types.
3. The outstanding example of this pinch-out would be sand and gravel deposits laid down in stream beds. In cross section, a bed may be tens of feet thick in one spot and have disappeared completely a few hundred feet away as shown in Figure 2.
4. Geologic cross sections keep their general characteristics for distances of several miles. For example, if most of the overburden at point A is limestone, most of the overburden at a point 2 miles east of A will probably be limestone.
5. Geologic sections can change considerably over a distance of ten miles. To continue the above example, the overburden at a point 10 miles east of A could well be shale.
6. Items 4 and 5 above indicate that for many mines (i.e., those which could be contained within a square a few miles on a side) there exists much common geology.
7. In Pennsylvania and northern West Virginia, there is little faulting. As one goes south faulting becomes more common. In western Kentucky faults with vertical displacements of tens of feet are not unusual.
8. Coal is one of the most persistent beds; that is, in general a coal bed will continue for greater distances than other rock beds.



Source: *Some Appalachian Coals and Carbonates,* Figure 4, W. Va. Geologic and Economic Survey, 1969, Geology Department of West Virginia.

FIGURE 2 STRATIGRAPHIC CROSS SECTION FROM STEUBENVILLE TO TORONTO USING THE BRUSH CREEK COAL AS THE DATUM

From these data and descriptions some general comments can be made. Seismic compressional velocities in the regions of the earth through which a miner's signal must travel, from the mine tunnel area to the surface, will range from that of limestone (as high as 14,000 feet per second) to that of the weathered layer (as low as 500 feet per second). It will generally be true that the higher velocities will be encountered at the greater depths and the lower velocities near the surface. The extreme range of compressional velocities encountered suggests that accurate knowledge of the velocity profile in the region under which the miner is trapped may be required in order to perform accurate location calculations based on arrival time differences.

III. BASIC SEISMIC DATA REQUIRED

If the arrival times are perfectly obtained, then the accuracy of the location is dependent on the accuracy of the model used to represent the earth in the computation of location. Elsewhere in this Volume, Crosson and Peters, and Powell, treat the effect of model errors on location errors. These analyses compare hypothetical laterally homogeneous, horizontally layered earths represented by similarly layered models or continuous models where the seismic velocity increases linearly with depth, and homogeneous half-spaces. These two studies show that the location errors that can be assigned to model errors of this class are much less than the errors experienced with the present seismic location system. This suggests several possibilities:

1. Horizontally layered earth models may be inadequate to represent the real earth.
2. Gross timing errors may have been introduced by the system instrumentation and/or by operator misinterpretation of the seismic recordings.
3. The depth of the weathered layers under the receiving geophones may not be properly taken into account with the present system.
4. Source cavity-produced errors may be present and unaccounted for.
5. Survey errors may have been large.

We are concerned here only with the possible inadequacies of the earth models used to date. It is not possible to say at present what effects gross model errors have, because the seismic properties of the real earth over coal mines are not adequately known. This lack of knowledge emphasizes the need for comprehensive seismic surveys at a few eastern coal mine sites.* These comprehensive tests would reveal what properties of the real earth need to be included in the model, in order to make the model errors small enough to reach the desired location accuracy. The survey tests are outlined elsewhere in this report but would include:

- Surface refraction surveys configured to yield layer data to at least the working depth of the mine.
- High resolution vertical reflection surveys to substantiate the refraction survey and/or identify spatially varying layer properties.
- Core holes with geological logging.
- Core hole to core hole velocity measurements to substantiate larger velocity properties.
- Arrival time plots from mine located impulsive sources as an additional confirmation of seismic properties.
- Precise measurement of weathered layered thickness at seismometer positions.

One of the objectives of this comprehensive seismic survey is to establish if a surface seismic survey can provide adequate detail for the preparation of a sufficiently accurate earth model for location computation purposes. Our discussions with persons experienced in surface refraction surveys[(4)] indicates that a careful refraction survey done by an experienced survey team can identify well defined layer boundaries to within a few feet to depths near a thousand feet, and that seismic velocities can be measured to within a few percent. The work of Crosson and Peters indicates the degree of location accuracy that would result for models of this accuracy. In addition to undertaking conventional refraction surveys, it may be desirable to consider the technique of Donath and Kuo[(5)] as discussed below.

The method of refraction surveys for determining the seismic velocity structure of the earth, which is based on fitting straight lines through sets of points on a distance versus arrival time plot, is geared to the specification of plane layered models of the earth. It will not pick up features such as varying layer thicknesses or fractures. However, it is possible to interpret refraction survey data in a more sophisticated manner to reflect, if appropriate,

* See Appendix A.

the complex nature of the underlying structure. The construction of wavefront diagrams (Donath and Kuo) enables observed travel-time curves to be fitted well when discontinuities or tilts in the topography are present. This type of interpretation of refraction data can be accomplished by a computer program implementable on a minicomputer.

It should be noted that refraction methods do not always give a unique solution and that their interpretation depends on knowledge of the general geological environment as well as on geometrical solution of the travel-time curves. The accuracy with which velocity models can be determined in Eastern coal mining regions, and the need for the wavefront, as against the straightforward, methods of interpretation of refraction surveys in these areas, are matters ultimately to be resolved by controlled field measurements. It can be estimated however, that velocity models should be measurable to within a few percent.

The conduct of the comprehensive seismic survey and the analysis of the data obtained should provide answers to a number of questions that have been raised. Among these questions are: Are earth properties other than horizontal layering of importance to location? Is there any velocity anisotropy of importance? What ranges do the velocity profiles occupy? Can a simple earth model suffice for most mines? Is a simple surface survey adequate to characterize the underlying region?

IV. AN INTERIM EARTH MODEL

Based on available information, and recognizing the uncertainty of important data, Powell has developed a seismic earth model which can be expected to be typical of eastern soft coal regions. The model is not intended to be one for use in the location of miners at a mine disaster, but is rather one which can be used to determine the behavior of arrival times for hypothetical source locations in an earth that has the structure of the model. From such sets of arrival times the accuracy of various location earth models can be established, and a grasp of how accurately the location earth model must approach the real earth can be obtained. As such we consider this model to be an interim one, which can be used for theoretical analyses of location earth model performance, and can be varied to determine the sensitivity of alternative location earth models. The model, which is composed of laterally homogeneous horizontal layers, is described in Table 1. Crosson and Peters, in Part Three of this Volume, use earth models based on this interim model, but simplified to cases of 2 and 4 layers and the case of a continuous velocity variation.

TABLE 1

INTERIM EARTH MODEL

Layer number	Layer thickness (ft)	Layer velocity (ft/sec)
Surface		
1	5	1,500
2	15	2,000
3	30	3,000
4	50	4,500
5	100	6,000
6	200	8,000
7	300	11,000

V. CONCLUSIONS

A comprehensive seismic survey at a number of coal mine sites is recommended as a means of obtaining data to the accuracy necessary for further miner location, earth model development, including a comparison of alternative models. An interim seismic velocity earth model is suggested on the basis of general geological properties of soft coal regions. This model is based on laterally homogeneous horizontal layers, which may be inadequate to properly describe a real mine environment. Its accuracy can only be determined when all potential sources of error in arrival time measurements have been accounted for.

VI. REFERENCES

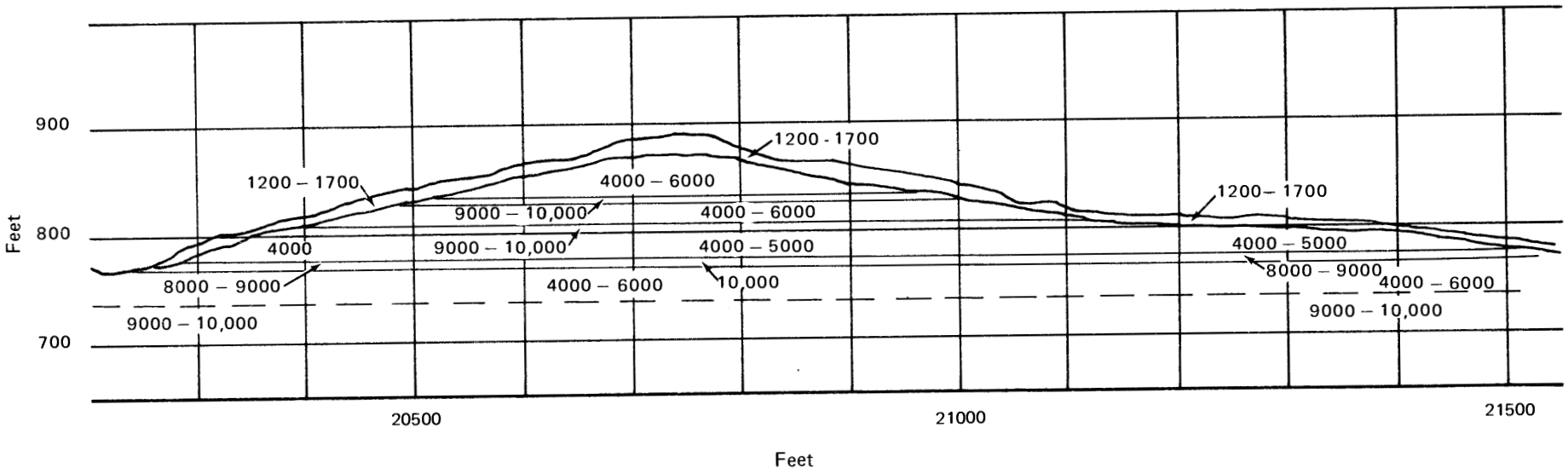
1. Geology Department of West Virginia, Some Appalachian Coals and Carbonates, W. Va. Geologic and Economic Survey, 1969.
2. U.S. Geologic Survey, Professional Paper 621.
3. Press, Frank, in Handbook of Physical Constants, S.P. Clark, Jr., editor. Geological Society of America, New York, 1966.
4. Mr. Vincent Murphy of Weston Geophysical Engineers and Rev. Daniel Linehan of Weston Observatory.
5. Donath, F.A. and Kuo, J.T. (1962) Geol. Soc. Am. Bull, 73 429-434.

APPENDIX A

SEISMIC SURVEY OVER THE CLARION 4A COAL SEAM

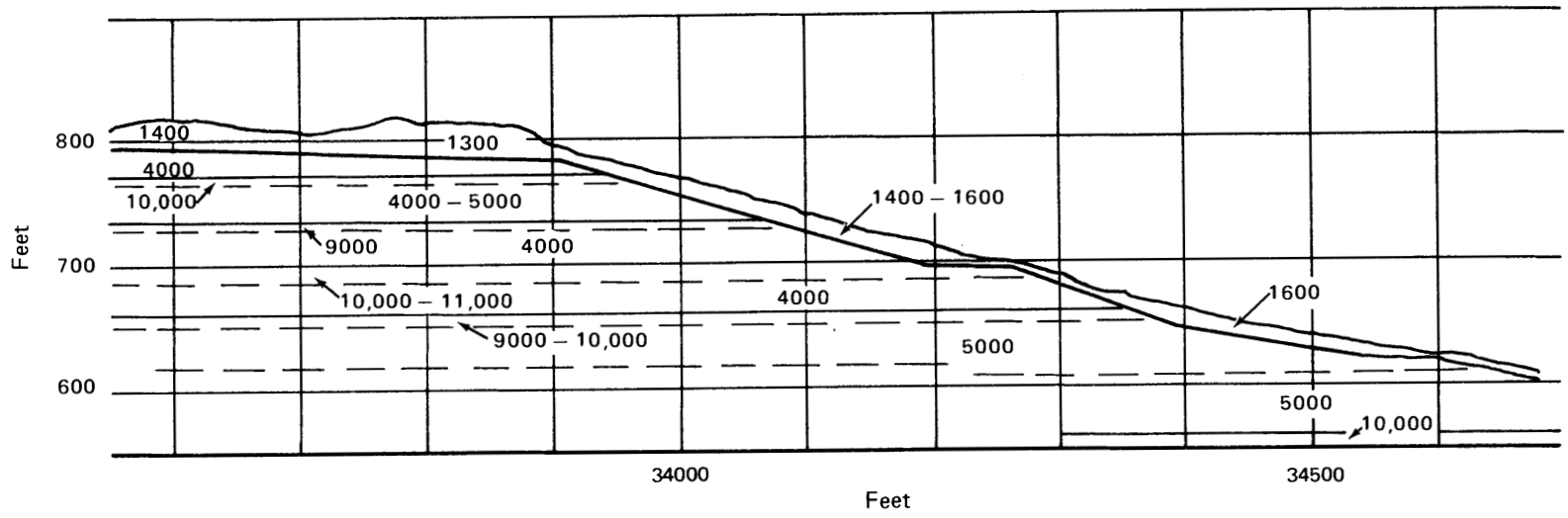
Since the completion of the work upon which this report is based, we have obtained seismic velocity profiles through the good offices of Mr. Dennis Rubin of American Electric Power Service Corporation. These profiles were taken for AEP by Weston Geophysical Engineers, Inc. of Weston, Massachusetts. These profiles were taken in the Meigs County area of Ohio over the Clarion 4A coal seam. Elevations and distances on these profiles are scaled with major divisions equal to 100 feet. Velocities are in feet per second. The profiles are shown in Figures A1, A2, A3, and A4.

These data provide part of the needed base for developing good earth models as noted in this Part. The nature of these data also emphasize the need for further data, to greater depths and higher accuracy over other coal seams.



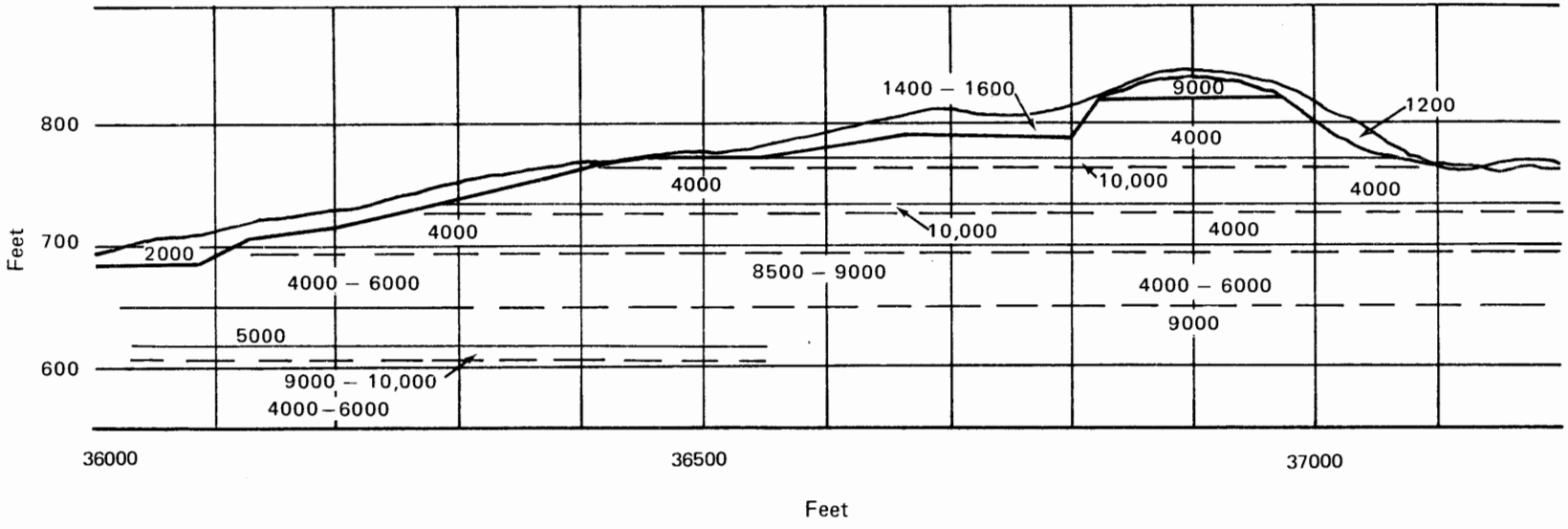
Source: American Electric Power Service Corp. and Weston Geophysical Engineers, Inc.

FIGURE A1 SEISMIC VELOCITY PROFILE



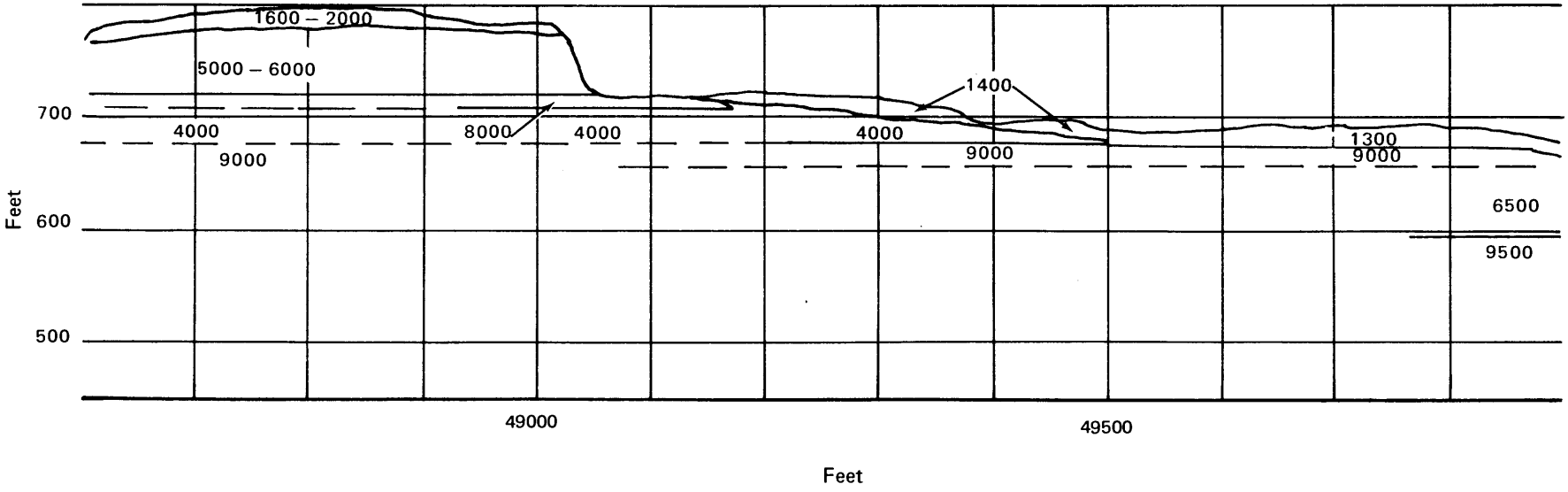
Source: American Electric Power Service Corp. and Weston Geophysical Engineers, Inc.

FIGURE A2 SEISMIC VELOCITY PROFILE



Source: American Electric Power Service Corp. and Weston Geophysical Engineers, Inc.

FIGURE A3 SEISMIC VELOCITY PROFILE



Source: American Electric Power Service Corp. and Weston Geophysical Engineers, Inc.

FIGURE A4 SEISMIC VELOCITY PROFILE