Statistical Studies of Indiana Bedrock Velocities: Mapping Applications

Albert J. Rudman
Department of Geology
Indiana University, Bloomington, Indiana 47401
and
Maurice E. Biggs, Robert F. Blakely and Joseph F. Whaley
Indiana Geological Survey
611 N. Walnut Grove, Bloomington, Ind. 47401

Abstract

More than 11,000 seismic refraction shots were made in Indiana by geophysical crews of the Indiana Geological Survey. Results of these measurements previously were used to measure the thickness of overburden materials. All of the interpreted data are now catalogued on magnetic tape and permit rapid statistical analyses of velocities by computer. Results show that velocities near 1,000 feet per second are associated with dry, aerated or weathered unconsolidated material; those about 6,000 feet per second with water saturated glacial drift or other unconsolidated material; 10,000 feet per second with shales or sandstones; and near 16,000 feet per second with limestone and dolomite. Only slight differences in velocity are noted for rocks having similar lithology but different geologic ages.

Wherever strong velocity contrasts occur between bedrock units, seismic refraction methods offer a technique for subsurface mapping. A portion of Jasper and Pulaski Counties was surveyed by seismic methods. The resulting velocities were plotted on a geologic map and contoured. Contacts between the New Albany Shale and Devonian limestones were well defined by the velocity contours. Lithologic differences within Silurian limestones were also identified.

Introduction

Present knowledge about the geology of the sedimentary section in Indiana was developed over the past century and a half, mainly through studies of surface exposures and investigations of subsurface well records and samples. Unfortunately, this classic geologic approach has faced severe limitations, due primarily to the thick glacial deposits which cover approximately four-fifths of the state, and to the uneven distribution of test wells, both geographically and in depth. Obviously, to form a cohesive regional geologic picture, supplemental information is required for many parts of the state. Ultimately, geophysical methods offer the most convenient and least expensive method for developing the interrelationships and configuration of the sedimentary sequence in all parts of Indiana.

Seismic refraction is the most widely used geophysical technique used in Indiana. Thus far the principal application of these seismic refraction surveys has been to measure the depth to bedrock beneath glacial and alluvial materials. Many of these seismic refraction shots also have been observed to yield limited information about the lithologies of buried bedrock. Results of investigations of these velocity-lithology relationships in Indiana have not been reported previously in geologic literature. These relationships of bedrock velocities with lithologies are vague and difficult to interpret; nevertheless, bedrock lithologies deduced from seismic refraction shots may provide the only geologic information for the construction of a complete geologic map. Results of this "refraction velocity-lithology" investigation form an integral aspect of this study.

Although seismic refraction surveys have been used extensively in the exploration for oil in the United States since 1923 (2), little work was done in Indiana by this technique until 1950. At that time a seismic refraction party began a reconnaissance survey to measure the thickness of glacial deposits in northern Indiana for the Indiana Geological Survey. That work later was expanded to include intensive surveys at sites for which foundation information was required, in connection with groundwater investigations, in searches for mineral resources, and to supplement studies of the glacial geology of particular localities. In all, more than 11,000 seismic refraction shots have been made by Geological Survey crews during the past 23 years. Data from these shots are catalogued on computer tapes for rapid access and printout, and have been disseminated widely and incorporated in numerous geologic reports and maps.

The seismic refraction method is based on the physical laws that also govern the propagation of light through homogeneous media. These principles are developed in terms of elastic waves in most standard geophysics textbooks (1). Elastic energy propagates outward from an energy source (the shot) as expanding spherical waves, according to Huygen's Principle. Whereas the transmission of elastic energy is derived from Huygen's Principle, the direction of the transmitted or refracted wave is governed by Snell's law:

$$\frac{\text{Sin i}}{\text{Sin r}} = \frac{V_1}{V_2} \qquad \text{Equation 1}$$

In this equation the angle of incidence i of a wave (defined with respect to a line drawn normal to the interface between layers) is related to the angle r of the refracted wave directly as the ratio of the interval velocities above and below the interface (V_1/V_2). If the layers are not horizontal, a correction must be applied to the apparent interval velocities in order to obtain the true velocity of the refracted waves. Reverse shots (shots made at each end of the line of recording instruments) record apparent velocities that are greater than true velocities for the up-dip case, and apparent velocities that are less than true velocities for the down-dip direction. True velocity may be obtained from these apparent velocities by a simple mathematical computation.

An accurate interpretation of seismic refraction records depends in part upon geologic conditions at a seismic station. The method is based upon the requirement that velocities of the layers beneath a shot must increase with depth. Where low velocity layers lie beneath layers having higher velocity, refracted energy from the low velocity layers will not be recorded and depths computed for layers beneath the higher velocity material will be erroneous. In some instances for which the velocities of the layers do increase with depth, refracted energy for a relatively thin intermediate velocity layer may not be recorded by conventional methods. Seismic refraction interpretations, therefore, must be made carefully and in coordination with the best available information about the geology of a locality.

Statistical Summary of Seismic Velocities

Major Stratigraphic Units

A review of 10,745 velocities obtained from seismic refraction shots is plotted in groups of 100 feet/sec (Fig. 1). Where possible, velocities were calculated to include corrections for dipping layers (by reverse shooting), for low velocity layers, and for intermediate velocity layers. Velocities from these shots range from 400 feet/sec to 24,700 feet/sec. Four rather indistinct maxima may be noted on this plot of velocity distribution. One group of velocities is centered about 1,000 feet/sec and represents velocities associated with dry or weathered unconsolidated material. Another group centered about 6,000 feet/sec is characteristic of most unconsolidated material in Indiana. Whether the material is alluvium or Wisconsin glacial deposits appears to have little bearing on the seismic velocity of the deposit. Higher velocities, near 8,000 feet/sec, have been recorded for material that is considered to be Illinoian till. The range of velocities from about 4,000 feet/sec to nearly 9,000 feet/sec is characteristic of saturated or nearly saturated unconsolidated materials that differ mainly in degree of compaction.

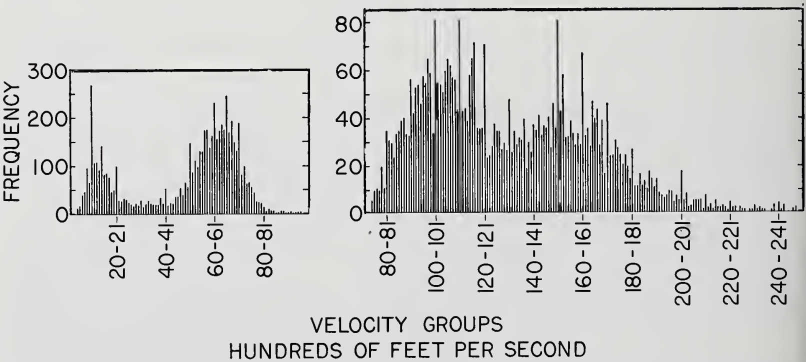


FIGURE 1. *Histogram of seismic velocities of Indiana sediments for 10,745 measurements.*

In the range of velocities associated with bedrock two indistinct overlapping groups may be observed. The lower of these two has a peak at about 10,000 feet/sec and is characteristic of shales and sandstones. The second group of bedrock velocities, ranging from about 13,000 feet/sec to more than 24,000 feet/sec is related to limestones and is centered about 15,000 feet/sec. Irregular spikes on the plot of velocities (Fig. 1) show some operator bias for certain velocities such as 1,000, 5,000, 10,000 and 15,000 feet/sec, and a somewhat higher partiality to even than to odd numbers.

In the initial processing of seismic records a geologic age is assigned to bedrock for each station on the basis of the best available information—usually from geologic maps of the area and well data. A lithology is also assigned to bedrock, partly on the basis of geologic maps and well information, and partly on the basis of the bedrock velocity obtained from the time-distance plot for that record. As a result of this interpretation, nearly all velocities have been assigned to two lithologies, shale or limestone. Only 26 shots were interpreted as recording velocities from sandstone.

Statistical analysis of these records, therefore, includes velocities of shales and limestones of five units ranging in age from Ordovician to Pennsylvanian. Table 1 summarizes the results of a statistical analysis of these records. The range and distribution of velocities for Indiana rocks having similar lithologies but quite different geologic ages are almost identical. However, there are measurable differences in velocities of differing lithologies. Shale velocities vary less than those of the limestones. For example, the difference in velocity between the Pennsylvanian shale, having the lowest mean velocity (10,068 feet/sec), and Silurian shales having the highest mean velocity for shales (11,047 feet/sec), is only 979 feet/sec, somewhat less than the lowest standard deviation for shales (1,099 feet/sec). Limestones show a somewhat greater spread in mean velocities—1,793 feet/sec between the Ordovician (lowest) and Devonian (highest). That difference, too, is in about the same range as the standard deviations. The conclusion reached from these comparisons is that shales may be distinguished from limestones, but rocks of the same lithology but different ages cannot be separated on the basis of velocity alone.

TABLE 1. *Average velocities and other statistical data for 8,868 velocities of shales and limestones of Ordovician to Pennsylvanian age.*

			Feet per Second	
Age	Rock Type	Number	Mean Velocity	Standard Deviation
Ordovician	limestone	338	14,538	2,174
Silurian	limestone	1,924	15,195	2,353
Devonian	limestone	1,815	16,331	1,877
Mississippian	limestone	430	15,145	2,143
Pennsylvanian	limestone	42	14,600	1,577
Ordovician	shale	26	10,930	1,365
Silurian	shale	59	11,047	1,099
Devonian	shale	544	10,825	1,195
Mississippian	shale	931	10,269	1,361
Pennsylvanian	shale	2,759	10,068	1,189

Selected Stratigraphic Units

The distributions of velocities shown by the histograms (Figs. 2 to 5) demonstrate several interesting relationships, and pose some intriguing questions, particularly for cases represented by more than 100 samples. Taken as a group, the limestones show a wide range of velocities, large standard deviations, and because of the large standard deviations, large coefficients of variation and variance (Fig. 2). The range of velocities for the Silurian limestones is exceptionally large, covering 15,500 feet/sec—from 7,000 to 22,500 feet/sec. Distribution of velocities for the limestones is nearly Gaussian, that is skewness is low (0.726 maximum), and kurtosis is close to 3.0. The histogram for the Devonian limestones shows some skewness, which may be explained by the method of record interpretation. For a shot made over the Devonian limestone an arbitrary cutoff was made at a velocity of 12,000 feet/sec at the low end of the scale. All velocities below 12,000 feet/sec were regarded as New Albany Shale. Velocities at the high end of the scale were permitted to go as high as plotted, that is, up to 23,500 feet/sec.

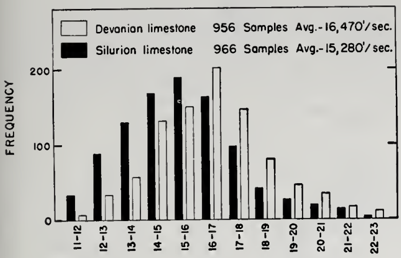
The distribution of shale velocities (Fig. 3) excluding those for Ordovician rocks (26 samples) and for the Silurian rocks (59 samples) is very nearly normal. Standard deviations, coefficients of variation, and variance, generally are lower than those for the limestones. Kurtosis for the distribution of velocities for Devonian and Mississippian shales is below 3.0, that is the curves are slightly flattened; about an equal number of velocities for these shales may be expected in the range from 9,500 feet/sec to 12,000 feet/sec. Skewness is low for the distribution of shale velocities because calculations provided for both high and low arbitrary cutoffs. At the low end, velocities below 8,000 feet/sec were regarded as corresponding to unconsolidated materials; above 14,000 feet/sec the bedrock was considered to be limestone.

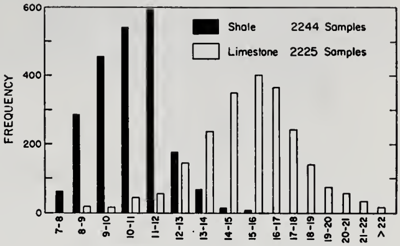
A histogram plot of about 4,500 measurements shows a sharp contrast between the average values of 10,400 feet/sec for shales *versus* 15,600 feet/sec for limestones (Fig. 4). However, there is overlap between 8,000 and 15,000 feet/sec because the curve for shale velocities is slightly skewed. Above 12,000 feet/sec, the interpreter tended to regard velocities as typical limestones. However, there is strong contrast and little overlap in the distribution of velocities measured over the stratigraphically adjacent New Albany Shale and limestones of Devonian age (Fig. 5). This relation indicates that velocity may be used to map bedrock geology in areas where contacts are covered by unconsolidated materials; provided the contacts are between rocks of favorable velocity contrast.

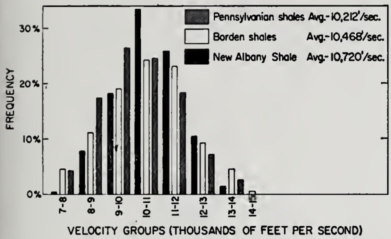
Bedrock Lithology Map from Velocities

In a region where bedrock is covered by unconsolidated deposits and where bedrock formations characteristically have contrasting lithologies, a rapid reconnaissance of bedrock geology based on velocities may be made to supplement information from drilling. From a geologic standpoint the Jasper-Pulaski County area offers bedrock having a diversity of ages and lithologic types (Fig. 6). In addition to the now familiar shales and siltstones of the Borden Group, the New Albany Shale, and the Devonian limestones, bedrock also includes the

Michigan Basin equivalents of these rocks. Also present are the Rockford Limestone of Mississippian age and Silurian rocks of the Salina Formation and Niagaran Series.







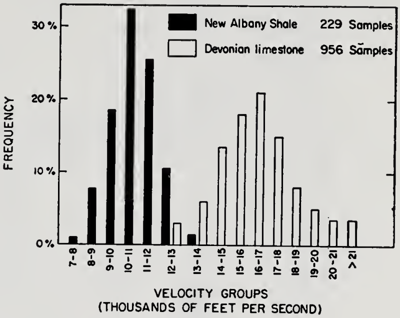


FIGURE 2. *Histogram of seismic velocities for some Indiana limestones.*

FIGURE 3. *Histogram of seismic velocities for some Indiana shales showing differences in three stratigraphic units.*

FIGURE 4. *Histogram of seismic velocities of Indiana shales and limestones.*

FIGURE 5. *Histogram of seismic velocities of New Albany Shale and Devonian limestone.*

More than 450 seismic refraction shots were made in the Jasper-Pulaski County area to measure the thickness of glacial materials. Where possible, bedrock velocities recorded at each station were corrected for dipping layers, and for errors due to the presence of low and intermediate velocity layers. A map showing bedrock velocity for each seismic station and the most recent interpretation of bedrock geology (Fig. 6) demonstrates the correspondence between velocity and lithology that was indicated by the statistical studies.

Velocity contours on Figure 6 focus attention on certain regional patterns. In the southwestern part of the map there are closely spaced contours that show the separation of New Albany Shale and Devonian limestone. Note that the contours closely parallel the mapped contact. Contours in the north-central part of the map also delineate a similar geologic boundary, although not as closely as the southwestern area. At certain localities underlain by New Albany Shale in the northern part of the area, velocities for that formation were not recorded. This difficulty resulted from the relative thickness and velocities of the glacial drift, New Albany Shale, and underlying Devonian limestone.

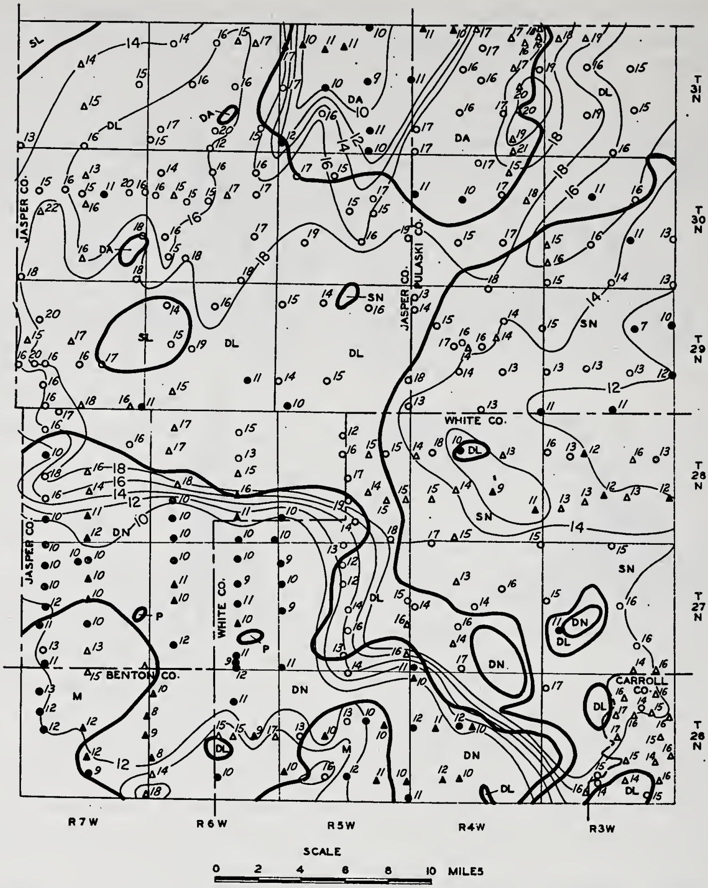


FIGURE 6. *Map of a portion of Pulaski and Jasper Counties showing bedrock geology and seismic velocity contours. Heavy solid lines mark geologic contacts between P (Pennsylvanian shale), M (Borden Group and Rockford limestone , DA (Antrim Shale), DL (Devonian limestone), SL (Salina Formation) and SN (Niagaran series). Contour interval is 2000 feet/sec. Solid symbols (circles and triangles) represent measured shale velocities; open symbols represent limestone velocities.*

Velocities of Silurian rocks in the eastern part of the map may be used to identify important differences in bedrock lithologies. Regions of 13,000 feet/sec coincide with fine-grained, silty dolomite, whereas velocities in the 15,000-16,000 feet/sec range represent coarsely crystalline, non-silty dolomite. In addition, there are other local areas where the mapped geologic contacts (highly extrapolated) might be altered slightly on the basis of the New Albany Shale-Devonian limestone velocity contrasts. Note that the resolution of velocity data is not sufficient to distinguish between the Borden and New Albany Shales.

Conclusions

Seismic velocities for more than 11,000 refraction shots in Indiana are catalogued on magnetic tape. Data are available on request from the Indiana Geological Survey, Bloomington, Indiana. Extensive statistical studies identify velocities for certain lithologic and stratigraphic units. Applications in mapping buried bedrock geology is feasible with the seismic refraction method in regions of contrasting lithologies.

Literature Cited

1. DOBRIN, M. B. 1960. Introduction to geophysical prospecting, 2nd ed. McGraw-Hill Book Co. New York, N.Y. 446 p.

2. NETTLETON, L. L. 1940. Geophysical prospecting for oil, 1st ed. McGraw-Hill Book Co., New York, N. Y. 444 p.