Seismic Methods

by

*Phillip M. Wright

*University of Utah Research Institute
Earth Science Lab Division
420 Chipeta Way, Suite 120
Salt Lake City, Utah 84108

Abstract

Seismic methods utilize the propagation of elastic waves in the earth. These waves are reflected and refracted when they intersect a boundary between rocks of different acoustic impedance in the earth, and the detection of the reflected or refracted components allows the boundaries to be mapped.

Although seismic methods have found broad and sophisticated application to petroleum exploration, they have contributed far less to metals exploration. The reasons for this are 1) that the geologic environments that contain most metals deposits are commonly more complex than are the petroleum environments, and 2) the petroleum industry has invested a great deal of money to optimize the seismic method for the petroleum environment, but a corresponding investment by the mining community has not been made. Thus, seismic exploration has a reputation of being expensive and useful in only a few special cases. Geophysicists generally agree, however, that research and development could substantially improve the method for mining application.

The seismic methods are effective at target depths beyond those appropriate for the electrical methods that now dominate minerals exploration. In addition, seismic methods can often detect smaller targets. Consequently, the cost effectiveness of seismic techniques will increase as targets become smaller and/or deeper and as optimization of these techniques to the mining environment is achieved through research and development.

SEISMIC METHODS

Introduction

Seismic methods are just now finding routine application to metallic minerals exploration although they have been well developed for petroleum exploration and for determining details of the earth's interior. The two main reasons for the relative lack of use in minerals exploration are the high cost of most seismic surveys and the difficulty, using present equipment and techniques, of consistently getting good results in the structurally complex areas where many mineral deposits are found. Nevertheless, there is agreement that seismic methods can contribute a great deal if some problems can be solved.

Principles

Seismic methods are concerned with the propagation of elastic waves in the earth. There are two types of body waves: *compressional waves* and *shear waves*. These two wave types are often called *longitudinal* and *transverse* or *"P-waves"* and *"S-waves"*, respectively. Compressional waves are ordinary sound waves in rock with particle motion back and forth along the direction of wave propagation; shear waves consist of particle motion perpendicular to the direction of wave propagation. Because fluids do not support shear stresses, shear waves are propagated only in solids. Compressional waves propagate in both solids and fluids.

Seismic waves travel through rock at speeds that depend upon the elastic properties of the rock. This dependence is given in the following equations:

$$V_p = \sqrt{\frac{\lambda+2\mu}{\rho}} ,$$

and

$$V_s = \sqrt{\frac{\mu}{\rho}} ,$$

where

V_p = P-wave velocity, V_s = S-wave velocity,

λ = a Lame coefficient = $\frac{E}{(1+\sigma)(1-2\sigma)}$

μ = modulus of rigidity = $\frac{E}{2(1+\sigma)}$

ρ = density,

E = Young's modulus, and

σ = Poisson's ratio.

Typical values for these elastic parameters for well-indurated or crystalline rocks are $E = 10^{12}$ dyne/cm^2, $\sigma = 0.25$, and $\rho = 2.67$ gm/cm^3, so we can determine that $\lambda = 4\text{x}10^{11}$ dyne/cm^2, $\mu = 4\text{x}10^{11}$ dyne/cm^2, and typical seismic velocities in these rocks are $V_p = 6.7$ km/sec (22,000 ft/sec) and $V_s = 3.87$ km/sec (12,700 ft/sec). Because σ can never exceed $\frac{1}{2}$, λ is always positive. Thus, V_p is always greater than V_s. Table 1 lists general ranges for seismic velocities as a function of rock type.

In addition to P- and S-body waves, there are waves that propagate along the earth's surface. Raleigh waves and Love waves are two such surface waves. They travel at speeds slightly lower than S-waves. These surface waves are not used in prospecting, and indeed they cause ground roll that can obscure signals from depth.

Seismic waves in rocks are *reflected and refracted* when they intersect a boundary between rocks of different acoustic impedance, where acoustic impedance is defined as the product of density and seismic velocity for the rock. Figure 1a shows a seismic ray approaching a boundary between rocks of different acoustic impedance, $\rho_1 V_1$, at an angle of incidence, i. Part of the ray is reflected at the boundary and part is refracted, and the proportion of

TABLE 1

SEISMIC VELOCITIES OF ROCKS

MATERIAL	SEISMIC VELOCITY, KM/SEC	
	P	S
Air	0.33	---
Water	1.46	---
Alluvium, Clay, Moraine	0.75-2.5	0.45-1.5
Sandstone and Shale	1.2 -3.7	0.75-2.0
Limestone and Dolomite	3.5 -6.5	1.5 -4.0
Metamorphic Rocks	3.5 -7.0	2.0 -4.0
Granite and other crystalline rocks	5.0 -7.0	2.5 -4.0
Basalt	3.5 -6.5	1.8 -3.9

reflected to refracted energy depends upon the acoustic impedances on each side of the boundary and upon the angle of incidence. In addition, a portion of the incident P-wave energy is converted to reflected and refracted S-wave energy, and incident S-wave energy is partly converted to reflected and refracted P-wave energy. The reflected portion travels upward at an angle of reflection, ϕ, that equals the angle of incidence, and the reflected wave can be detected when it reaches the surface, thereby forming the basis for locating the interface by the seismic reflection method.

The refracted portion travels onward in the lower medium in accordance with Snell's law which states that the sines of the angles of refraction, θ, and incidence, i, are related to the velocity contrast as shown in Figure 6-1a. Notice that $\theta > i$, if $V_2 > V_1$.

For each velocity contrast where $V_2 > V_1$, there is one angle of incidence at which the refracted wave travels along the boundary between V_1 and V_2, i.e., $\theta = 90°$ if $i_c = \mathrm{Sin}^{-1} \frac{V_1}{V_2}$. In this case, the seismic wave travels at velocity V_2, and the boundary becomes a continuous source of energy, some of which propagates back upward at angle i_c (Fig 1b). This refracted wave can return and be detected at the surface, forming the basis for locating the interface by the seismic refraction method. If $i > i_c$ or $V_2 > V_1$, there is total reflection and no energy enters the lower medium. Both P- and S-waves are reflected and refracted, but P-waves are used in prospecting because they arrive back at surface detectors first due to their higher velocity. Arriving P-waves cause the seismic trace to move, and this often obscures S-wave arrivals.

Another wave often detected at the surface is a result of *diffraction*. Figure 2 shows an edge that has become a source of seismic radiation as a result of seismic energy incident upon it. The diffracted arrivals at the surface often have characteristic hyperbolic patterns on the seismic record that allow them to be recognized and used to locate the edge (Telford, et al., 1976).

For mineral exploration purposes seismic waves are generally man-made. A common source is dynamite, which produces a signal consisting of a spectrum of frequencies. Small charges usually are richer in high frequencies than are large charges. An alternative to explosives is to employ the Vibroseis[1] technique where one or more heavy, tractor- or truck-mounted vibrators are used to introduce a seismic signal into the ground. Vibroseis sources produce a signal that is swept through the frequency range of interest over a typical interval of 2 seconds and thus give more control on frequency. Another alternative is Mini-Sosie[2], which uses an ordinary earth tamper to introduce a long duration pseudorandom wave train into the ground. In both the Vibrosies and Mini-Sosie systems the signals detected by geophones are cross-correlated with a reference signal produced by a sensor attached to the seismic source to produce the equivalent of conventional seismic records. Signal stacking by observing repeated reflections from the same point on a horizon at depth allows good, high-resolution records to be produced even with the relatively weak Mini-Sosie tamper source.

When the signal arrives at the surface, it is detected by a series of *seismometers* or *geophones* that are positioned along a line. They are placed firmly in the soil so that vertical vibrations of the earth having displacements as small as 10^{-4} cm can be detected. The geophones send the electrical signals by multiconductor cable to a recording truck located along the line.

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[1] A trademark of Continental Oil Company.
[2] A trademark of Societe Nationale El-Aquitane (Production).

Typical installations have 24 to 48 channels of information and record seismic signals along with precise shot time and other information on digital or FM magnetic tape.

The Seismic Reflection Method

Figure 3(a) shows a typical seismic reflection survey in an area where acoustic impedance contrasts are subhorizontal. The figure illustrates a few of the many reflected seismic ray paths. The reflection from interface 1 will be the first reflection detected. At later times, on each geophone, reflections from interfaces 2 and 3 can be detected. The reflection from interface 1 will arrive on a moving seismic trace as a result of the earlier arrival of either the direct wave from shot to detector or of a refracted wave. At some time late in the record, about 0.5 to 2 seconds, slow-traveling surface waves will be recorded at each geophone site. The total effect is that reflections early in the record, from reflectors shallower than about 500 to 1,000 feet (153 to 305 m), can be difficult to detect because of geophone motion due to the first arrivals, and deep reflections late in the record can likewise be obscured as surface waves cause motion of the geophones. Between cessation of first arrival motion and onset of the surface wave motion there is a window in time that is optimum for recording reflections. One of the challenges is to widen this time window through correct geophone deployment, filtering of signals, using an array of sources, and/or controlling the frequencies so that both shallow and deep reflections can be more easily seen. Reliable detection of shallow reflectors is especially important in mining applications.

When the seismic reflection data are recorded in the field, computer processing is required before interpretation of the seismic record sections can begin. A typical sequence of data processing might be (Shuey et al., 1977, Telford, et al., 1976): 1) demultiplex the field-recorded magnetic tapes, 2) edit sections of extraneous noise, 3) design stacking procedures and gather the data by common depth point (see below), 4) make initial static corrections, 5) make a velocity analysis, 6) make secondary static corrections, 7) make a final velocity analysis, 8) make normal movement corrections, 9) apply deconvolution, and 10) apply band-bass filtering and display. Descriptions of these important corrections can be found in Telford, et al. (1976).

Almost all reflection surveys today employ field techniques that allow *common-depth-point (CDP)* stacking. Common-depth point (CDP) stacking refers to a method of increasing the ratio of signal to noise (Figure 3(b)). Information from the interface at point P can be obtained by shooting at A and receiving with a geophone at B or by shooting C and receiving at D. It is obvious that there are many other shot/geophone pairs that record energy reflected from P on the interface. In common survey practice, shot points and geophone stations are moved along the line in such a way that there is enough redundancy of data to obtain a number of reflections from specific parts of the interface. In the processing, each shot/geophone pair that has recorded information from a specific point on the interface is identified and the results are composited or stacked to increase total signal. This survey and processing procedure is called *multifold surveying,* and results in a *6-fold CDP survey* or a *12-fold CDP survey,* for example.

When the corrections are applied and the seismic section is displayed, other processing techniques generally follow. In areas of complex geology where the dips of reflectors are not gentle, data *migration* must be effected. Migration is the technique of locating the lateral positions of the reflecting points at depth. If dips are steeper than about 20°, migration may be required earlier in the processing. Consideration must also be given to whether or not a true depth section can be constructed from the record section which uses time for a vertical axis. If enough velocity information is at hand from deep drill holes, or if it can be derived from the survey data, then the velocity section can be used to convert the time section to a depth section. Depths are important for certain applications while velocity sections, which usually illustrate the structure well enough, are often sufficient.

The Seismic Refraction Method

In this method, use is made of the wave refracted along the boundary between media of different velocities. This wave travels at the speed of the lower medium. For geophones near the shot, the first arrivals of seismic energy will be the direct wave from the shot as shown on Figure 4. But for geophones at a distance, the wave that travels down to the interface at velocity V_0, along the interface at velocity V_1, and then back to the surface at velocity V_0 will arrive first. By plotting the times after shot detonation of the first arrivals versus distance, a break in slope of the curve will be seen. The near segment will have a slope of $^1/V_0$, whereas beyond a crossover distance (X_{cr}) the slope will be $^1/V_1$. The depth, Z, to the interface can be found from

$$Z = \frac{t_i}{2}\sqrt{\frac{V_1 V_o}{V_1^2 - V_o^2}}$$

or

$$Z = \frac{X_{cr}}{2}\sqrt{\frac{V_1 - V_o}{V_1 + V_o}}$$

where t_i is the *intercept time* and X_{cr} is the *crossover distance* (Figure 4).

The above explanation of the method can be extended to multilayer cases, to cases of dipping interfaces, and to mapping of faults. Dobrin's (1976) discussion of the method is recommended for more detail.

Problems in Mineral Application

In its present stage of development, most applications of the seismic method in the mining industry could be classed as relatively unsophisticated compared to uses of the method by the petroleum industry. The seismic method has a number of problems in its application to minerals exploration or mining. We will discuss some of these before giving two examples of applications.

The wavelength of a seismic wave (λ), its frequency (f), and its velocity (V) are related as follows: $V = f\lambda$. From this relation we see that, for a particular velocity, waves of longer wavelength have lower frequencies and waves of shorter wavelength have higher frequencies. Now whether a structure of the type shown in Figure 5 will produce a reflection or not is dependent upon its thickness, t, relative to the wavelength of the seismic wave and upon the acoustic impedance contrast between the first and second layers. If the thickness is less than about one-tenth of a wavelength, the seismic wave will be so little affected by V_2 that no detectable reflection will be produced, regardless of impedance contrast. If $t > \lambda/6$, it may be possible to resolve the upper and lower boundaries. For a typical, well-indurated sedimentary rock or a crystalline rock of velocity 6.0 km/sec, a 10 Hz seismic wave has a wavelength of 600 m whereas a 100 Hz seismic wave has a wavelength of 60 m. We conclude that planar features such as faults or discrete beds are not likely to be detected or resolved by seismic waves of frequency less than 100 Hz unless they are greater than about 6 m thick. In addition to detection, precise location of these features requires seismic waves that have short wavelength or high frequency. Thus, although most petroleum exploration is effectively accomplished using frequencies in the 10 Hz to 50 Hz range, the higher resolution necessary for most mining problems requires frequencies in the 50 Hz to 500 Hz range. Instrumentation for such high-resolution surveys is not universally available from seismic contractors.

The need for high frequencies creates other problems not generally encountered in oil and gas exploration. The rate of attenuation of seismic signals as they travel through rock is a function of frequency as follows:

$$I = I_0 \frac{e^{-\beta r}}{r}$$

in which I = amplitude at distance r from source,

I_0 = initial amplitude,

β = absorption coefficient, and

r = distance from seismic source.

The $^1/r$ dependence is caused by the spreading of a given initial amount of energy over larger and larger spherical surfaces as the wave moves outward from the source. The exponential decrease in signal amplitude with distance results from frictional dissipation in the medium. The absorption coefficient, β is larger for higher frequencies and for material of lower seismic velocity. Therefore, at the higher frequencies needed for high resolution, seismic signal strength attenuates faster than it would at lower frequencies. This attenuation is most severe in the low velocity weathered layer near the surface, where high-frequency energy is very rapidly attenuated both in the downgoing wave and in the emerging wave. Figure 6 illustrates the way attenuation affects length of useable record as a function of frequency. Note that at the frequencies needed for high resolution, the useable record time, given as that region for which amplifier gains less than 128 db are needed, rapidly shortens as frequency increases. In many mining applications at least 1000 milliseconds of time is desirable in order to detect reflectors of the order of 1500 m deep. In some areas, a high-resolution survey may require placing either or both shot and geophones in holes that penetrate the weathered layer to reduce its attenuation. This requirement would, of course, increase costs.

The high resolution commonly needed for mining problems has implications other than simply higher frequency. For one thing spatial sampling, i.e., the geophone spacing, must be decreased so that horizontal resolution is nominally the same as vertical resolution. Whereas typical petroleum surveys use standard geophone spacings of 67 or 100 m, high resolution surveys require spacings of 5.0 to 33.5 m. High resolution also requires closer timing of events and higher sampling rate for digital recording and processing. Many petroleum surveys are conducted with events timed to the nearest millisecond and a sampling rate of 2 milliseconds. For recording of high frequency signals, timing to 0.1 milliseconds and a sampling rate of 0.25 to 0.5 milliseconds is needed. Figure 7 shows two seismic sections that the difference in level of detail obtained by using closer geophone spacing (5 m compared to 10 m) and shorter sampling time (¼ millisecond compared to ½ millisecond). Each of the traces on these seismic sections was recorded from the output of a single geophone array. Portions of the section that show alignment of peaks or troughs from trace to trace represent arrival of reflected or refracted seismic energy at the surface. Not only is correlation of seismic events easier from trace to trace, but the additional detail can be interpreted in terms of geologic complexity, giving a more detailed geologic picture.

Figure 8 illustrates another of the problems in attempting to apply the reflection seismic method in areas of complex geology. Because of the steep dip of the interface only a relatively small portion of the interface is mapped with one shot. Reflections from deep on the interface do not return to the surface at a sufficiently close distance for a practical deployment of geophones to detect them. This problem is compounded somewhat by the fact that mining applications usually use close geophone spacings to increase resolution so that the entire array does not cover much distance.

Existence of steeply dipping interfaces in many mining environments also causes problems in data reading. One field technique employed to diminish ground roll noise caused by surface waves is to deploy a series of geophones in, say, a circular pattern at each receiving site. The radius of the circle is adjusted such that some geophones are moving upward while others are moving downward as the horizontally traveling surface waves pass. This produces cancellation of surface wave signal by the geophone array. But such an array discriminates against all horizontally travelling waves, including those from steep reflectors (Figure 8). Thus the geophone array itself can cause signed cancellation. A compromise must be reached in geophone deployment. In certain cases it may be necessary to place the geophones in holes below the influence of surface waves.

Steeply dipping reflectors also can cause problems with the automatic data processing routines used in conventional seismic work. Migration may be needed prior to stacking. Great care must be taken in data processing.

The main reason for dwelling on the problems of applying seismic surveys in mining is not to discourage use of the technique but simply to emphasize the fact that good seismic equipment and techniques, specifically designed for mining problems, are just now being developed.

Applications

The seismic methods, particularly the reflection method, are effective at target depths beyond those appropriate for the electrical methods now dominant in much of the industry. In addition, smaller targets can often be detected. Consequently, the potential cost-effectiveness of seismic techniques relative to other geophysical methods will increase as targets become smaller and/or deeper. The most cost-effective use of the technique at present may be in deposit delineation or mining exploitation, rather than in exploration.

Refraction seismic techniques have been used in the mining industry for several decades. The main applications have been: 1) determination of depth to bedrock in placer mining and for other engineering reasons; 2) determination of thickness of the weathered zone or of overburden thickness for the purpose of correcting gravity data; 3) determination of rock quality in mining and engineering problems where rock quality can be related to seismic velocity; and 4) study of sedimentary rocks in the search for mineralization or to determine structure where the section is subhorizontal and reasonably simple.

Figure 9 gives an example of the use of the refraction method to study the Butte Valley, Nevada, porphyry copper deposit. This deposit lies about 50 miles north of the Robinson District near Ely on the west side of the Cherry Creek range. Gulf Science and Technology in cooperation with Bear Creek Mining Co. used the area as a test to determine the applicability of refraction and reflection to study of a deep, blind disseminated sulfide system. Some results of Gulf's work were reported by Fix (in Shuey et al., 1977).

At Butte Valley the prospect area is covered by 30 to 300 m of basin fill that overlays an unaltered, unmineralized Paleozoic sedimentary section. The Paleozoic rocks have apparently moved as a unit under the influence of gravity to cover an old, thin fanglomerate which overlies the sulfide system. Drilling therefore goes through the alluvium into fresh Paleozoic sedimentary rocks, through a fault zone into the fanglomerate, and then into mineralized rocks at a depth of about 610 m. Figure 9 shows several refracting horizons as detected by the Gulf survey and how the seismic interpretation fits the geology determined by lithologic logs from several deep drill holes. Seismic data interpretation in this case was from the refraction inversion program developed by the U.S. Bureau of Mines (Scott et al., 1970).

Several lines of reflection data were obtained at Butte Valley also. The survey was performed with standard petroleum instrumentation but with geophone spacings of 34 m and six-fold coverage. Frequency content was between 16 Hz and about 75 Hz for most of the survey. Figure 10 shows the data for an east-west line over the prospect along with an interpretation. The seismic data reveal great structural complexity over the deposit, in the center section of the line. Numerous faults can be interpreted by noting restricted lateral extent of reflecting horizons. To the west, good reflections from the undisturbed, unaltered sedimentary section can be seen. It is evident that these seismic data are rich in detail that would be useful both in exploration and mining planning.

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Figure Captions

Figure 1(a)	Reflection and refraction of seismic rays.
Figure 1(b)	Refraction along an interface.
Figure 2	Diffraction of seismic waves from an edge.
Figure 3(a)	Illustration of typical seismic reflection survey.
Figure 3(b)	Common depth point shooting.
Figure 4	Time-distance plot and ray path in a seismic refraction survey (after Dobrin, 1976).
Figure 5	Detection of a thin structure. Seismic waves of wavelength, λ, shorter than about 10t are needed for detection of a thin bed or fault.
Figure 6	Attenuation of seismic energy as a function of frequency. This figure shows that for record times beyond 500 ms the frequency content rapidly shifts to lower frequency (after Shuey et al., 1977).
Figure 7	Illustration of increase in detail obtained when data sampling time and geophone spacing are halved (after Shuey et al., 1977).
Figure 8	Reflections from a steeply dipping interface.
Figure 9	Results of seismic refraction survey, Butte Valley, Nevada compared to drill hole lithology (after Shuey et al., 1977).
Figure 10	Results of seismic reflection survey at Butte Valley, Nevada (after Shuey et al., 1977).