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Article abstract

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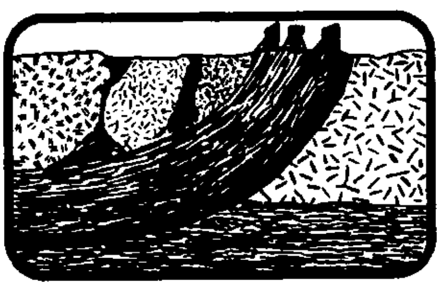
# Articles



## Appraisal of the Parameters of the LITHOPROBE Abitibi-Grenville Seismic Reflection Survey

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### SUMMARY
The 1990-1991 LITHOPROBE Abitibi-Grenville seismic reflection survey comprises 989 km of regional data collected for crustal exploration and 81 km of high-resolution data collected for mineral exploration. A proper interpretation of the data requires an understanding of its limitations; these are a function of the acquisition parameters. The vertical resolution is ~38 m for the regional data and 15 m for the high-resolution data. The maximum reflector dip that can be imaged in shallow data is ~70°, but deep data are biased toward subhorizontal reflections. The principal sources of noise are vibrator truck noise, ground roll, and shear wave refractions. Power-line noise is surprisingly important on some high-resolution lines. The seismic signal penetrates to the Moho, revealing differences in Moho reflectivity across the survey.

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### RÉSUMÉ
En 1990 et 1991, des données de sismique réflexion ont été enregistrées dans le cadre de la première phase du projet LITHOPROBE Abitibi-Grenville. Plus de 989 km de levés régionaux permettant l'étude de la croûte terrestre et 81 km de levés à haute résolution pour l'exploration minière ont été réalisés. Une interprétation convenable des données doit tenir compte des limites imposées par les paramètres d'acquisition. La résolution verticale des levés régionaux est d'environ 38 m, tandis que celle des levés à haute résolution est de 15 m. La méthode permet de reconnaître des structures géologiques peu profondes dont les pendages sont inférieurs à 70°; le pendage maximum des structures imagées en profondeur est plus faible. Le bruit le plus important provient des ondes de surface et des ondes de cisaillement réfractées. Malgré l'utilisation d'un nouveau système d'acquisition atténuant le 60 Hz ambiant, ce bruit demeure important sur certains profils à haute résolution. La pénétration du signal sur la majorité des profils est suffisante pour atteindre la discontinuité de Mohorovicic, ce qui suggère que sa non-réflectivité a une signification géologique. Néanmoins, la structure de la croûte profonde doit être interpretée prudemment parce que la plupart des profils sismiques ont une longueur insuffisante pour imager correctement des structures inclinées à ce niveau.

### INTRODUCTION
The LITHOPROBE Abitibi-Grenville seismic reflection survey was recorded in the fall of 1990 and the spring of 1991 to obtain an image of the crust along a transect through the Superior and Grenville geologic provinces of the Canadian shield (Fig. 1). The transect lies in western Quebec and eastern Ontario, a region of great geologic interest due to its many important mines. It comprises 989 km of deep seismic (regional) reflection data and 81 km of shallower high-resolution data recorded with techniques borrowed from petroleum exploration. The data are excellent.

A seismic transect can be thought of as representing a cross section of the earth, and it is this that gives it power and appeal. However, a seismic transect is not a geologic cross section, due to limitations inherent in the seismic method. To be properly interpreted, the limitations of seismic data must be understood, and this requires an understanding of the influence of the acquisition parameters.

This is a review of the acquisition parameters employed in the LITHOPROBE Abitibi-Grenville seismic survey. The effectiveness of the key parameters is evaluated in terms of seismic resolution, noise and signal penetration. The intent is to clarify these concepts so that the data can better be interpreted. Because these concepts are general, much of this review applies to other deep seismic reflection transects.

### ACQUISITION PARAMETERS
The acquisition parameters employed in the 1990-1991 LITHOPROBE Abitibi-Grenville seismic reflection surveys are typical of current practice (Table 1). Recording was accomplished with a Sercel 330 telemetry system, which avoided data multiplexing and reduced electrical noise. No filters were applied

to the data during acquisition except a standard anti-alias filter. In place of an analog 60 Hz notch filter, individual shot records were recorded such that the vertical sum of all sweeps cancelled pure 60 Hz noise. The parameters for the high-resolution survey meet the requirements for "full resolution recording" as set forth by Vermeer (1990), while those for the regional survey come close to meeting them.

Acquisition parameters determine or influence the seismic data resolution, noise and signal penetration. Frequency content is arguably the most important of the parameters, because it determines the resolution. Ideally, the frequency content of the data is equal to that of the seismic source, but local variations in geology, noise and recording conditions, as well as data processing, cause substantial differences in the final frequency content. This can be seen in Figure 2, a comparison of representative frequency spectra from four lines of the Abitibi-Grenville survey. All four lines were recorded with the same 10 Hz to 56 Hz sweep, but their spectra differ. Spectral differences translate into differences in resolution, noise and signal penetration.

## RESOLUTION

Resolution pertains to the ability to distinguish one geologic structure from another. The resolution inherent in seismic reflection data is difficult to appreciate because it usually greatly exceeds outcrop scale. The aspects of resolution discussed below are vertical resolution, horizontal resolution, and maximum resolvable dip. To simplify the discussion, the frequency content of the data is taken to be that of the source sweep. This has the effect of making the estimates of resolution possibly smaller (and hence better) than they really might be.

### Vertical Resolution

The seismic wavelet is our tool for probing the earth, and it must be of a size appropriate for the geologic targets. Figure 3 illustrates the size of the effective wavelets employed in the Abitibi-Grenville survey by comparing them with the CN tower. Both wavelets are large. The main body of each wavelet, where the amplitudes are most significant, has a length that is an appreciable fraction of the height of the tower. (The total length of each wavelet is longer than shown, but is of little importance.) The vertical resolution of these wavelets can be quantified by the standard measure of vertical resolution, the Rayleigh resolution limit (Kallweit and Wood, 1982). The Rayleigh resolution limit is a function of the velocity and frequency of the seismic waves; it is 38 m for the regional data and 15 m for the high-resolution data. This means that reflectors must be at least 38 m apart to be separately resolvable on the regional data, and at least 15 m apart to be separately resolvable on the high-resolution data. More intuitively, the vertical resolution of a wavelet is roughly the width of its main centre peak. Referring again to Figure 3, this width is 45 m for the regional wavelet and 18 m for the high-resolution wavelet. The minimum thickness of a reflective layer that can produce a distinguishable reflection depends on several factors, but it is usually a small fraction of the vertical resolution (Widess, 1973).

Another aspect of vertical resolution concerns how much the main peak of a seismic wavelet stands out above the

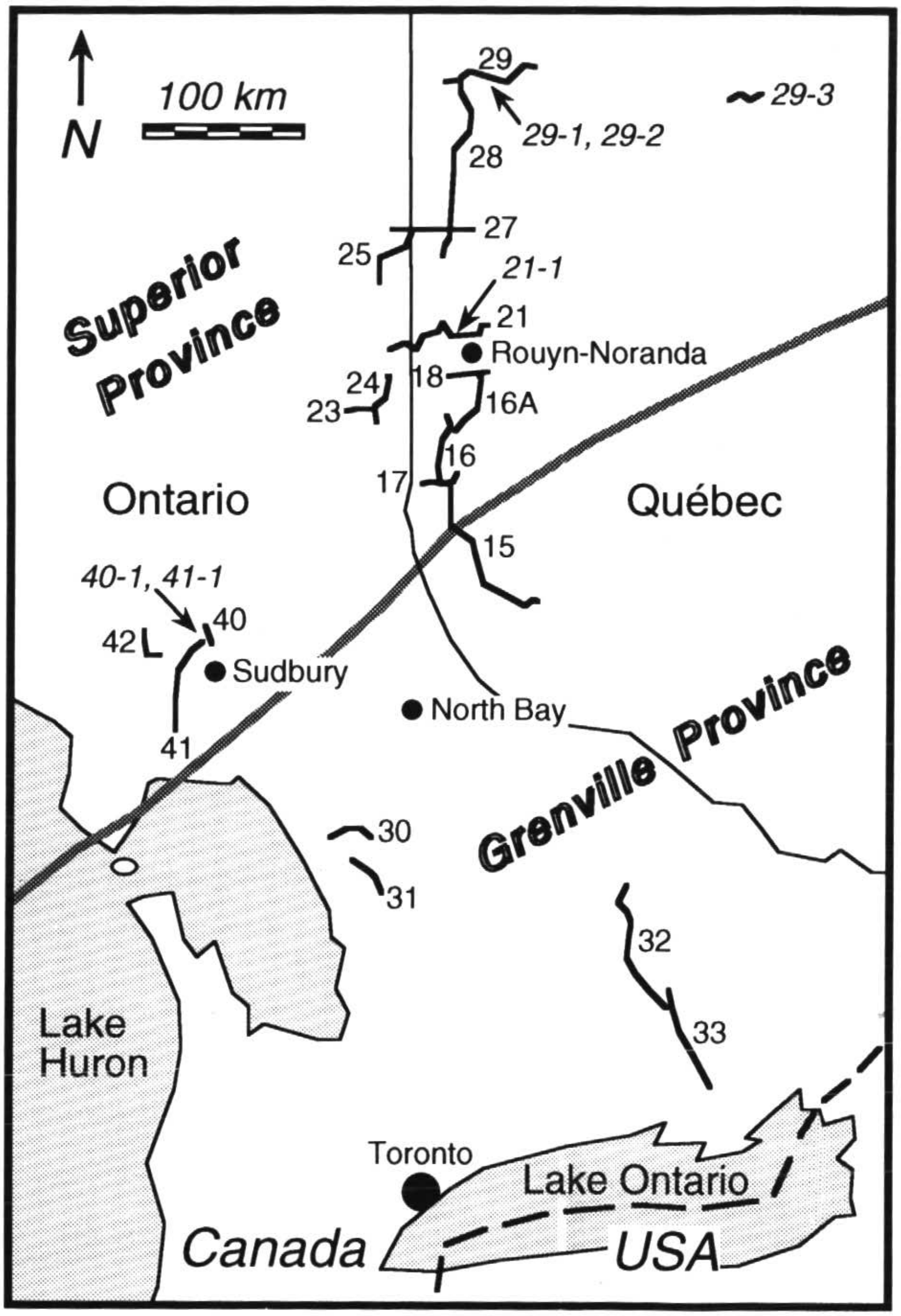


**Figure 1** *Location map of the LITHOPROBE Abitibi-Grenville seismic reflection survey. High-resolution line numbers are italicized; all other numbers refer to regional lines.*

**Table 1** **Acquisition parameters for the 1990-1991 LITHOPROBE Abitibi-Grenville deep- and high-resolution seismic reflection surveys.**

| *PARAMETER* | *REGIONAL* | *HIGH RESOLUTION* |
|---|---|---|
| *Source* | vibroseis, 4 trucks | vibroseis, 2 trucks |
| *Sweep Frequencies* | 10-56 Hz | 30-140 Hz |
| *Sweep Length* | 14 seconds | 12 seconds |
| *Listening Time* | 18 seconds | 4 seconds |
| *Receivers* | 10 Hz, 9 per group | 30 Hz, 9 per group |
| *# of Receivers* | 240 | 240 |
| *Source Spacing* | 100 m | 20 m |
| *Receiver Spacing* | 50 m | 20 m |
| *Fold* | 60 | 120 |
| *Geometry Type* | assymetric split | split-spread |
| *Near Offsets* | 150 m, 150 m | 0 m, 20 m |
| *Far offsets* | 4 100 m, 8 100 m | 2 380 m, 2 400 m |

side lobes (Widess, 1982; Berkhout, 1984). This is controlled by the bandwidth of the wavelet: the wider the bandwidth, the better the main peak stands out. In the Abitibi-Grenville survey, the bandwidth is 2.5 octaves for the regional acquisition and 2.2 octaves for the high resolution. Something between 2 octaves and 3 octaves is standard in modern reflection seismology. By this measure, the regional survey rates better than the high-resolution survey.

**Horizontal Resolution**

Horizontal resolution is commonly quantified by the Fresnel zone (Sheriff and Geldart, 1989). While this is a convenient measure, it constitutes a worst-case estimate because it applies to stacked seismic data, not to migrated seismic data. This merits explanation.

Migrated seismic data is the final product of the seismic method, whereas

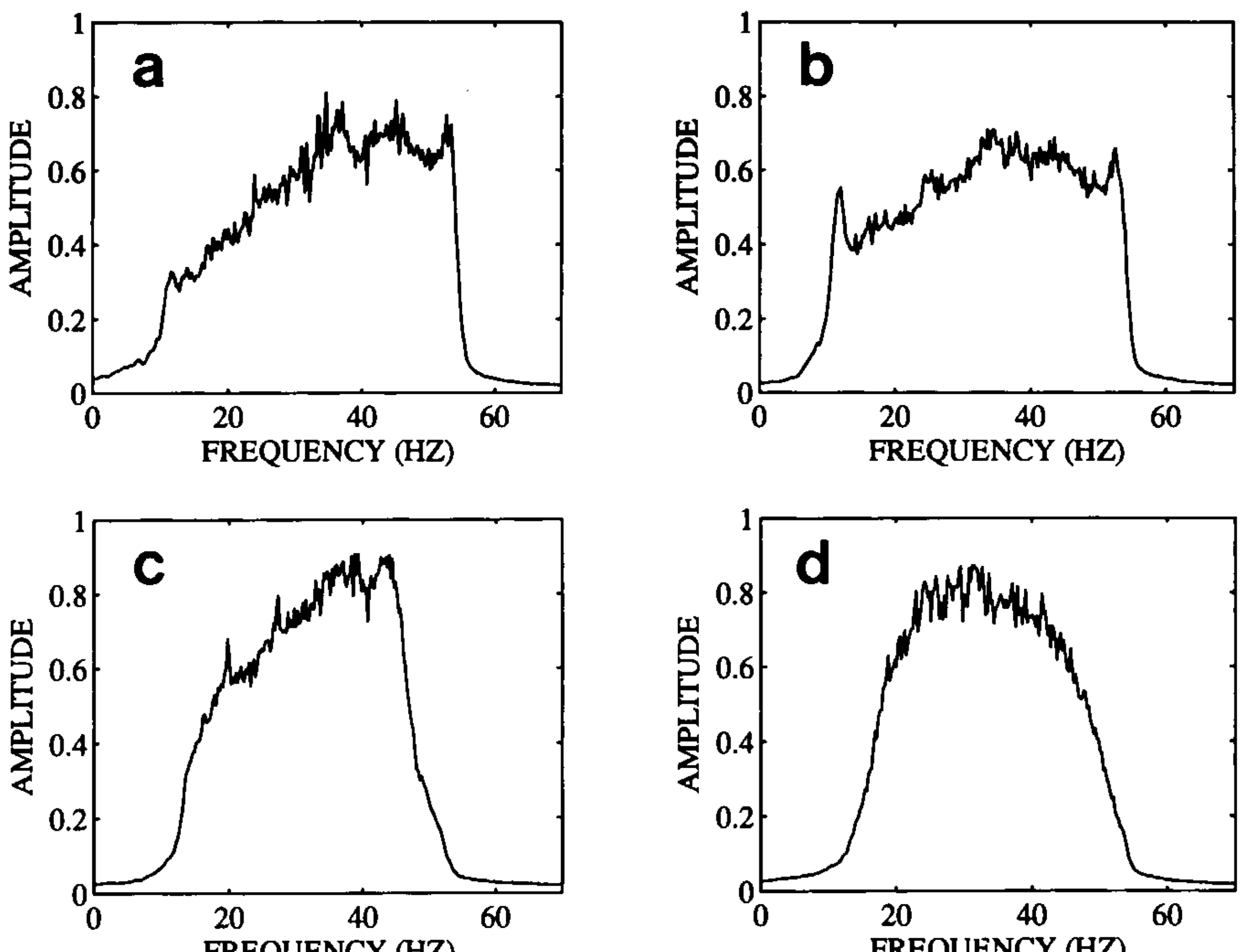


**Figure 2** *Amplitude spectra for four seismic reflection lines of the Abitibi-Grenville survey: (a) line 15, (b) line 16A, (c) line 21, and (d) line 29. These spectra were calculated on selected windows of good-quality stacked and filtered data. Each comprises 301 consecutive traces from 0.0 seconds to 4.0 seconds.*

stacked seismic data is an intermediate product. The goal of the migration process is to move (hence "migrate") reflections to their correct spatial locations. In this way, migration focusses the seismic image, correcting distortions and greatly improving horizontal resolution. Another way of saying this is that migration reduces Fresnel zones to a small zone called a focus (Claerbout, 1985; Sheriff and Geldart, 1989). The horizontal resolution after migration depends on the size of this focus, which in turn depends on the frequency content of the data and on the success of the migration. In theory, horizontal resolution can be as good as about twice the final trace interval (Claerbout, 1985), which is 50 m for the regional data and 20 m for the high-resolution data. In practice, horizontal resolution is several times the trace interval in the early portions of migrated data, and approaches the size of the Fresnel zone at late record times where migration performs poorly. Fresnel zones are surprisingly broad. For example, the Fresnel zone for 90 Hz at 3 km depth is 300 m, and for 30 Hz at the Moho it is 2.0 km. The marked improvement in horizontal resolution gained by migration is demonstrated in the example of Figure 4.

Complex 3-D geologic structures pose an irresolvable problem for a 2-D survey, such as the Abitibi-Grenville transect. 3-D geology renders a 2-D migration incomplete, resulting in ambiguity about whether reflectors lie beneath the seismic line, or off to one side. Still, an incomplete migration is better than none at all (Sheriff and Geldart, 1989; Lindsey, 1989).

**Maximum Resolvable Dip**

The maximum dip that can be recorded is normally restricted by the geophone array response, but the high seismic velocities encountered in the Abitibi-Grenville survey make the wavelengths of the signal too long to be affected by our arrays. This is a problem typical of seismic surveys in crystalline rock. Instead, the maximum dip of a seismic reflector that can be imaged on a migrated seismic section is that dip at which the reflection just begins to alias spatially. Spatial aliasing occurs when the seismic data trace spacing is too large to correctly image a dipping reflection, resulting in distortion. This distortion is worst for steep dips and high frequencies.

Spatial aliasing is minor on the data of the Abitibi-Grenville transect, so the maximum resolvable dips are potentially large. The maximum resolvable dip for the regional data varies from 80° at 10 Hz to 47° at 56 Hz, and for the high-resolution data it varies from 79° at 30 Hz to 47° at 140 Hz. As a practical matter, the maximum resolvable dip lies between the two extremes. Requiring the reflection to have a bandwidth of at least 1 octave yields a maximum resolvable dip of ~70° for both surveys. This means that geologic structure with dip greater than ~70° will not be imaged directly on our data. This is still very good, but, as discussed below, steep dips will only be imaged in the shallow data.

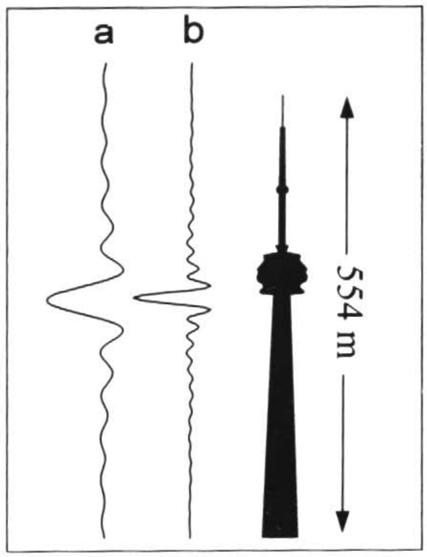


**Figure 3** *The effective source wavelets employed in the Abitibi-Grenville seismic survey compared with the CN tower for scale, appropriate for a velocity of 6 km•s$^{-1}$: (a) regional wavelet, (b) high resolution wavelet.*

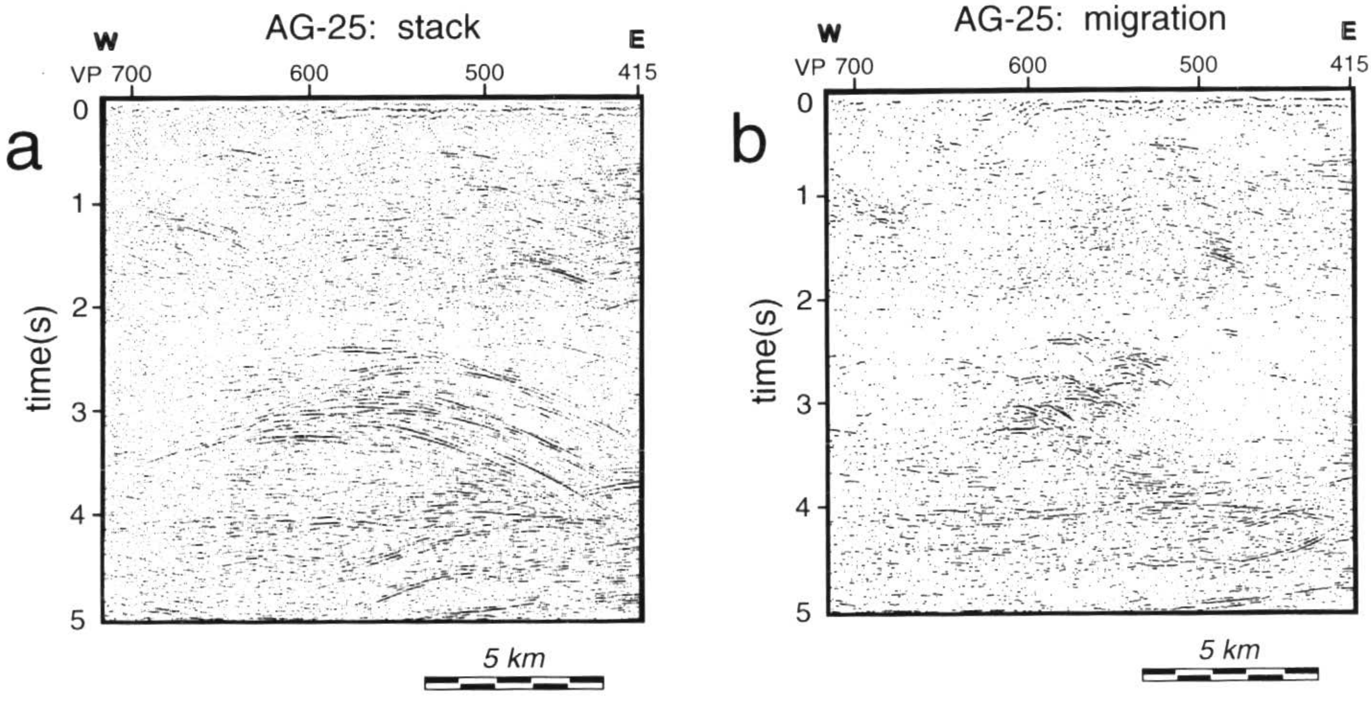


**Figure 4** *An example from Abitibi-Grenville line 25 showing that migration greatly improves horizontal resolution: (a) stack section, (b) migrated section.*

As practical rules, the total record length of a seismic line should be about 1.5 times the arrival time of the deepest reflection of interest, and a reflection should be at a distance from the end of the seismic line no less than its depth (Lynn and Deregowski, 1981; Denham, 1984). These rules are based upon requirements that must be satisfied if migration is to properly image reflectors with dip of 45° or less. The deepest reflection in the Abitibi-Grenville regional survey is the Moho, at a time of ~12 seconds. As the record length is 18 seconds, approximately 1.5 times the arrival time of the Moho, the Abitibi-Grenville regional survey satisfies the rule for sufficient record length. It is less successful in satisfying the rule for sufficient line lengths. A seismic line should have a length roughly 80 km or more in order for structure at 40 km depth to be well imaged in its center. By this rule, only the longest lines were successful: 15, 21, 28 and 32. The shorter lines are unable to image deep structure well. For example, line 24 at 20 km length images well only to 10 km, or ~3 seconds record time. At greater record times, the maximum reflector dip left after migration decreases, so that the lower crust appears dominated by flat reflectors, regardless of the true structure. Short lines are therefore less reliable at depth and must be interpreted more cautiously. Figure 5 illustrates these ideas with the example of line 28, the longest line of the Abitibi-Grenville survey.

On the high-resolution data, the zones of interest are almost all shallow at <3 km, or ~1 second record time, and have relatively limited extent. The happy result is that the line lengths are sufficient for proper imaging, and the record length, at 4 seconds, is more than sufficient.

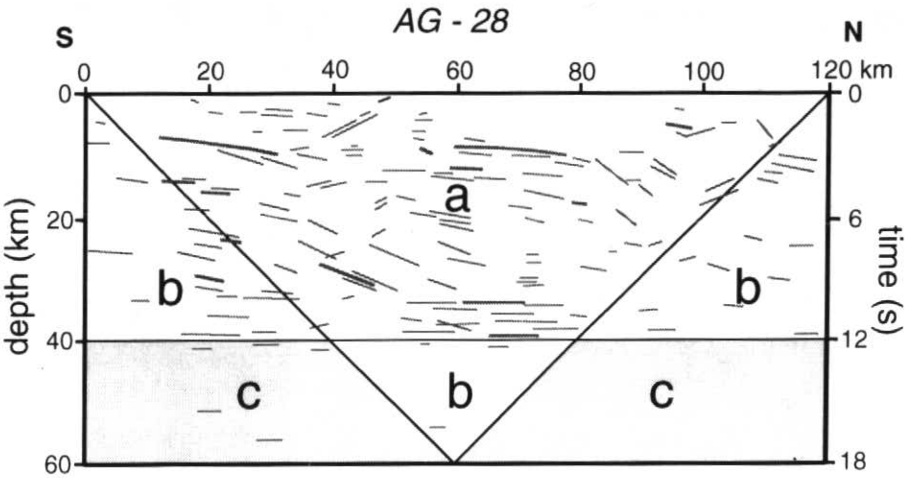


**Figure 5** *Zones of data reliability on Abitibi-Grenville line 28: (a) most reliable, (b) less reliable, (c) least reliable. These zones are determined by the ability to migrate an event of dip 45°. The depth scale assumes an average crustal velocity of 6.7 km•s¹.*

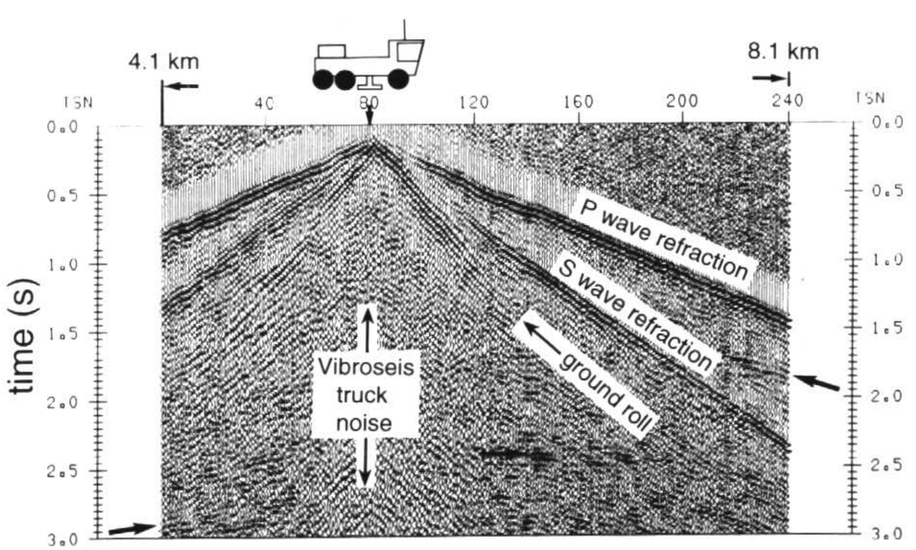


**Figure 6** *A typical shot record, from Abitibi-Grenville line 29. Solid arrows point to reflections.*

## NOISE

As with all seismic surveys, the Abitibi-Grenville survey is degraded by noise, including wind noise, cultural and traffic noise, vibroseis and recording truck noise, surface waves, converted waves, air waves, and powerline noise. Wind noise levels are low, and traffic and cultural noise are important only near a few towns and mines. Air waves are negligible. Vibroseis truck noise, as always, is important, and recording truck noise is locally important. This leaves three important types of noise: electric powerline noise, ground roll, and shear wave refractions.

### Powerline Noise

Powerlines induce 60 Hz noise in the wires and electric cables of a seismic survey. This noise adds to an analog signal, but does not effect a digital signal. In the Abitibi-Grenville survey, the analog-to-digital conversion of the data was accomplished by small boxes set in the field at every receiver station. These boxes transmitted digital data to the recording truck, thereby greatly reducing the amount of wire susceptible to powerline noise. However, powerline noise still entered through the wires that connected the geophones to the digitizing boxes.

Powerline noise is not a problem for the regional data because 60 Hz lies outside the frequency band of the 10 Hz to 56 Hz signal. It should not have been a problem on the high-resolution data either, even though 60 Hz lies in the middle of the 30 Hz to 140 Hz range of the signal, because of the noise cancellation system described above. Nonetheless, on some of the high-resolution lines, which were all recorded close to mines served by large powerlines, many field records exhibit considerable powerline noise. That means that the 60 Hz noise cancellation system failed, for reasons unknown. The failure could possibly have been caused by powerline noise with a frequency slightly different from 60 Hz.

### Ground Roll

Ground roll and shear waves are source-generated noise, meaning they are created by the seismic source along with the compressional waves that form the seismic signal (Sheriff and Geldart, 1989). Ground roll is the generic name given to any surface seismic wave. It is characterized by high amplitudes, low frequencies, and low velocities (Fig. 6). Throughout the Abitibi-Grenville survey, ground roll is controlled by the overburden, or "weathering layer," which is largely composed of various glacial deposits. Ground roll tends to be strong where the overburden is thin or lacking, and tends to be weak where the overburden is thick. The reason is as follows. Geophone arrays are designed to attenuate ground roll and to ensure against aliasing of seismic waves reflected from steep structure. The 50 m array length used in the regional survey attenuates ground roll energy of wavelength ≤56.25 m. The ground roll velocities in the overburden are, at most, ~700 m•s$^{-1}$, and so the arrays largely cancelled out all ground roll energy with frequencies >12 Hz. For the high-resolution data, the 20 m array length removed ground roll energy with wavelengths ≤22.5 m, which means frequencies ≥31 Hz. Considering the frequency content of the surveys, ground roll is effectively removed when the survey is recorded on substantial overburden.

When recording is on outcrop, the ground roll has a velocity approaching 2 200 m•s$^{-1}$. A 50 m array then removes ground roll ≥39 Hz (if there is any with such high frequency), and a 20 m array removes ground roll ≥98 Hz. Hence, the arrays were ineffective where the survey was recorded on outcrop or on thin overburden, and ground roll becomes a problem. The "stack array" (Anstey, 1986) also fails to remove this ground roll by cancellation during the stacking process because the ground roll wavetrain is too short for the stack array to be effective.

**Shear Wave Refractions**

Although shear wave refractions are rarely seen on seismic data, they are ubiquitous throughout the Abitibi-Grenville survey (Fig. 6). They are an important problem because they obscure reflections from shallow geologic structure. They tend to be strong and well defined where the overburden is thick, and nearly disappear and are ill defined where the overburden is thin. They are created by compressional waves that convert to shear waves at the interface between the overburden and underlying crystalline rock (Lash, 1986; White *et al.*, 1992; see Fig. 7). These shear-waves travel along this interface, radiating both shear waves and reconverted compressional waves back to the surface. Energy conversion is significant

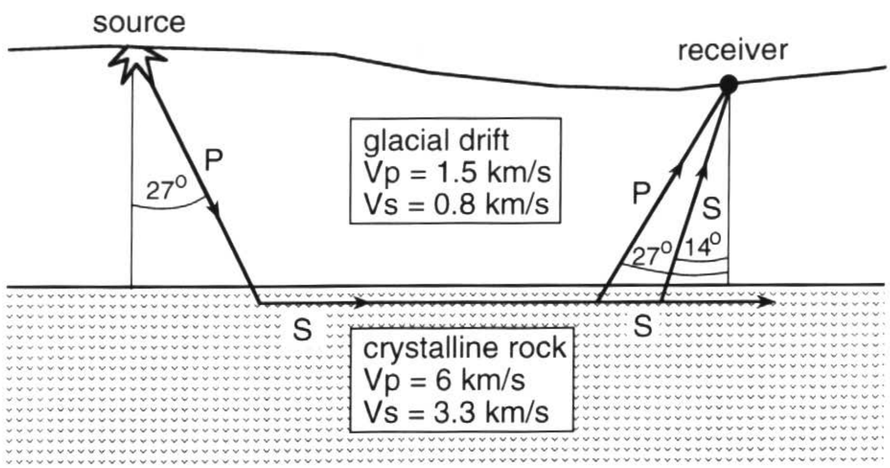


**Figure 7** *An illustration of compressional wave energy (P) converted into refracted shear wave energy (S) at the boundary between a thick glacial overburden and underlying crystalline rock.*

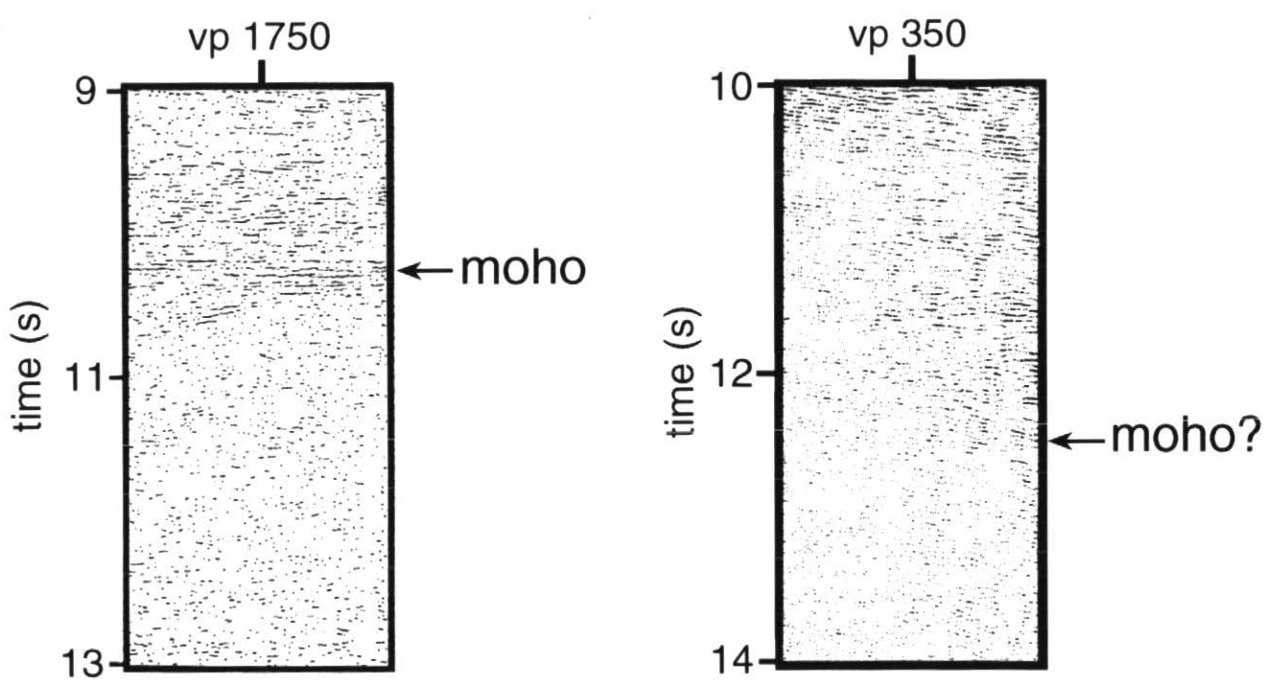


**Figure 8** *Two 5 km sections from the Abitibi-Grenville survey with marked differences in Moho reflectivity: (a) line 15, (b) line 29.*

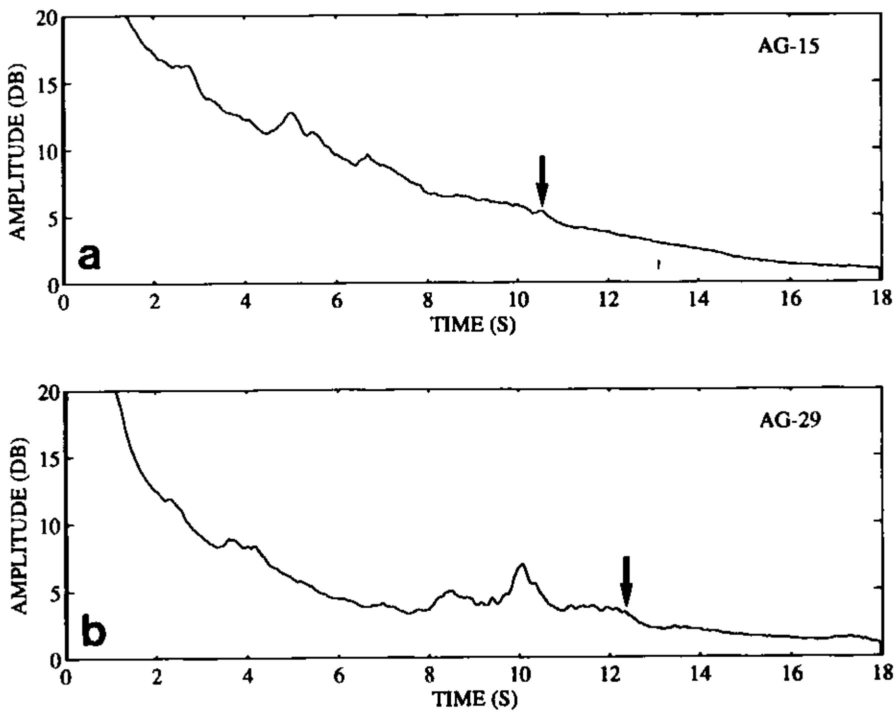


**Figure 9** *Amplitude decay analysis for estimates of signal penetration: (a) Abitibi-Grenville line 15, and (b) line 29. These were calculated from the data before stack corresponding to the sections of Figure 8. The arrows point to the position of the Moho.*

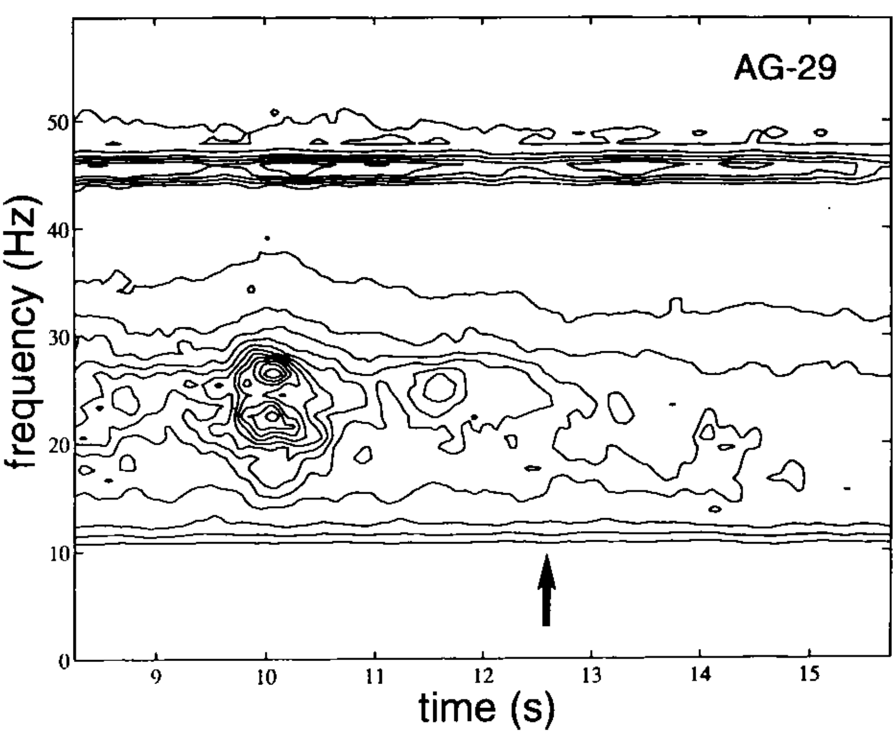


**Figure 10** *Spectrogram for line 29 corresponding to the data of Figure 8b, calculated before stack from the traces with offsets between 1 km and 2 km. The band of power at 45 Hz is engine noise from the recording truck. The arrow points to the position of the Moho.*

because of the great contrast in densities and velocities. The geophone arrays do not attenuate these waves because they arrive at the surface with raypaths close to the vertical, making the apparent wavelength on the ground far longer than the arrays. The vertical response of the individual geophones attenuates much of the refraction that arrives as a shear wave, but has little effect on the compressional wave component.

## SIGNAL PENETRATION

The maximum depth in the earth that can be explored with reflection seismology is called the limit of signal penetration. This limit exists because seismic energy decreases in both amplitude and frequency content as it propagates, due to absorption, scattering and wavefront spreading, and at some point it becomes too weak to be discerned above the prevailing noise (Mayer and Brown, 1986). The limit of seismic signal penetration corresponds to approximately that record time when the seismic amplitude ceases to change. This assumes that the noise is largely stationary, that is, with average characteristics that do not vary with time. Hence, a cessation of amplitude decay indicates that the seismic signal has been overwhelmed by stationary noise, while continued decay strongly suggests continued signal penetration in depth. This is true whether or not the returned energy is coherent.

Signal penetration is at the heart of deep reflection seismology because the goal is to image structure as deep as possible. Insufficient signal penetration can cause a die-out of reflections that resembles a lack of reflectors. Hence, before conclusions are drawn about reflectivity changes with depth, it must be established that signal penetration is adequate. This is especially necessary for the deep seismic reflection data of the Abitibi-Grenville transect because distinct and continuous Moho reflections are lacking everywhere but on line 15. Instead, the Moho appears to be characterized by patchy reflections or by a gradual die-out of reflections.

Signal penetration can be deduced from the nature of the seismic amplitude decay. Lines 15 and 29 represent extremes in Moho reflectivity (Figs. 8a and 8b): line 15, with a distinct Moho reflection at 10.5 seconds, has a penetration limit of ~16 seconds, whereas line 29, with an indistinct Moho at 12.5 seconds, has a limit of ~14 seconds (Fig. 9). This confirms adequate signal penetration and suggests that the differences in Moho reflectivity represent geologic differences. Signal penetration is better on line 15 than on line 29 because the overburden is thick on line 29, but is thin or absent over most of line 15. The deposits of sands and gravels that form the overburden are especially absorbent of seismic energy. A thick overburden layer acts like a lowpass filter, attenuating the high frequencies and thereby decreasing penetration and resolution.

Spectrograms offer a different perspective on signal penetration by showing how the seismic energy is distributed in both time and frequency. Figure 10 is a representative spectrogram, derived from the data of line 29 shown in Figure 8b. Several features stand out. The seismic signal is restricted between 12 Hz and 35 Hz. The strong band of power at 45 Hz is noise from a generator in the recording truck, which was nearby. A drop in power at 12.5 seconds corresponds with the drop in amplitude observed at the same time on Figure 9b, interpreted to represent the Moho. This demonstrates again that signal penetration is adequate to reach the Moho, and that the signal has been reduced to the 12 Hz to 35 Hz portion of the initial 10 Hz to 56 Hz source spectrum.

## DISCUSSION

The acquisition parameters of the LITHOPROBE Abitibi-Grenville seismic surveys are typical of those employed in deep continental exploration. The methods are borrowed from petroleum exploration, and the parameters are modified only to suit the scale of the experiments. Hence for deep surveying, the recording times are longer, the source is larger, the vibroseis sweep frequencies are lower, and the source and receiver intervals are greater. The parameters for the high-resolution survey are closer to those employed in petroleum exploration, although the source interval is less (20 m instead of ~50 m), the receiver interval is slightly less (20 m instead of ~25 m), and the sweep frequencies are higher. The fold achieved by both surveys (60 and 120) equals or exceeds that achieved in petroleum exploration on land (24 to 60). The acquisition parameters of the Abitibi-Grenville survey continue long-

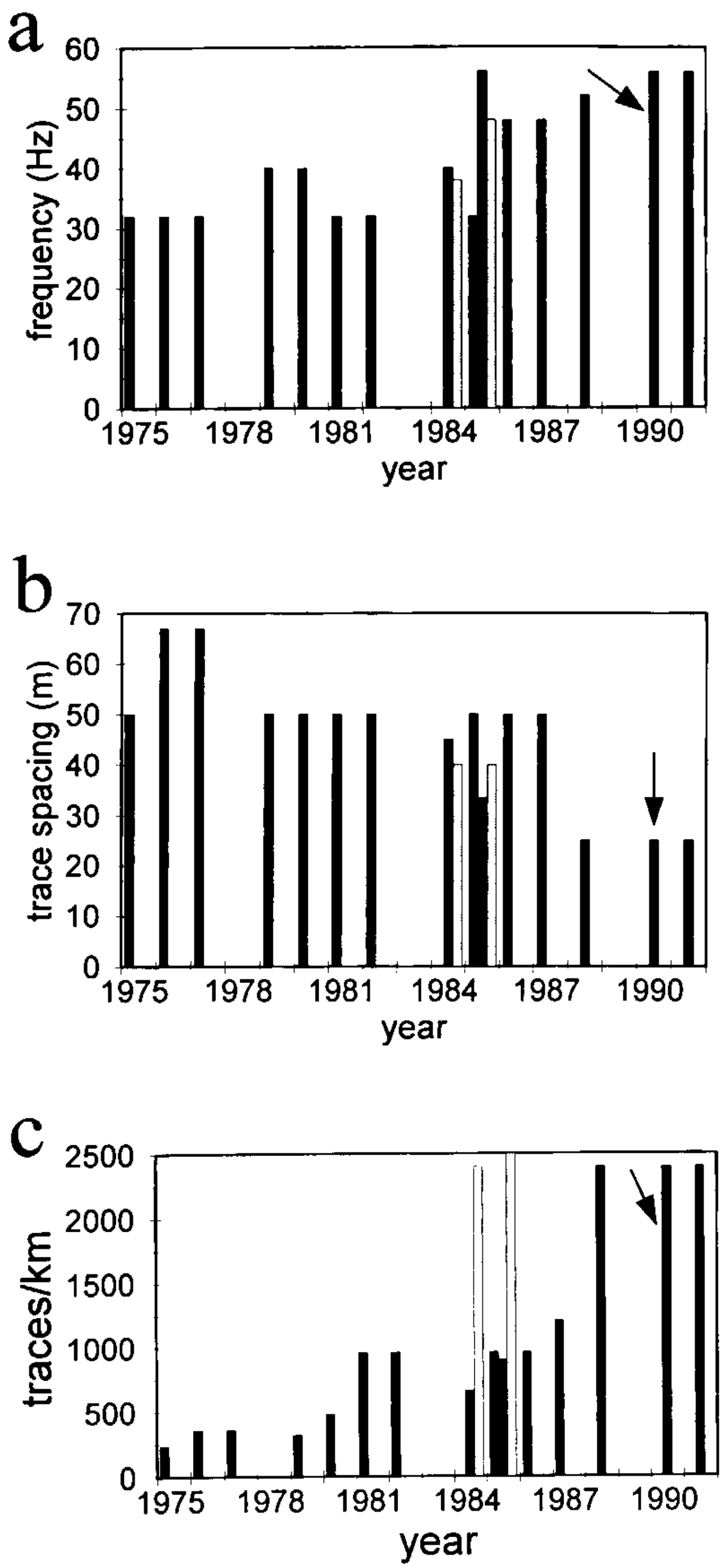


**Figure 11** *A comparison of various LITHOPROBE, COCORP, and other vibroseis deep seismic reflection surveys, showing the trends in (a) maximum sweep frequency, (b) stack trace spacing, and (c) number of prestack traces per kilometre. The arrows point to the Abitibi-Grenville survey.*

standing trends in deep reflection seismology toward higher resolution and greater data density. This is manifested by a higher frequency content, shorter trace spacing, and more traces recorded per kilometre of survey, as shown in Figure 11.

The seismic velocities encountered in crystalline rock are roughly twice those of sedimentary rock. This has several ramifications for the Abitibi-Grenville survey. High seismic velocities act to reduce vertical resolution. As a result, the high-resolution survey has about the same vertical resolution as a typical survey for petroleum exploration, even though much higher frequencies were used. High seismic velocities also increase the depth of penetration and the maximum observable dip, and they lengthen ground roll wavetrains to the extent that standard receiver arrays cannot remove them.

The principal sources of noise are vibroseis truck noise, shear wave refractions, ground roll, and powerline noise. Powerline (60 Hz) noise is troublesome on some of the high-resolution lines, in spite of the telemetry recording system and the 60 Hz noise cancellation system. Although both shear wave refractions and ground roll are widespread, the shear wave refractions tend to be strongest where the overburden is thick, and weakest where the overburden is thin, whereas ground roll is strongest where the overburden was thin, and weakest where the overburden is thick. In general, the data are better where recorded directly on outcrop or on negligible overburden, in good part because this avoids attenuation losses in the overburden. Such attenuation losses are especially severe for a high-resolution survey. Dynamite in holes that penetrate the overburden could help where the overburden is thick and where the need for greater resolution justifies the added expense.

Because the Abitibi-Grenville transect is a 2-D survey recorded across complex 3-D geologic structures, there is the unavoidable ambiguity about whether reflectors lie beneath the seismic line or off to one side. Further complications arise where seismic lines are especially crooked. These effects greatly complicate the data, and diminish their utility as a kind of geologic cross-section.

Signal penetration is adequate to reach the uppermost mantle. Therefore, the nonreflective character of the Moho seen on most lines has geologic significance, and suggests a gradational crust-mantle boundary. The 18 second record length is appropriate for imaging structure, after migration, at the depth of the Moho, corresponding to ~12 seconds. Because notable reflectivity is lacking beyond Moho record times, little would have been gained by recording longer. The short line lengths of most lines introduce a bias toward subhorizontal reflectors that increases with depth.

Several general rules for interpreting the migrated data of the Abitibi-Grenville transect can be drawn from this analysis. These rules apply, more or less, to any seismic survey recorded in crystalline rock. The first rule is "think big" because the resolution is inherently coarse, far greater than outcrop scale. The second rule is to consider the possibility of 3-D effects. Without crosslines, seismic data are ambiguous about the true location of a reflector. The third rule is to beware of the strong bias toward flat reflectors, both deep and at the sides of seismic sections. The layered lower crust seen on shorter lines could look very different if the lines had been longer. The fourth rule is to be suspicious of marked lateral changes in the seismic data that persist up and down the record. These changes often signify a problem in the survey, such as noise from a town or busy road, a sharp bend in the line, or a large variation in overburden thickness.

A fuller appreciation of the strengths and limitations of deep seismic reflection data leads to a better understanding of the earth.

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