PITFALLS IN SHALLOW SEISMIC REFLECTION

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ABSTRACT

Substantial progress has occurred during the past 15 years in development of shallow CDP seismic-reflection techniques, but there are occasional interpretation problems with the resulting data. We discuss examples of the pitfalls of the method, along with some procedures to help avoid them. Problems that often occur include spatial aliasing of ground roll, interpreting processed ground-coupled air waves as true seismic waves, misinterpreting refractions as reflections on stacked CDP sections, and not recognizing processing artifacts. Aliasing occurs when data are not sampled often enough in time and/or space. Decreasing the geophone interval by a substantial amount (such as a factor of two) will improve coherency of a true reflector, but will destroy coherency of spatially aliased ground roll. It is often difficult to separate shallow reflections from shallow refractions during processing. Reflected energy from shallow depths tends to have frequency content close to that of the direct wave and/or early refracted arrivals on field seismograms. Refractions on a stacked section tend to be a bit lower in frequency because the NMO correction in a CDP stack assumes hyperbolic moveout, while refractions arrive as a linear time-distance function. Hence, they don't stack as coherently as reflections, which decreases their frequency. Processing artifacts from inadequate velocity analysis and inaccurate static corrections are at least as troublesome on shallow reflection sections as they are on classical reflection surveys from petroleum exploration. It has been our experience that occasional field records will display unusually good reflections. These field seismograms can be used to correlate to the processed seismic sections. Unequivocally separating shallow reflections from shallow refractions is clearly one of the major limitations of the shallow-seismic reflection method at present.

INTRODUCTION

The proper use of seismic-reflection methods can help in the geologic and hydrologic characterization of the near surface at some sites. Some of the biggest problems facing environmental geophysicists today involve the delineation of preferential permeability paths to allow quantitative modeling by hydrologists. Lateral heterogeneity, unexpected faulting and/or stratigraphic layering, and flow anisotropy are some of the critical factors that limit the effectiveness of hydrologic predictions. Seismic reflection, when appropriately used in conjunction with other techniques, can often provide useful structural and/or stratigraphic information for input to models. Incorrect or inappropriate interpretation of seismic data, however, can hinder rather than assist the modeling process. We present some basic experimental and analysis procedures that can help discriminate true reflections from pseudo-reflections.

Substantial progress has occurred during the past 15 years in development of shallow seismic-reflection techniques. The optimum-window technique (Hunter et al, 1984) is now widely and routinely used in engineering, environmental and ground-water applications. Our own research has focused on extending the limits of the resolution and the applications of shallow seismic reflection using common-depth-point (CDP) techniques and extensive routine

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digital processing (Steeples and Miller, 1990). Each of these techniques has a place in shallow exploration (Pullan et al, 1991). Both approaches to shallow seismic-reflection profiling have potential for misuse by individuals who do not pay close attention to the most basic fundamentals of seismogram analysis. It is the purpose of this paper to point out some of the pitfalls of the methods and how to avoid them or at least decrease the chances of erroneous interpretations.

It is impossible to evaluate an interpretation of a processed shallow seismic reflection section without having access to at least one field file and possibly copies of one or more of the intermediate processing steps. Problems that often occur include spatial aliasing of ground roll, enhancing (or not attenuating) ground roll during CDP processing, interpreting processed ground-coupled air waves as true seismic waves, misinterpreting direct waves as reflections on stacked CDP sections, and not recognizing processing artifacts. Near-surface refractions can also be misinterpreted as reflections on stacked CDP sections, and we consider this to be one of the most serious problems and limitations of the shallow reflection method today. In the following paragraphs, we discuss examples of some of the pitfalls that can be avoided in recording, processing, and interpreting shallow seismic-reflection data.

DATA COLLECTION PITFALLS

Field Testing

Before performing a CDP survey at a new site, it is necessary to perform field testing. Some practitioners either try to use pretty much the same setup and field parameters, regardless of the location or objective of the project or they stick firmly to generalized "rules-of-thumb" that often work. We always budget at least a half day (preferably a whole day) of walkaway noise testing at the beginning of each project. We take two sets of geophones and at least two possible types of seismic sources (i.e. weight drop, explosive, projectile) and at least a couple sizes of each (i.e. 12 and 20 lb sledge hammer, 8 and 12 gauge downhole shotgun) with us to each new project. We have a large selection of possible filter combinations available, and we always try at least three filter settings on the walkaway test. It is also advisable to try geophone station spacing on walkaways that is half what is probably needed for the production survey and to use shot-to-geophone offsets to at least one and one half times the depth of the target.

There are good reasons for recording shallow reflection data without analog locut filters, the chief among them being phase distortion and loss of bandwidth. However, the overriding consideration must be the limited dynamic range of the seismograph, particularly with instruments that do not have floating point amplifiers or A/D conversion of 16 or more bits. If the gain of the seismograph is not high enough to set at least one or two bits most of the time with reflection data, then the cause is lost from the beginning. Alternatively, if the gains are too high and the data are clipped, the reflection data are recorded in an ambiguous way that renders them useless.

The relative amplitudes of reflections compared to ground roll are to some degree a function of coupling to the ground. It is well-known that the best coupling under most circumstances is obtained with geophones firmly planted, usually on long spikes. To the degree that the geophones are poorly coupled to the ground, ground roll is enhanced relative to reflections because poor coupling favors low frequencies (see Krohn, 1984; Hoover and O'Brien, 1980, for example.)

When we arrive at a site, we have a specific set of parameters in mind for planning purposes, but we find that most of the time we change at least one or two of the parameters when we start the production phase of the survey.

Ground Roll

Ground roll has been a problem for hydrocarbon-exploration seismologists since the 1920's. Generally speaking, it is less a problem in shallow surveys than in deep ones. We have performed shallow reflection surveys at over 100 sites, including locations with volcanics at or near the surface and sites with water tables 200 or more feet below the surface. We have never worked at a site where the reflections in the upper 300 ms were not at a frequency nearly double that of the ground roll. That is not to say that they do not exist, but we have never seen shallow reflections with dominant frequencies that low, relative to the dominant frequency of the ground roll. Hence, it is usually possible to decrease the amplitude of the ground roll by frequency filtering, or by a combination of frequency filtering and f-k or tau-p filtering. This assumes the dynamic range of the equipment is great enough to allow the recording of reflection energy in the presence of high amplitude noise. This is not always the case even with systems with quiet electronics and 16 bits or more of A/D conversion.

Alternatively, if the reflections can be maintained in the Hunter optimum window, the ground roll can sometimes be removed by surgical muting.

Frequency of Data Too Low for Shallow Reflections

There is a lower limit to acceptable frequency on any shallow reflection survey. This can often be determined by ray-trace forward modeling or by simple calculations. For example, let us assume for the moment that we try to record shallow reflections at a time of 30 ms with a field situation that produces only 40 Hz data. Assume further that the first arrival comes in at 10 ms on the nearest trace on the field files, which would not be uncommon for such a shallow survey. Note that in this example, the trailing edge of the first arrival wavelet would not clear out until about 35 ms on the near-offset traces, which comes from the period of a 40 Hz wavelet (25 ms) being added to the 10 ms for the first arrival. Hence, any energy on the stacked sections at times less than 35 ms would be contaminated with direct waves, and it would not be possible to record useful reflection records at 30 ms under this set of circumstances.

In reality, the first arrival will nearly always ring just a little bit. In other words, a 40 Hz dominant-frequency wavelet in the above example will not be totally out of the way even after 35 ms. Hence, a few additional milliseconds must pass before reflection information can be recorded without interference in this example.

Our students and colleagues have tried every technique that we can think of, including tau-p and f-k filtering, and slant stacking to separate refractions and direct waves from shallow reflections. The only thing that we have found that consistently works is to use much higher frequencies than are commonly used for deeper reflection surveys. Obviously, in some localities it is not possible to work at frequencies that are high enough to allow us to separate the reflections from ground roll, refractions, and direct waves. In such cases, the seismic reflection method is inappropriate in its present stage of development.

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Spatial and Temporal Aliasing

Aliasing occurs when data are not sampled often enough in time and/or space. For instance, buggy wheels sometimes appear to turn backward in western movies even though it is obvious that the buggy itself is moving forward. This phenomenon occurs because the movie camera does not sample the viewing field often enough to accurately represent what is actually happening. Aliased images appear to be something they are not, hence the name. If aliasing can make buggy wheels appear to turn the wrong direction, imagine how seriously aliasing might affect seismic data.

Temporal aliasing is prevented in modern engineering seismographs by factory-installed anti-alias high cut filters. Some modern seismographs will automatically select an appropriate anti-alias filter and implement it before recording data. Other machines require the operator to make a conscious adjustment to the seismograph each time the sample rate is changed. The important thing to remember is that the anti-alias filter must attenuate signals at the Nyquist (aliasing) frequency by at least 24 dB, preferably more. The Nyquist frequency is half the sample rate. The problems of and solutions to temporal aliasing are well known in the seismology and digital signal processing businesses, so we do not dwell on the subject here.

Less well known, however, are problems of spatial aliasing where data are not sampled sufficiently often in space. An example of spatially aliased shallow seismic data is given in Steeples and Miller (1990, p. 10). The authors have noted the occurrence of spatial aliasing of ground roll at several sites over the past decade. The unsuspecting seismologist might take spatially aliased data and build a whole survey around it only to wonder later why the "reflector" disappeared in processing or, worse yet, one might plot aliased common-offset ground roll as an interpretable reflection. We have developed a few tricks listed below to help avoid that trap:

(1) If a coherent event on a field file seismogram is a true reflector, moving the shotpoint about one or two geophone intervals (or fractional intervals) closer to (or further away from) the geophone spread will have essentially no effect on the appearance of the reflector. If the coherent event is spatial aliasing of ground roll, the effect is often substantial, especially if the near-surface is not flat and uniform.

(2) Decreasing the geophone interval by a substantial amount (such as a factor of two or three) will improve coherency of a true reflector, but will destroy coherency of spatially aliased ground roll.

(3) If something is known geologically about the site (such as uphole traveltime, depth to bedrock, the availability of a sonic or other geophysical log, etc.), it is possible that the geologic information can be used to determine when the reflection should be expected on the record and what its normal moveout (NMO) should be. Steeples and Miller (1990) provide a pocket calculator program for calculating a least-squares-fit hyperbola to a set of T and X points measured directly from a field file seismogram. The inputs to the program are two or more arrival times of the suspected reflector along with their corresponding shot-to-geophone distances. The program solves for NMO velocity, intercept time (To), depth-to-reflector interface, and correlation coefficient of the reflection hyperbola to the data points. The reader should remember that the correlation coefficient is meaningless unless three or more time-distance measurements are included as inputs. The output from the program can be of tremendous help in field analysis of seismograms regardless of whether the reflectors are real. We caution the reader that this will not help to separate reflections from refractions, because the transformation performed by this program simply changes a linear refraction arrival into a different linear form.

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(4) Reflected energy from shallow depths tends to have frequency content close to that of the direct wave and/or early refracted arrivals on field files. If the observed frequency on field files or on displayed common offset or CDP sections is much lower than the first arrivals, then the energy is probably from ground roll rather than from reflections.

PROCESSING PITFALLS

Ground-coupled Air Wave

Most seismic sources emit some noise that people standing nearby can hear. This noise often couples into the ground, or at least to geophones attached to the ground. The resulting ground-coupled air waves (often called air blast) can cause tremendous problems in processing shallow reflection data. Our experience shows that if severe low-cut filters of 200 Hz or higher are used, air blast waves commonly show a dominant frequency near that of whatever low-cut filter is used on the data. If little low-cut filtering is used, the dominant frequency of the air blast is usually in the 150 Hz and higher range. It is very difficult to effectively remove air blast with simple frequency filtering. We prefer to use a muting window to surgically remove the air blast. We have found that f-k filtering must be used with caution in removing air blast to avoid enhancing components of the air coupled wavelet that stack coherently on CDP sections. In most cases due to the long duration of the air-coupled wavelet (several cycles) some portion of the high frequency wave will fall outside the mute window in f-k space. The portions of the air wave that remain could stack coherently at velocities consistent for near-surface materials. The problem is more dramatic if the data are scaled or trace balanced after the filtering process.

Miller and Steeples (1990, p. 11) show an example of a CDP seismic section with apparent coherent reflections at 60 to 70 ms that are air blast, and not true reflections at all. We are aware of a high resolution seismic-reflection survey in which about a dozen "reflections" were interpreted on a section processed by experienced professionals. Close inspection revealed that all of the "reflections" had a dominant period of about 9 ms, from times of 80 ms to 600 ms. Furthermore, the "reflections" had the highest signal to noise ratio where the CDP fold was smallest. Signal to noise ratio of reflections on CDP stacked sections should increase proportionally to the square root of the fold, rather than decrease with increasing fold. Reprocessing of the data with an appropriate surgical mute of the air blast revealed that no usable reflections were present, and that the whole geologic interpretation, complete with sand lenses that supported drill data, was based on CDP stacking of air blast.

Refractions

It is often difficult (if not impossible) to separate shallow reflections from shallow refractions on field files prior to or during processing. Reflected energy from shallow depths tends to have frequency content close to that of the direct wave and/or early refracted arrivals on field files, so they cannot be easily separated by frequency filtering. Also, wide angle shallow reflections and shallow refractions have phase velocities that are very similar, which prevents the effective use of f-k filtering to remove only refractions. Sometimes the refractions and reflections interfere with one another, either destructively or constructively, over a large range of geophone offsets. It is not possible to use f-k filtering to separate overlapping events with such similar phase velocities because of the side-lobe effects of the filters.

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While it is often difficult to distinguish refractions from reflections on field files, it is nearly impossible to separate unequivocally shallow reflections from shallow refractions on processed sections without looking at the field files. One clue to look for on a processed seismic section is a frequency inversion with depth. Under normal geologic circumstances, the frequency of reflections on a shallow-reflection section decreases with depth because of attenuation with increased travel paths. If inspection of a seismic section shows the apparent frequency of coherent events changes from low frequency at small reflection times to higher frequency at deeper times, the chances are good that shallow refractions have been stacked into the data.

During NMO correction in a CDP processing scheme, the reflection times undergo a transformation from a hyperbola to a straight line. True shallow reflections typically lose 20% to 30% of their high frequency information in this process due to NMO stretch (Miller, 1992). Refractions are also stretched by a similar amount, but because they do not respond in phase to a hyperbolic transformation, the mis-alignment of individual wavelets that is present during CDP stacking drastically reduces their apparent dominant frequency.

The most common pitfall is the mis-identifying of a refraction as a reflection. However, it is possible to make the opposite mistake and throw away a genuine reflection because it looks like a refraction. One way to avoid that mistake is to make time and distance measurements on a field file and work the problem as a refraction problem to see if an essential contradiction develops. Simply measure the velocities and intercept times of the first arrivals of the direct wave and of the refraction/reflection that is in question. Plug these measurements into the basic refraction equations for a layer over half space and solve for the critical distance. If the critical distance is greater than the distance at which the phase is observed, it must be a reflection because a refraction cannot exist at distances smaller than the critical distance.

In the case of two or more layers over half space, the same set of refraction calculations can be done to see if an essential contradiction in the refraction assumption develops.

Another clue occurs when the apparent structure on a stacked section mimics the surface topography. While this is not impossible geologically, it is a warning flag that suggests the possible presence of refractions, incorrect static corrections, or an incorrect near-surface velocity model.

It is interesting to note that the geologic conclusions reached on the basis of assuming an event is a reflection may be correct even if it is, in fact, a refraction. Because increased depth to a velocity discontinuity leads to increased intercept times of refractors as well as to increased two-way reflection times, stacking of refraction arrivals with CDP reflection software can sometimes lead to a correct geologic interpretation with totally inappropriate and erroneous geophysical analysis!

It has been our experience that occasional field records will display unusually good reflections. These field seismograms can be used to correlate to the processed seismic sections. The refracted arrivals can also be carefully muted, field file-by-field file, during the early stages of the processing to reduce the chance of them stacking in on the section. For quality control purposes, it is sometimes useful to process the data leaving the direct waves and refractions in the data, just to see where they end up on the processed sections. The resulting sections can be used as a diagnostic tool to make sure refractions, or vestiges of refractions, are not present on the final processed section where surgical muting of refractions was used. Unequivocally separating shallow reflections from shallow refractions is clearly one of the major limitations of the shallow-seismic method at the present time.

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Processing Artifacts

Processing artifacts from inadequate velocity analysis and inaccurate static corrections are at least as troublesome on shallow reflection sections as they are on classical reflection surveys from petroleum exploration. It has been our experience that occasional field records will display unusually good reflections. These field seismograms can be used to correlate to the processed seismic sections.

We find that deconvolution of shallow reflection data commonly degrades the quality of reflections. One or more of the theoretical assumptions of deconvolution (Yilmaz, 1987) are usually violated with shallow data. For one thing, the high-frequency components of the source wavelet commonly change substantially as near-surface conditions change. Hence the wavelet changes with horizontal location, which violates one of the main assumptions of spiking deconvolution. Secondly, the frequency of shallow reflectors often changes rapidly with depth in the earth, a problem that can be at least partially addressed with time-varying deconvolution. Also, with shallow reflection data there are usually not enough reflective horizons to represent a random reflectivity series, which is one of the primary assumptions of statistics-based deconvolution algorithms. The presence of only one, two or three reflectors does not constitute a random time series of reflectors. Finally, the signal to noise ratio of shallow reflection data sets is notoriously poor, and this is exacerbated by the use of deconvolution.

The use of an f-k filter (or other filter) does not "remove" refractions, ground roll, and air waves; it can only suppress certain aspects of them. If there is no reflection information present in the seismic data, the vestiges of refractions, ground roll, and air waves that invariably remain in the data after filtering, as well as artifacts from wrap-around and bandwidth problems, can (and often do) process nicely into things that look like reflections but are not. This is why it is imperative to see at least occasional reflections on the raw field files, or at least on frequency filtered field files. Otherwise, there is no way to know for certain that the data show legitimate seismic reflections. In every successful shallow reflection survey with which we have been involved, we have been able to extract a convincing reflection from at least one field file or one CDP gather by simple scaling and/or frequency filtering.

The use of f-k filtering and deconvolution together can generate processing artifacts. If a data set contains spikey noise on several traces or several shots as a result of faulty electronics or other sources, the deconvolution operator is inverted at the base of its window and scaled proportionally to the amplitude of the spike. The f-k filter operation can spread this contamination to other traces because of its trace-mixing characteristics. To test whether a data set has that problem, vary the operator window length up and down by a factor of two or three. Theoretically the deconvolution operation should be most sensitive to reflection wavelets within the autocorrelation window. If the wavelet moves more than a few milliseconds, it is almost certainly a processing artifact rather than a reflector.

The processor's choice of automatic gain control (AGC) window length can have a tremendous effect on how a seismic section looks. Displaying the data with an AGC window of both 50 ms or 500 ms, for example, can sometimes give a substantially different set of conclusions, or at least a very different look to the seismic section.

Many processing flows that can be used have the potential to make coherent events, which in turn can be erroneously interpreted as reflections. In addition to the processes noted above, residual statics and dip filters, for example, are also coherency filters. Also, horizontal stacking (mixing or adding adjacent traces) favors coherency and sets up the other coherency filters to manufacture "reflectors".

When to Quit Processing

Sometimes the brute stack stage is a good place to stop and conclude that the data do not contain sufficient reflections to continue the project. We have never been able to satisfy ourselves that we are dealing with genuine reflection data if we can't see it on either the field files or the brute stack.

INTERPRETATION PITFALLS

If one is confident that the above pitfalls (and others not listed) have been avoided, the geologic interpretation can begin, which is the whole purpose of the seismic survey in the first place. Some coherent peaks on a seismic section indicate individual reflections and some do not.

Because deconvolution is so seldom successful on shallow seismic reflection sections, the effects of source wavelet shape are often present on a seismic section. As a result, an individual reflector may be represented by one or two (or more) peaks, depending on the acoustic impedance contrast at individual interfaces. The wavelets shown in source comparisons (Miller et al, 1986; 1992) for typical shallow sources result in two peaks for individual reflections from a surface where a larger acoustic impedance is encountered. Conversely, when reflecting from an interface with a material having a smaller acoustic impedance, most of these shallow seismic sources produce only one peak per reflector.

Interpretation pitfalls can be avoided to some degree by the careful and judicious use of synthetic seismograms or, at a minimum, check shot data. Provided some well control and some geophysical logs are available, it is often possible to generate synthetic seismograms that can be used to tie reflections to individual geologic units. This can help immensely in making a correct geologic interpretation, which in most cases must ultimately be tested by other methods, including confirmation drilling in critical spots.

Low Fold on Some Geophones

Sometimes the recording geometry, the optimum recording window, and the depth to reflectors combine in such a way that fold of the processed data varies greatly with depth on a seismic section. In that case, if full fold is 12, for example, calling the data for the whole section 12-fold is highly misleading.

In some cases the fold may drop so much that the data on the shallowest parts of the section more closely resemble a common-offset section. If the signal-to-noise is great enough, one might try plotting the common offset sections for one or more of the near-trace offsets after the statics and filter have been applied (both with and without the distorting NMO correction) to see if any of the common offset sections resemble the final stacked section. This can help during the interpretation of CDP sections.

Pullan and Hunter (1985) showed that substantial distortion of the reflected wavelet occurs at wide angles as the angle varies with shallow reflections. It is possible that the common offset sections from one or more of the closer offsets can provide important information from reflected wavelets that have not been distorted by NMO corrections. Caution should be taken that close-offset single traces are not corrupted by over-filtering, producing apparent high frequency wavelets that are not real.

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CONCLUSIONS

As the cost per channel of modern seismographs and the cost of hardware and software to process the resulting data have decreased, the shallow seismic reflection technique has become available to a larger number of users. This in turn has resulted in new applications of shallow seismic reflection surveys. Occasional interpretation problems with the resulting data stem partly from the fact that, while the physics is the same for shallow and deep reflection surveys, the relative importance of various parts of the physics varies between the two types of surveys.

The shallow seismic-reflection method has tremendous potential for misuse, so one must be exceptionally careful not to misinterpret as reflections those many coherent waves that are not, particularly wave coherencies that are developed or enhanced by digital processing. Problems that often occur include spatial aliasing of ground roll, interpreting processed ground-coupled air waves as true seismic waves, misinterpreting refractions as reflections on stacked CDP sections, and not recognizing processing artifacts. It has been our experience that occasional field records will display unusually good reflections. These field seismograms can be used to correlate to the processed seismic sections.

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