Shallow refraction seismology for the new millennium

Derecke Palmer
University of New South Wales, Australia
d.palmer@unsw.edu.au

SUMMARY

In the last fifty years, the advances in shallow refraction seismology have been very modest. There have been few developments comparable to CMP, digital processing, or the 3D methods of reflection seismology.

The most critical requirement is the development of an efficacious method for digital processing using the complete seismic refraction trace. Digital processing is an essential requirement for deriving more information from existing data as well as for efficient handling of the increased volumes of data typical of most 3D surveys.

The refraction convolution section (RCS) is a new method for the digital processing of seismic refraction data. It can result in more detailed geological models of the subsurface through the convenient use of amplitudes as well as traveltimes. It also facilitates the examination of important issues such as signal-to-noise ratios, the resolution of ambiguities in refractor models, 3D refraction methods and azimuthal anisotropy, signal processing to enhance second and later events and stacking data in a manner similar to CMP reflection methods.

The RCS provides an effective domain for the advancement of shallow refraction seismology using the model provided by seismic reflection technology.

Key words: RCS, 3D, refraction, anisotropy, amplitudes

INTRODUCTION

In the last fifty years, there have been major advances in the acquisition, processing and interpretation of seismic reflection data. These advances have been driven largely by the spectacular developments in the electronic and computer industries.

The first was the common midpoint (CMP) method for acquiring data (Mayne, 1962). CMP methods improve the signal-to-noise (S/N) ratios of primary reflections through stacking redundant data.

The second was the application of signal processing with digital computers (Yilmaz, 1988). Digital processing achieves improvements in S/N ratios through the attenuation of coherent and random noise and some types of multiple energy, with CMP stacking and velocity filtering. It can also improve vertical resolution with deconvolution, and lateral resolution with migration or imaging.

In the last twenty-five years, three dimensional (3D) seismic reflection methods have revolutionized the exploration for, and production of petroleum resources. Where data were once acquired along single profiles, they are now obtained over densely sampled grids in the great majority of surveys (Weimer and Davis, 1996). The improved images of the subsurface geology are a result of the recognition that most geological targets are in fact three dimensional, and that it is essential to employ spatial sampling densities and processing methods which recognize and accommodate this reality. It is now generally accepted that in many cases, two dimensional seismic reflection methods can give an *incorrect* rather than an *incomplete* picture of the sub-surface (Nestvold, 1992).

An integral component in the interpretation of the increased volumes of data is the use of computer-based interpretation programs. These programs facilitate the extraction of more and greater detail and therefore, the generation of more complex geological models.

There have been similar advances in the airborne magnetic and radiometric methods used in the geological mapping of fold belts (Gunn, 1997). The advances have occurred in the improved resolution of the instrumentation, the higher density of spatial sampling, the quality of the processing and the greater detail of geological interpretation of the data with image processing methods.

RECENT INNOVATIONS IN SHALLOW REFRACTION SEISMOLOGY

By contrast, the advances in shallow seismic refraction methods over the same period of time have been very modest. There have been few developments comparable to the common midpoint method, digital processing, or the 3D methods of reflection seismology.

Most research has focused on the inversion of scalar first arrival times. They include the standard approaches, such as wavefront construction methods, the conventional reciprocal method, (which is also known as the ABC method in the Americas, Hagiwara's method in Japan, and the plus-minus method in Europe), Hales' method, and the generalized reciprocal method (GRM). In recent decades, model-based inversion or tomography (Zhang and Toksoz, 1998; Lanz et al, 1998) has become popular.

Many of the standard approaches for inverting shallow seismic refraction data share fundamental similarities through the addition of forward and reverse traveltimes to obtain a measure of the depth to the refracting interface in units of time, and the differencing of the same traveltimes to obtain a measure of refractor wavespeeds. Many methods also employ refraction migration in order to accommodate the offset distance, which is the horizontal separation between the point of refraction on the interface and the point of detection at the surface. Furthermore, most of these methods can be demonstrated to be special cases of the GRM, (Palmer, 1980; Palmer, 1986). Nevertheless, there are still publications which seek to emphasize differences between the disparate inversion methods, rather than reach a consensus on the intrinsic similarities. They represent a defensive and backward-looking culture which has done little to promote innovation in shallow refraction seismology (Palmer, 2000a).

There have been few advances in the acquisition of shallow refraction data. This can be largely attributed to the limited capabilities of most field systems, and the use of traditional field operations. While the channel capacity of most reflection field crews has increased from about 96 in 1980, to in excess of 1000 in 2000, the equivalent increase for most shallow refraction crews has been from 12 to 24 channels. In addition, few if any, shallow refraction field crews in Australia employ radio shot firing systems. Such systems have been available for many decades and they represent the application of relatively simple and readily available technology for improving the efficiency of field operations.

Standard field operations are still largely based on the static geophone spread with multiple shot points (Walker and Win, 1997). With this approach, 15 or more collinear shots which are located both within the geophone spread and at various offset positions on either side, are recorded with a linear pattern of 12 or 24 geophones. The geophone spread is then re-deployed beside the previous set-up, commonly with an overlap of 2 geophones. A more efficient roll along approach, which is the norm for acquiring CMP reflection data, produces more data from the critical near surface layers but less shot points per unit distance. Commonly, there can be a reduction of up to 40% in the number of shot points. Continuous single-pass roll-along acquisition methods can result in more reliable interpretations, less environmental impact and lower unit costs (Palmer, 2000b).

In the last two decades, the roles of most geophysicists in the petroleum and mineral exploration industries have changed from having a significant data acquisition and processing component, to being largely an interpretation role in conjunction with other geoscientists. This has been made possible through the extensive use of specialist seismic contractors who have maintained competitive costs and continual advancement of their products and services. Similar changes in emphasis from acquisition and processing towards interpretation and the generation of more complex geological models have yet to occur with most groups using shallow seismic refraction methods.

In many cases, the shallow seismic methods are applied to geotechnical investigations, and as a result, they reflect an engineering culture which is characterized by conservative approaches, risk minimization and standard practices. It contrasts with the culture of the exploration industry which is characterized by experimentation, risk taking and innovation.

In summary, most shallow seismic refraction operations have not taken advantage of advances in technology for acquisition, processing or interpretation, they are under-capitalized and they are inefficient. Where shallow refraction methods were once perceived to follow reflection methods by twenty years, the difference is now nearer half a century.

DIGITAL PROCESSING WITH THE RCS

The point of departure for this paper is that the current methods of acquiring, processing, and interpreting seismic reflection data provide compelling models for the advancement of shallow refraction seismology. Of these, one of the most critical aspects is the development of an efficacious method for digital processing using the complete seismic trace. Digital processing is an essential requirement for deriving more information from existing data as well as for efficient handling of the increased volumes of data which are typical of most 3D surveys.

This paper presents a new method for digital processing of shallow seismic refraction data with the refraction convolution section (RCS), (Palmer, 2001a). It is simple, efficient and very rapid. The RCS generates a time cross-section similar to the familiar reflection cross-section through the convolution of forward and reverse traces. The addition of the traveltimes with convolution is equivalent to that achieved graphically with Hales' and wavefront methods and arithmetically with the GRM. Accordingly, the RCS shows the same structure on the refracting interface in units of time as do many of the standard methods of inversion. The convolution process also multiplies the amplitudes and to a very good approximation, it compensates for the effects of geometrical spreading and dipping interfaces. The RCS facilitates the examination of important issues such as S/N ratios, the resolution of ambiguities in refractor models, 3D refraction methods and azimuthal anisotropy, signal processing to enhance second and later events and stacking data in a manner similar to CMP reflection methods.

Past use of amplitudes in shallow refraction seismology has been virtually non-existent, mainly because of the very large geometric spreading component. It can be much larger than the theoretically derived reciprocal of the distance squared function and it dominates any geological effects. The geometric spreading component also results in varying S/N ratios across the refraction spread, and therefore varying accuracies with measured traveltimes. The compensation for the geometric effect with convolution equalizes S/N ratios, and results in RCS amplitudes which vary as the square of the head coefficient, the expression relating head wave amplitudes to the petrophysical parameters.

In addition to the large geometric spreading component, the use of head wave amplitudes has been limited by the lack of a convenient quantitative relationship with petrophysical parameters. Although the original formulations of the head coefficient were first published more than forty years ago, they are sufficiently unwieldy to prevent their use in most applications. Just as the normal incidence approximations of the Zoeppritz equations are used widely in reflection seismology, so there is a need to develop a convenient form of the head coefficient, for use in routine shallow refraction seismology.

The proposed approximation of the head coefficient is the ratio of the specific acoustic impedance (wavespeed-density product) in the upper layer to that in the refractor (Palmer, 2001b). This approximation facilitates the application of head wave amplitudes to a number of important problems.

The first is the fundamental issue of non-uniqueness which is not adequately addressed with most current approaches to refraction inversion. Amplitudes can be useful in resolving many ambiguities in determining wavespeeds in the refractor.

Secondly, amplitudes provide an efficient means of improving spatial resolution, particularly with 3D sets of data, because they provide a measure of wavespeeds at each point whereas the use of traveltimes generally provides a measure over several detectors. The improved resolution is comparable with that achieved with tomographic inversion, but without the need to acquire more than an order of magnitude of additional data.

The third application of amplitudes is in the qualitative measurement of azimuthal anisotropy using 3D acquisition methods. Azimuthal anisotropy, which can be caused by foliation, fracture porosity, etc. is a measure of rock fabric which can be of considerable importance in environmental, groundwater and geotechnical investigations. Although there has been a small number of studies of azimuthal anisotropy, mainly with series of 2D profiles of varying azimuth over relatively uniform refractors, none has sought to resolve refractors exhibiting both complex 3D structure and anisotropy. Significant variations in depths, wavespeeds and azimuthal anisotropy can occur in the refractor in the cross-line as well as the in-line directions, and each can be resolved with the application of simple processing methods to relatively small volumes of data, using standard methods such as the GRM.

The use of amplitudes has also been limited by the ubiquitous concerns about the effects of coupling of the geophone with the ground on the observed amplitudes. However, the major cause of "amplitude statics" is variations in the petrophysical properties, usually the wavespeed, of the near surface layers, and there are relatively simple methods for recognizing and accommodating these effects.

Another long-standing limitation of traditional shallow seismic refraction processing methods has been the almost complete reliance on the first arrival signal. Although the potential value of later events to assist in the resolution of undetected layers or in shear wave studies has often been noted, nevertheless there are no widely accepted approaches to the use of the complete seismic refraction trace. The convolution operation also generates a relative time-depth profile for any later events and it can be highlighted with simple processing methods such as dip filtering of the RCS in the f-k domain.

An important advantage of convolution is the preservation of the phase relationships. The most common energy sources for shallow seismic refraction surveys are impulsive sources such as explosives or dropping weights, which generate minimum phase wavelets. When two such minimum phase wavelets are convolved with one another, as is the case with the generation of the RCS, then the resultant is also minimum phase. Accordingly, the time structure determined in the RCS correlates with that computed with the traveltimes measured on the shot records. It also is facilitates further processing in order to improve vertical resolution using, for example, deconvolution.

Perhaps one of the most important implications of the compensation for the large geometric effect and the equalization of S/N ratios with the RCS is that it facilitates stacking in a manner similar to the CMP methods of reflection seismology. Stacking may eventually achieve improvements in S/N ratios sufficient to reduce the relatively large source energy requirements of acquisition, which traditionally have limited the application of refraction methods because of cost and environmental impact. Furthermore, it is possible that stacking in the RCS may promote fundamental changes in data acquisition which are necessary to achieve much needed efficiencies in field operations, as well as to generate data with suitable fold or redundancy for stacking.

In summary, the use of head wave amplitudes can result in more detailed geological models of the subsurface, and the RCS can provide an effective and convenient domain for processing and interpreting shallow seismic refraction data in order to obtain the amplitude information. Furthermore, many of the benefits of the RCS can be maximized with acquisition programs which resemble those used in current seismic reflection surveys. Accordingly, the RCS provides a suitable domain for the continued advancement of shallow refraction seismology using the model provided by current seismic reflection technology.

SHALLOW REFRACTION SEISMOLOGY FOR THE NEW MILLENNIUM

The point of departure for this paper was that most current shallow seismic refraction operations have not taken advantage of advances in technology for acquisition, processing or interpretation, they are under-capitalized, and they are relatively inefficient. What then are the major features of seismic refraction operations which might be appropriate to the requirements and the technology of the new millennium?

A major conclusion of this paper is the superiority of 3D results over 2D. There is simply no substitute for the improved quality and quantity of information which can be obtained from even simple cost-effective 3D surveys such as those described here. It is essential that 3D refraction methods be adopted as a matter of some priority.

It is likely that the acceptance of 3D shallow refraction methods will parallel the acceptance of 3D reflection methods by the petroleum exploration and production industries and the acceptance of high resolution airborne magnetic and radiometric data by the mineral exploration industries. Initially, cost was considered to be the major reason for the relatively low levels of acceptance of these methods. However, this situation changed rapidly when it was widely demonstrated that high spatial sampling densities in all directions, is one, if not the most important factor, in reducing risk through improved geological interpretations.

The development of a 3D oriented approach implies the use of specialist seismic contractors for acquisition in order to employ field systems with greatly increased capabilities, as well as to promote efficient field operations. It is difficult to justify the use of relatively expensive professional expertise to carry out routine unskilled field duties with under-capitalized systems and inefficient operations.

Increasing channel capacity to at least 150 and doubling the number of shot points could achieve efficient 3D field operations. This would result in an increase of at least an order of magnitude in the amount of data, and in turn it would dictate the use of efficient methods of data processing and interpretation. Full trace processing with the RCS is a simple and efficient approach for processing *any* volume of seismic refraction data.

It is likely that the increased quantity and quality of data obtained with 3D surveys might stimulate a change in the roles of the geophysicist from acquisition and processing towards interpretation. It also implies inclusion of other geoscientists at earlier stages of the interpretation process, in order to generate more complex and more geologically meaningful interpretation models.

The format of data processed with the RCS facilitates the convenient application of current reflection processing and interpretation technology to shallow seismic refraction data. Although the existing software developed specifically for refraction seismology represents many man-years of effort, it is relatively insignificant when compared with the software developed for reflection seismology. Just as the use of imaging processing software, which was developed originally for remotely sensed data, has increased the detail of the geological interpretation of magnetic, radiometric and gravity data, so seismic reflection software is a vast resource which has the potential to extract even greater information from refraction data. In particular, the data processed with the RCS is suitable for analysis with software used for the interpretation of processed seismic reflection data. Such software includes basic functions for picking times and amplitudes of horizons, as well as post-processing functions, such as attribute analysis. Attribute processing of RCS data may have as large an impact on increasing the detail of the interpreted geological model as it has with reflection data.

The author's preference for an approach which is essentially an extension of the GRM, is hardly surprising. However, other approaches, such as tomography are currently not viable alternatives. The major shortcoming of tomography is that the large increase in the number of shot points, commonly by at least an order of magnitude over a simple GRM approach suggested here, would result in high and possibly prohibitive costs of acquisition. Furthermore, tomography has yet to satisfactorily address either the issues of non-uniqueness, large variations in wavespeeds in the refractor, or anisotropy.

The RCS offers a new approach to generating more complex geological models from shallow seismic refraction data through the use of the complete seismic refraction trace and therefore, the use of amplitudes as well as traveltimes. In time, it may stimulate the development of routine refraction methods which are comparable in sophistication to current 3D reflection methods.

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