Chapter 1

Introduction

Geophysicists have long been interested in using reflection seismic data to determine interval velocities (the propagation speed of seismic waves within given layers, or intervals, of sediment). Many different approaches have been tried. The most interesting are those that allow velocity to be determined even in the presence of strong lateral velocity variations. Such approaches are apt to be kinematic: that is, based on travel time rather than on wavelet shape or amplitude. They are also likely to be based on ray tracing rather than on the wave equation.

I propose such a kinematic, ray-tracing-based approach. It is similar, at first glance, to the method of tomographic traveltime inversion (Bishop et al., 1985). This latter method derives its name from its use of picked traveltime data to determine interval velocities and depths of reflecting horizons. The term "tomographic" does not have a precise definition. It is typically used, however, to describe methods such as this one, which are kinematic and based on ray tracing. The tomographic method is often associated with inversion of borehole-to-borehole traveltime measurements, but this association is not exclusive; the tomographic method can be used to invert reflection seismic data as well.

There is a major difference between my approach and that of tomographic traveltime inversion. Bishop et al. use traveltime picks from interpreted horizons (horizons are discontinuities between sedimentary intervals that give rise to strong reflections). I, on the other hand, use traveltimes and ray parameters that can be picked automatically from common-shot and common-geophone gathers. The automated picking of such parameters is the basis of the method of Controlled Directional Reception (CDR), which is described in Chapter 2. I do not assume that horizons are continuous; I assume only that the seismic wave field has reflected from short reflectors or from diffractors. I invert only for interval velocities, not for reflector positions or horizon depths. Because of the differences between my method and standard tomographic traveltime inversion, a different approach to the inversion problem is necessary.

1.1 The objective function

Inverse problems are usually formulated in terms of a search for the minimum of an objective function, where the objective function describes the mismatch between the real data and the data predicted by a model. Typically, tomographic velocity inversions seek to minimize the discrepancy between observed and predicted traveltimes. I have chosen a somewhat unusual objective function. Rather than trying to minimize the traveltime error, I attempt to minimize the horizontal distance between the endpoints of each pair of down-going and up-going rays. The results of CDR picking are used as input data to this minimization problem, so I refer to my method as CDR tomographic inversion.

Some tomographic methods operate under the assumption that the rays travel in straight lines. Like Bishop et al. (1985), I allow curvature of rays. It is possible with some methods to invoke Fermat's principle as justification for using the same raypaths over several iterations, even though the velocity may have changed. My objective function, however, does not allow this.

1.2 Optimization

My objective function, which is based on the distance between the endpoints of rays, is non-linear. I use the Gauss-Newton technique to minimize it. An initial velocity model is chosen, and the rays that correspond to the various traveltime and ray-parameter picks are traced through this model to find the value of the objective function. In conjunction with the ray tracing, differential values are found to describe how the ray paths (and thus the value of the objective function) change with respect to small changes in velocity. These results are used to form a linearized least-squares inversion problem. This least-squares problem can be solved by a conjugate-gradient method; the solution is used to update the velocity model. Rays are traced in the new velocity model, re-linearizing the problem, and thus the sequence of iterations continues.

The tomographic inversion scheme has been successfully tested on noise-free and noisy synthetic data. The inversion has also been tested on real data with good results.

It is not always possible to distinguish effects due to velocity variations from effects caused by variation in horizon depth (Stork and Clayton, 1986). Some of these ambiguities are eliminated, however, when data from more than one reflecting horizon are available.

1.3 Advantages and disadvantages

There are several advantages to the CDR tomographic method that is proposed in this paper. No assumptions are made about the shape or continuity of the reflectors. Data obtained from point diffractors will thus work as well as data from flat, dipping, curved, or faulted horizons. The picking is automated, so there is no need to interpret horizons and digitize traveltimes manually. The traveltime and ray-parameter picks occupy much less space than the original data set, saving both processing time and data storage space. These savings are particularly significant when 3-D data sets are considered (section 5.5, page 68). Many methods require two-point ray tracing, where a ray must be found that travels from a particular shot to a particular geophone. Two-point ray tracing is expensive, since it requires that many rays be traced in order to find the one unique ray that travels between two specific points. My method uses one-point ray tracing, in which the take-off point and take-off angle are known, and a single ray is traced. One-point ray tracing is much cheaper than two-point ray tracing.

The CDR tomographic method also has some disadvantages. Unlike the method of tomographic travel time inversion, the CDR tomographic method is not based on the implicit assumption that reflectors are continuous. A certain amount of robustness is lost as a result: the "focusing" of horizons is not used as a criterion in the inversion. Reflector position is not assumed to provide any information about the velocity structure; thus, sharp velocity contrasts at the reflectors are not incorporated into the model. Since the data are picked automatically, the inversion may be adversely affected by multiples and other coherent noise that a human interpreter could easily exclude. There is also the general problem inherent in any method where rays are traced—rays are fickle, and the smallest changes in velocity can cause them to shoot off in unpredictable directions. Solutions to the wave equation are usually more stable in this regard.

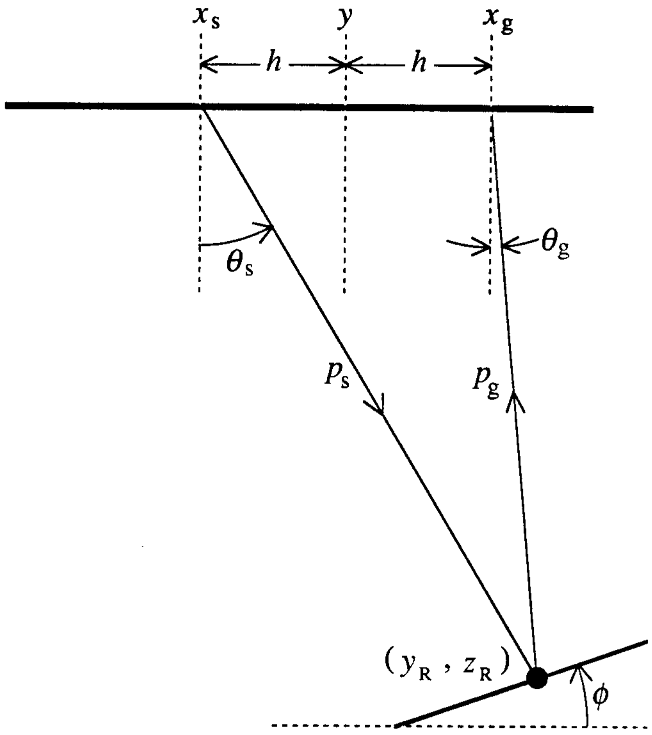

Figure 1.1: Typical recording geometry. The figure is drawn so that all parameters shown on it are positive.

1.4 Notation

It is useful, for the sake of clarity, to establish a consistent system of notation. Figure 1.1 shows a typical recording geometry. The notation used is:

x_s	Shot position
x_g	Geophone position
h	Half offset: $(x_g - x_s)/2$
y	Midpoint: $(x_g + x_s)/2$
y_R, z_R	Reflector position
t	Traveltime
p_s	Ray parameter of the down-going ray ($p_s = -dt/dx_s$)
p_g	Ray parameter of the up-going ray ($p_g = -dt/dx_g$)
θ_s	Angle (from vertical) of the down-going ray
θ_g	Angle (from vertical) of the up-going ray
ϕ	Angle (from horizontal) of the reflector

1.5 Summary of the thesis

Chapter 2 is a review of the CDR method. Methods of picking traveltime and ray parameters from the seismic data are described, and some simple techniques to image the data are shown. An important concept is that of CDR velocity: each set of picked parameters can be used to determine an average velocity in the medium. This CDR velocity, different for each set of picked parameters, can be used in velocity filtering.

Chapter 3 begins with a short historical overview of kinematic methods for solving the interval-velocity problem. The method of tomographic velocity inversion is then described, and synthetic results are shown.

Chapter 4 shows the results of processing field data.

Chapter 5 contains a discussion of possible future directions, including the inversion of 3-D and converted-wave data. Shortcomings of the current method are identified, as well as ways to overcome some of these problems.