Chapter 1

Introduction

The determination of seismic interval velocity is one of the main goals of exploration geophysicists when they are analyzing seismic data. The information about interval velocity can directly help the geological interpretation of seismic data, but its most important use is in the migration of the data. Migration needs an accurate velocity model to position correctly the geological interfaces and to focus the reflections. The goal of this thesis is to present a method for estimating interval velocities in cases in which conventional methods fail; that is, when there are dipping reflectors and the velocity varies rapidly in the lateral direction.

The proposed method uses the seismic data transformed by a local stacking operator, which I name "beam stack". The velocity model is estimated from the beam-stacked data by use of a tomographic procedure.

1.1 VELOCITY ESTIMATION FROM REFLECTION SEISMIC DATA

The goal of velocity analysis is to determine a velocity model to be used for migrating seismic data. Migration images the geological interfaces in the earth's interior by removing the effects of wave propagation from the data. To focus properly the reflectors at the original positions, migration needs a velocity function that predicts accurately the propagation effects of velocity on the recorded reflections. Only the primary reflections are usually imaged by migration, and thus the velocity function needs to model accurately only the transmission of the propagating waves, and not their back scattering. The transmission of seismic waves is most strongly influenced by the low-wavenumber components of the velocity model; thus the solution of the velocity-estimation problem is a model that accurately matches the low-wavenumber components of the actual earth velocity. The higher wavenumbers of the velocity are subsequently determined by migration. The result of migration is a map of reflectivity in the subsurface (Claerbout, 1984).

The low-wavenumber components of velocity mostly affect the traveltimes of the reflections, which are integral measures of the velocity function. Therefore traveltimes, more than amplitudes, are used for estimating velocity. In particular, the moveouts of the reflections, that is, the traveltimes as a function of offset, are the key elements in determining interval velocities. The conventional velocity analysis is based on the assumption of layered medium and consequent hyperbolic moveouts, but, as I will discuss in the next section, more general methods are needed with complicated earth models.

1.2 CONVENTIONAL VELOCITY ANALYSIS

The conventional methods for estimating seismic velocity are based on the measurements of stacking velocities. Stacking velocities are determined by measurements of the coherency of the data, sorted in common-midpoint (CMP) gathers, along hyperbolic trajectories in offset and time (Taner and Koehler, 1969). When the earth is layered and velocity is varying with depth, interval velocity can be approximately determined from stacking velocity by use of Dix formula (Dix, 1955), which assumes the equivalence of stacking velocities to root-mean-square (RMS) velocities. But when velocity varies laterally, and there are dipping reflectors, stacking velocities cannot be equated to RMS velocities and interval velocity cannot be estimated with the Dix formula.

When there are dipping reflectors the measured stacking velocities must be corrected by a factor equal to the cosine of the dip (Levin, 1971). If the dips are not known, or if there are conflicting dips in the data, the data must be corrected before stacking by use of the dip-moveout process (Bolondi et al., 1982; Hale, 1984). Unfortunately, even after the application of dip moveout, stacking velocity can be a multivalued function of zero-offset time: reflections with different dips are originated at different depths and thus they propagate through layers with different velocities. In these cases the contradictory information on interval velocity provided by stacking velocities can be unscrambled only by taking into account the angles of propagation of the reflections.

When velocity changes considerably within the span of a cable length, the moveouts of the reflections in a CMP gather are not hyperbolic. The non-hyperbolic moveouts can still be fitted with hyperbolic trajectories, but the simple, one-dimensional model assumed by the Dix's formula is not valid. The interpretation of stacking velocity as RMS velocity would lead to gross errors in the determination of interval velocity.

In areas in which dipping reflectors or rapid lateral variations in velocity cause the layered-earth assumption to break down, the relation between the kinematics of the reflections and interval velocity must be modeled by ray tracing instead of the simple Dix's formula. Ray tracing can be analytical in the simplest cases, or numerical when the velocity model is complicated. The velocity model is reconstructed by back projecting along the raypaths the discrepancies between the kinematics of the reflections measured from the data and the results of ray tracing. This procedure is similar to classical tomography, as it is used in medical imaging or cross-well seismic (Bois et al., 1972; Ivansson, 1985), and can be considered as "reflection tomography".

Figure 1.1 shows an example of a data set recorded in the Adriatic Sea and requiring a tomographic velocity estimation (Harlan, 1989; Leger et al., 1989). In the stacked section the time pull-down of the reflections around the midpoint location at 5.5 km is caused by a low-velocity anomaly. The anomaly is narrower than the cable length and thus stacking velocity analysis cannot be used for estimating the migration velocity. At best, stacking velocity can be used to estimate a velocity model that slowly varies in the lateral direction. Figure 1.2 shows the result of migrating the stack with such a velocity. The reflectors have been approximately focused, but the effects of the anomaly on the positioning of the reflectors have not been corrected.

1.3 REFLECTION TOMOGRAPHY FROM BEAM-STACKED DATA

In conventional tomography the absolute errors in traveltimes of the direct arrivals can be simply back projected along the raypaths, because the first breaks are easily detected and the positions of the sources and receivers are exactly known. Reflection tomography presents the additional difficulties that the reflections are not easy to detect, and the reflectors' positions are unknown. The way of solving these problems distinguishes the many tomographic methods that have been proposed for estimating interval velocity in complex areas.

The most straightforward adaptations of conventional tomography to the reflection

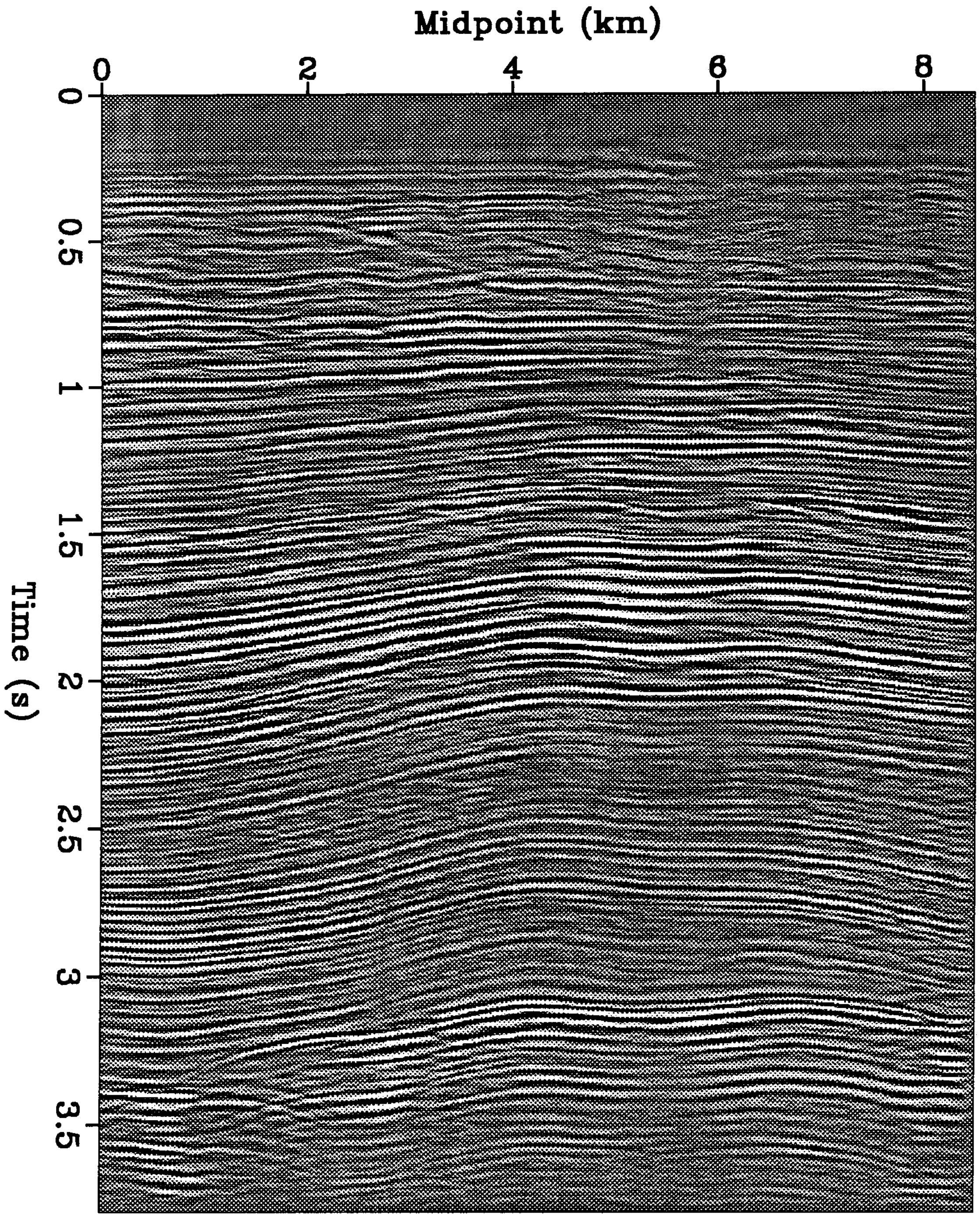

FIG. 1.1. The stacked section of a data set that needs a tomographic velocity estimation. A low velocity anomaly causes the time sag near the midpoint location of 5.5 km.

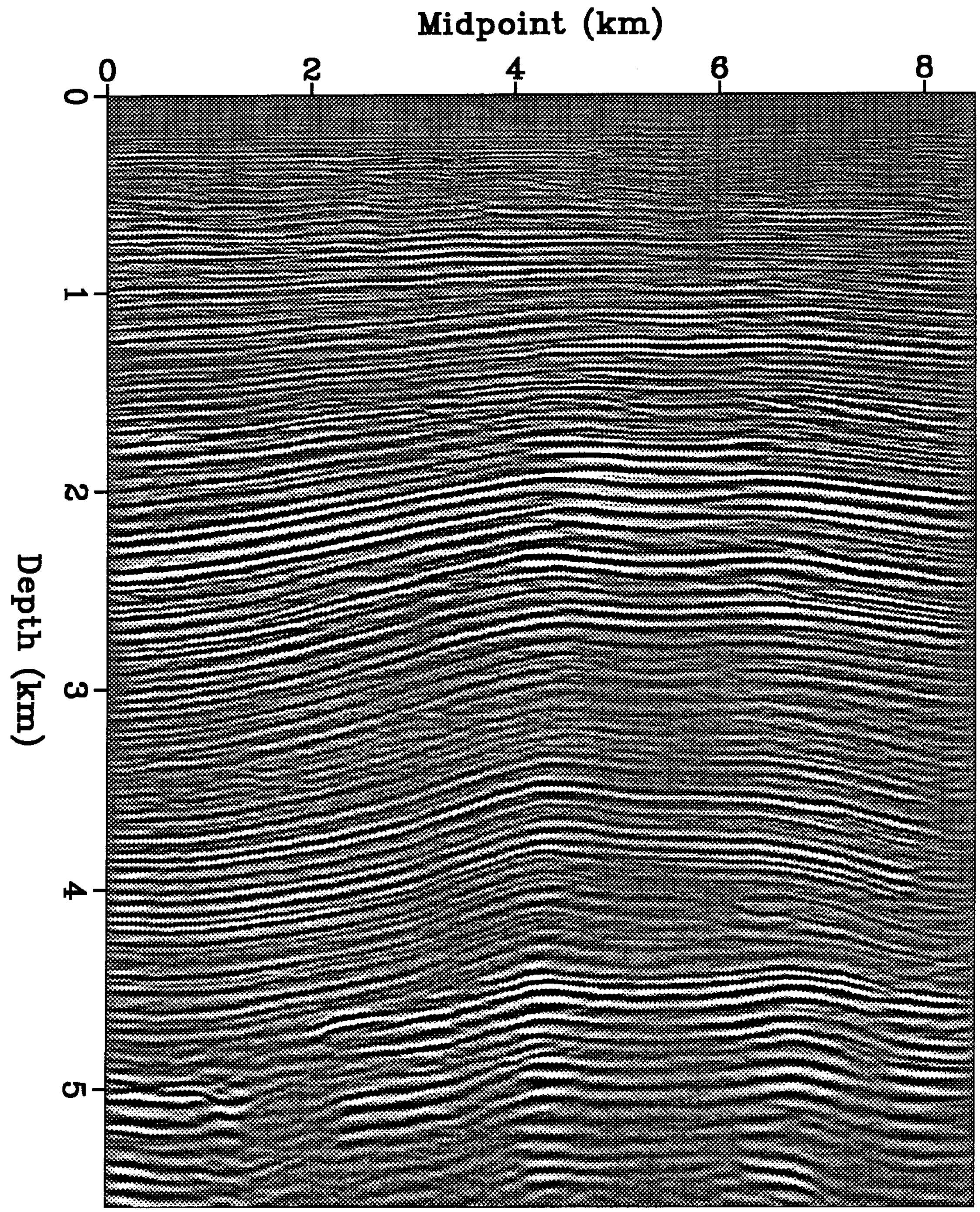

FIG. 1.2. The result of migrating the stacked data using the best velocity model that could be determined by conventional stacking velocity analysis.

experiment are the methods that are generally designated with the term "traveltimes tomography" (Bishop et al., 1985; Stork, 1988). These methods estimate the velocity model and the reflectors' positions from traveltimes picked from prestack data and horizons picked from migrated sections. The main drawback of these methods is that they require that the traveltimes of the events to be picked. Picking not only is a time-consuming procedure, but it is also subject to systematic errors that can seriously limit the reliability of the results. Furthermore, only the reflections with amplitudes considerably above the background noise can be picked reliably, and thus only part of the information contained in the data is used for the estimation.

Indirect measures of the moveouts in the data, such as stacking velocities (Toldi, 1985; Harlan, 1989) or prestack-migration velocities (Fowler, 1988), can be used instead of traveltimes picked from the prestack data. These measures contain information on the traveltimes because they determine which are the stacking hyperbola, or the prestack-migration diffraction curves, that best fit the moveouts in the data. The advantage of using these imaging operators for extracting information on the traveltimes is that the resulting measures are more reliable than the picks of the single traveltimes because they are computed by stacking together many seismic traces. Their limitation is that the moveouts of the reflections are described by only one parameter, stacking velocity or migration velocity. One parameter is not sufficient to completely describe non-hyperbolic moveouts; consequently some information on the traveltime is lost and the resolution of the velocity estimation is decreased.

Figure 1.3 shows an example of non-hyperbolic moveouts caused by lateral velocity variations. The CMP gather is from the Adriatic Sea data set and the non-hyperbolicity is caused by the low-velocity anomaly. The raw data are shown on the left side, while the same data after the application of a hyperbolic normal moveout with velocity of 2.79 km/s are shown on the right side. Residual time delays of about a quarter of a cycle of the seismic wavelet are uncorrected by the hyperbolic normal moveout.

1.3.1 Measuring reflections' moveouts by beam-stack

There is a trade-off between tomographic methods that use picked traveltimes, which provide a complete, but uncertain, description of the moveouts of the reflections, and the methods that use coherency measures, which contain more reliable, but incomplete, information on the moveouts. The tomographic method presented in this thesis uses

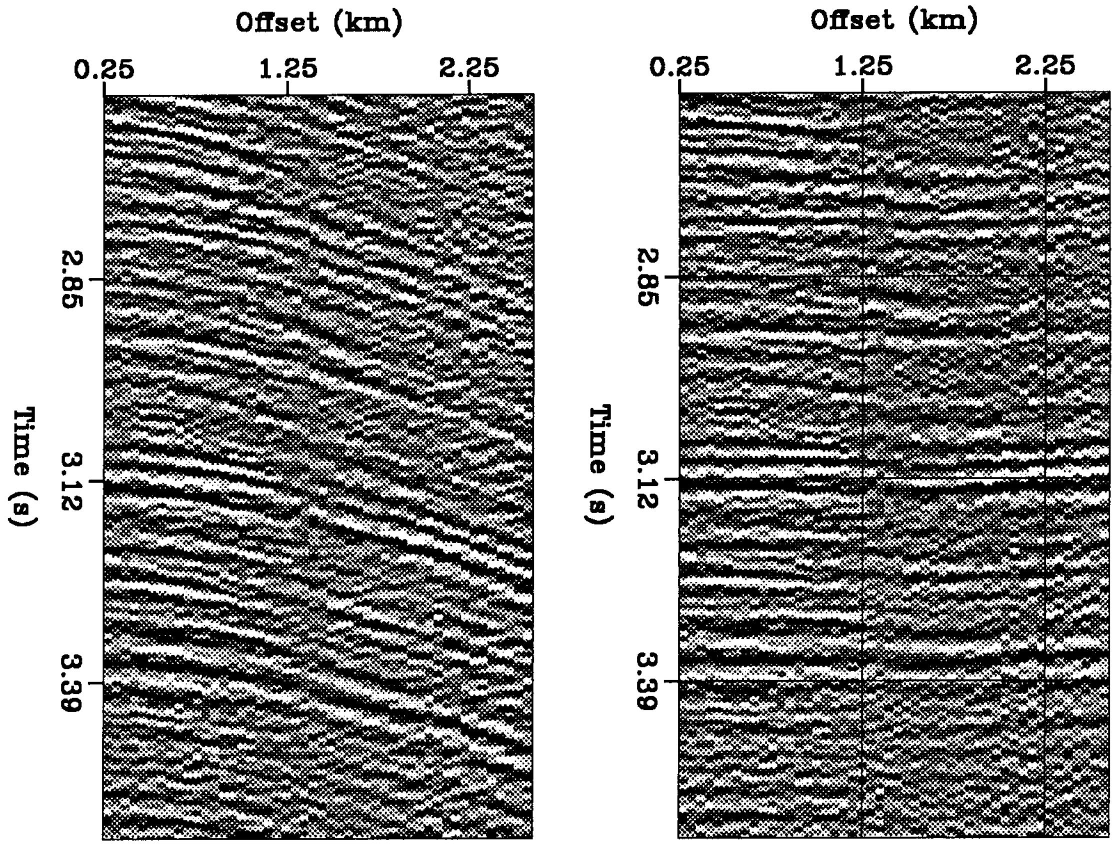

FIG. 1.3. A CMP gather from the Adriatic Sea survey containing non-hyperbolic moveouts caused by the velocity anomaly. The data before (left) and after the application of an hyperbolic normal moveout with velocity of 2.79 km/s (right).

measurements of the moveouts obtained by local coherency operators. Local stacks are more reliable than picked traveltimes, and they provide more detailed information on the moveouts in the data than imaging operators, which measure the coherency of the data over the whole cable.

Sword (1987) presented a method for estimating velocity from data transformed with local slant stack (Trorey, 1961; Hermont, 1979). The traveltimes and the ray parameters of the transformed data are picked together with the surface locations by an automatic procedure. Using an automatic procedure to pick the slant-stacked data is possible because slant stacking enhances the reflections. After picking, the velocity model is fitted to the picked values by a tomographic estimation procedure.

Instead of slant stack for transforming the data I use beam stack (Kostov and Biondi, 1987). Beam stack is a local stacking operator with curved stacking trajectories (hyperbolic or parabolic). The curvature of the trajectories can be determined given the traveltime, the offset, and the derivative of traveltime with respect to offset (Chapter 2). The use of curved stacking trajectories, instead of the straight trajectories of slant stack, improves the resolution of the transformation. The resolution of stacking operators is proportional to their "effective" length, that is, the length of the trajectories on which reflections are summed coherently (Appendix A). The curved stacking trajectories of beam stack well approximate the hyperbolic moveouts in the data and thus their effective length is not limited to the Fresnel zone of the reflections, as it is the length of local slant stack. The trajectories' length of beam stack can be adapted to the needs of the particular data set at hand and thus beam stack is a flexible tool for extracting velocity information on the moveouts of the data.

Being local coherency operators beam stacks can provide information on non-hyperbolic moveouts in the data, such as the reflections shown in Figure 1.3. Figure 1.4 shows beam stacks' semblance as a function of offset and ray parameter for the reflection shown at 3.12 s in Figure 1.3. The black line superimposed onto the semblance plot shows what the offsets would be as a function of the ray parameter if the moveout were perfectly hyperbolic. The non-hyperbolicity of the moveout is evident from the beam stacks; it is actually more evident in the beam stacked data than in the data shown in the usual time-offset domain (Figure 1.3).

When beam stacks are applied to non-hyperbolic moveouts, the shorter are the stacking trajectories, the more accurate are the measurements of the moveouts. However, accuracy comes at the expense of the reliability of the information. Chapter 5 describes a new method for estimating local coherency spectra that has higher resolution than conventional methods. The trade-off between resolution and accuracy of the measurements obtained by beam stack could be further improved if the new coherency criterion was used in measuring the moveouts in the data.

1.3.2 Model-driven detection of primary reflections

Beam stack transforms the coherent energy in the prestack data into semblance peaks. The tomographic estimation should fit the kinematics of the peaks corresponding to primary reflections, and should not be influenced by the peaks corresponding to multiples, or other coherent noise. Discerning among the legitimate peaks and the spurious peaks is

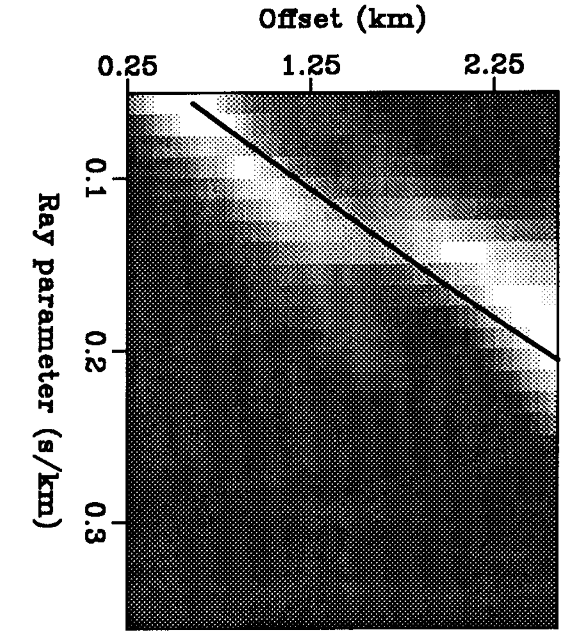

FIG. 1.4. Beam stacks' semblance as a function of offset and ray parameter for the reflection shown at 3.12 s in Figure 1.3. The black line superimposed onto the semblance plot shows what the offsets would be as a function of the ray parameter if the moveout were perfectly hyperbolic. The non-hyperbolicity of the moveout is evident from the beam stacks.

an important step for any tomographic method because it has great influence on the quality of the results. To solve this detection problem, I maximize semblance in the beam-stacked data, with a technique similar to the one used by Toldi in his thesis (1985). This procedure corresponds to a model-driven detection of events because, at a given iteration, the semblance peaks that influence the estimation process are determined by the current velocity model. The model-driven detection has the advantages, with respect to conventional picking algorithm, of being fully automatic and of allowing the setting of a priori constraints directly in the model space. On the other hand, a preliminary picking of the data dramatically reduces the size of the data, saving storage space and computational efforts.

1.3.3 Velocity model and reflectors' geometry

In reflection tomography the velocity estimation and the imaging problems are interrelated. An estimate of the reflectors' geometry is needed for tomography, but, at the same time, the determination of the reflectors' positions from the data depends on the velocity model. The two problems should be solved simultaneously, but usually they are solved iteratively in an alternative fashion (Stork, 1988). First an estimate of the reflectors' positions is obtained assuming a velocity model, and then the estimated reflectors' geometry is used for improving the velocity model.

In the velocity estimation presented in this thesis, the reflectors' geometry is determined by imaging the beam-stacked data by use of ray tracing. Because of the simplicity of the imaging principle, it is possible to take into account the movement of the reflectors when evaluating the tomographic operators that relates perturbations in the velocity model to perturbations in the kinematics of the data (Chapter 3). But, even if properly included in the linearization of the problem, the movements of the reflectors caused by velocity variations make the estimation process highly non-linear. Therefore many iterations of the imaging-tomography loop may be required before a satisfactory solution to the estimation problem can be reached. When estimating velocity from beam-stacked data it is possible to reimage the reflectors many times because the imaging of the reflectors from beam-stacked data is a much cheaper process than the prestack migration of the original data. This possibility is the main advantage of transforming unmigrated data, as opposed to migrated data. On the other hand, after migration with an approximately correct velocity, the reflectors are generally well imaged, although not in the correct position. Therefore the detection of the events in the migrated data is easier than in the unmigrated data. For this reason the many methods that have been proposed for estimating residual migration velocity (Gardner et al., 1974; Faye and Jeannot, 1986; Al-Yahya, 1989; Etgen, 1989) could have some advantages when the data are noisy or the structure is particularly complicated. When the residual velocity model varies rapidly in the lateral direction, the residual moveouts after depth migration are non-hyperbolic. In these cases one of the basic ideas of this thesis, that is, the measurements of reflections' moveout by local coherency operators, should be applied to measure the residual moveouts (Sword, 1988; van Trier, 1989).

1.4 ASSUMPTIONS AND LIMITATIONS

The development of the theory in this thesis assumes the Earth to be a two-dimensional acoustic and isotropic medium. The application of the theory to a three-dimensional medium should be straightforward but computational and storage requirements would challenge present computer technology.

The generalization of the theory to an anisotropic elastic medium is instead far more complicated. However the capability of local stacking operators to describe non-hyperbolic moveouts could be applied to the estimation of an anisotropic velocity model.

The derivation of beam stacks presented in Chapter 2 is based on the assumption that the moveouts of the reflections are approximately hyperbolic. The basic idea for extending beam stacks to more general moveouts is also presented in Chapter 2, but it is untested yet.