Chapter 1

Introduction

1.1 CONVENTIONAL PROCESSING

Conventional seismic imaging consists of three steps: normal moveout (NMO), stacking, and migration. Normal moveout is done using a velocity model obtained from velocity analysis. This velocity analysis is based on the normal moveout equation and gives *stacking* velocities that have to be converted to interval velocities to obtain a velocity model of the subsurface. Post-stack migration completes the imaging process by mapping reflectivities to their proper locations.

The velocities obtained from the NMO velocity analysis may be erroneous, due to the assumption of horizontal reflectors in the NMO equation. Dip moveout (DMO) can be applied after NMO to correct for dipping reflectors (Hale, 1983). With DMO included, the processing sequence becomes

NMO — DMO — STACKING — MIGRATION

This processing sequence has two main advantages. First, stacking collapses the data to a manageable size making some geologic features readily available. Second, it provides a way of estimating the velocity.

For constant velocities, the above sequence is equivalent to the single process of migrating the unstacked data (so-called "prestack migration"). When the velocity varies with depth only, the above sequence is only an approximation (Hale, 1983). When the velocity varies laterally, the above sequence should be replaced by the more theoretically correct prestack migration.

If we replace the above sequence by full prestack migration, we need a velocity model. Using NMO-based velocity analysis contradicts the need for prestack migration because prestack migration only needs to be done in areas where conventional velocity analysis fails. prestack migration. In other words, if we can determine the velocity using NMO, then we can simply use the conventional velocity analysis method to produce a stacked section and to migrate the stacked section using post-stack migration.

1.2 CONVENTIONAL VELOCITY ANALYSIS

The traveltime from the source to a reflecting surface and back to the receiver depends on the depth of the reflector (or its zero-offset traveltime), the source-receiver offset, and the velocity of the subsurface. The NMO equation ties these quantities together. Knowing the offset-dependence of the traveltime curve for a particular zero-offset traveltime, the only unknown parameter in the NMO equation is the velocity. However, this velocity is not the interval velocity (the velocity of the rocks) but the *stacking* velocity.

For horizontal reflectors, the stacking velocity is the root-mean-square (rms) velocity. The rms velocity in turn is related to the interval velocity by the Dix equation (Dix, 1955). In the case of a plane dipping reflector, the stacking velocity is higher than the rms velocity by a factor equal to the secant of the dip angle (Levin, 1971). When diffractors exist, they cannot be represented by a single dip and when the structure is complicated, the NMO approach is invalid. DMO can be used to correct for dips, but if the velocity varies laterally, DMO is also invalid.

1.3 MIGRATION VELOCITY ANALYSIS

To make velocity analysis valid for arbitrary reflector geometry and for areas where velocity varies laterally, I will replace NMO by prestack migration. The main reason for using migration is that it can be formulated for media with lateral velocity variations. Therefore, a migration velocity analysis methods are capable of handling complicated structures.

Velocity analysis cannot be done with zero-offset migration. Imagine the reflection from a horizontal reflector in a zero-offset experiment. The recorded reflection also makes up a horizontal image. If we migrate this reflection with any velocity, it will still be a horizontal image. Its location will change in depth as the velocity is varied but we do not know the depth of the reflector and therefore cannot resolve the ambiguity between depth and velocity.

The preceding argument implies that migration velocity analysis has to be done to unstacked data. As with NMO, the traveltime dependence on offset is used to measure the velocity. A direct analogue to conventional processing would be to migrate and stack the data with several constant velocities. Instead of NMO-stack velocities, we obtain migration-stack velocities from which interval velocities need to be obtained. Fowler (1985b) obtains the interval velocities from the migration-stack velocities using a method similar to the one used by Toldi (1985) for the NMO-stack velocities.

The velocity analysis proposed in this thesis is not a direct analogue to the conventional method. I use an iterative approach in which the error in the velocity model is estimated after migration with a preliminary velocity model. The data is then re-migrated and the error in velocity is estimated and so on. The process is terminated when the error in the velocity is small.

The input to the process described in this thesis is field profiles. The data is then processed without any use of the conventional CMP processing. The output is the velocity of the subsurface and the correctly migrated profiles. Simple stacking of these profiles produces a migrated stacked section. The unmigrated stacked section is bypassed, which may be a disadvantage to interpreters who would like to examine this traditional data representation.

1.4 PROFILE MIGRATION

In the previous section, I mentioned that prestack migration is an element in the velocity analysis scheme presented here. Prestack migration can be implemented by several schemes. These schemes vary both in the coordinates and in the domain in which the downward continuation is done. Of these several methods, profile migration is the most natural one because it is profiles that we record in the field. Nontheless, researchers have avoided processing profiles because it was impractical. This avoidance can be clearly seen, for example, in the work of Ottolini (1982) and Hale (1983). Two problems with profiles processing were commonly cited :

- A practical problem: computers of those days had limited capability, especially in memory. Large memory is needed because the profile may need to be padded with zeros so that events coming from outside the area under the cable migrate to their locations. By comparison, CMP gathers are less sensitive to structure.

- A theoretical problem: unlike common-midpoint gathers, profiles are not suitable for velocity analysis.

With reference to the first problem, computers have now progressed to a stage where those limitations do not exist. We are therefore left with the second theoretical problem, one that cannot be solved by technology. This problem can be solved by combining migration and velocity estimation, which is the subject of this thesis. It has long been recognized that these two processes should be combined (see for example Sherwood, 1976). I will show that we can do profile migration and velocity estimation at the same time. In this scheme, migration is done using profiles but the velocity analysis is done using common-receiver gathers (CRG's).

The discussion above shows that profile migration is *possible*. Profiles also have features that make them *attractive*. These features include:

- The shot-geophone (s, g) space is the most suitable space when the velocity varies laterally (Clærbout, 1985).

- Sampling of the receiver axis is usually better than that of the shot or offset axes, so spatial aliasing is less than it is in common-midpoint gathers (Jacobs, 1982).

- When complications in the shooting geometry are introduced, they are most easily included in the profile description. Examples of such complications are uneven receiver sampling and 3-D coverage where concepts like a common-midpoint gather are inappropriate.

Several ways exist to migrate profiles. One method of profile migration is by double downward continuation. This method consists of downward continuing both the source and receivers and applying an imaging principle that defines reflectors to be at the time coincidence of the downgoing and upcoming waves (Jacobs, 1982). In Appendix A, this classic method is compared with a slightly different method that replaces the downward continuation of the source by time shifting.

1.4.1 Parallelism in profile migration

Prestack migration is more expensive than post-stack migration. Since migration is repeated several times in prestack migration velocity analysis, cost becomes a serious concern. The cost is, however, decreasing as more powerful computers are introduced. In fact before parallel computers were available, methods that used prestack migration were so slow they were considered impractical.

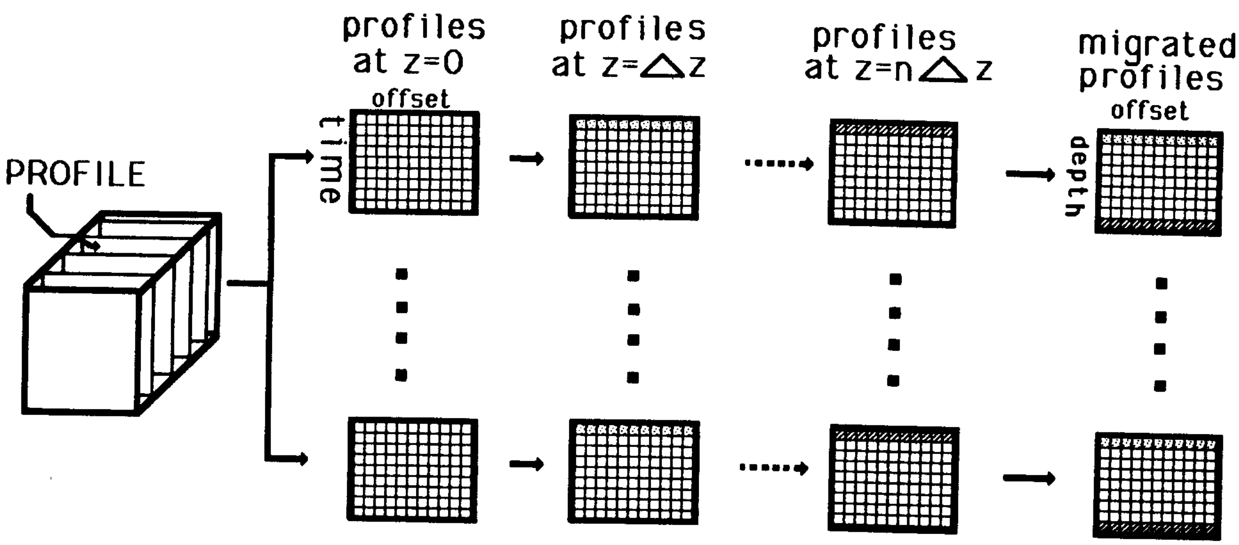

FIG. 1.1. Profile migration scheme. The shaded strip is the image at the given depth at t=0. The strip is placed at the corresponding depth in the migrated profile.

As illustrated in Figure 1.1, a high degree of parallelism exists in profile migration. The first parallelism is over the shot axis; the second is over the offset axis. Since I do the migration in the frequency domain, there is a third parallelism over the frequency axis. When extrapolating the data from one depth to the next, frequencies are independent and therefore can be extrapolated in parallel.

If we were able to use this three-fold parallelism, the cube of data, $p(s,g,\omega)$, could be extrapolated from one depth to the next in one step. This level of parallelism does not exist in today's computers, but the commonly available single level of parallelism has made the process faster by an order of magnitude. The process will be made drastically faster when the level of parallelism increases.

1.5 PROFILE RECORDING

1.5.1 Split-spread recording

Energy that is recorded by a profile may come from outside the area under the cable. This happens if there is a dipping reflector away from the cable as shown in Figure 1.2a. This figure also shows that for this geometry, the image is within the CMP gather. As mentioned previously, this difference between profiles and CMP gathers is one reason profile migration has not been favorable.

To capture the migrated image, the usual practice is to pad the profile with zeros from both sides before migration. This practice is especially important in off-end recording (where the receivers are only at one side of the source), as shown in Figure 1.2a.

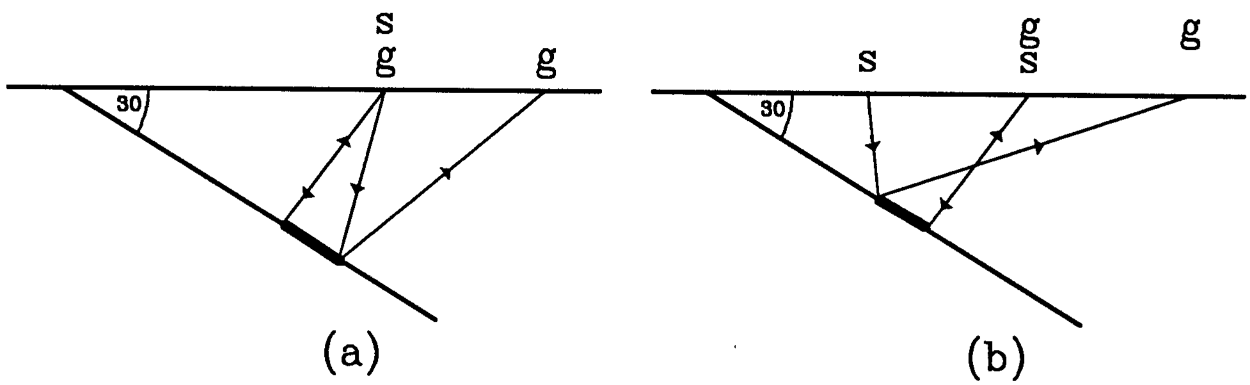

FIG. 1.2. Comparison of off-end recording of a profile with CMP recording. The illuminated area of the reflector is marked by the heavy line. (a) Showing energy coming from the reflector is outside the cable extent. (b) Showing energy coming from the reflector is within the CMP gather.

If we replace the off-end recording by split-spread recording (where receivers are on both sides of the source), Figure 1.3 shows that the energy comes from within the cable extent. The split-spread geometry is therefore a more sensible way of recording profiles. Of course, a steep-dipping reflector may still be recorded in the profile while being outside the cable extent even if the profile is split-spreed, making zero-padding necessary. However, in

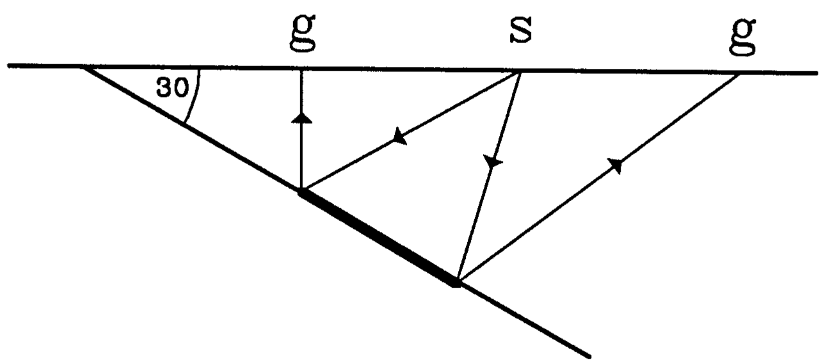

FIG. 1.3. Split-spread recording of a profile. The illuminated area of the reflector is marked by the heavy line. The same reflector in Figure 1.2 is now within the cable extent.

this case the CMP gather is not better off; the image will also be outside the CMP gather.

Figures 1.4 and 1.5 illustrate the idea of Figures 1.2 and 1.3 using a synthetic profile. In Figure 1.4, no zero padding was applied because the image is within the cable extent. In Figure 1.5, zero padding was applied when migrating the right half of the profile because the image is outside the cable extent. These figures show that by recording split-spread profiles we have a better look at the subsurface and a reduced need for zero padding when migrating profiles.

1.5.2 Density of coverage

I have mentioned that one of the advantages of profile processing is that receiver spacing is usually smaller than shot or offset spacing. Receiver spacing should be made as small as possible in order to increase the spatial resolution. On the other hand, to reduce the expense of the seismic survey, shot spacing should be made as large as practical. Note that it cannot be made arbitrarily large because profiles are required to overlap. There are two reasons for this requirement. First, when examining CRG's, images from overlapping profiles are analyzed. Second, the final subsurface image is obtained by stacking all profiles. This stacking increases the signal/noise ratio, which is especially important for attenuating edge diffractions. Overlap of profiles is thus required even in methods where velocity analysis is done for a single profile at one time (see Mora, 1987).

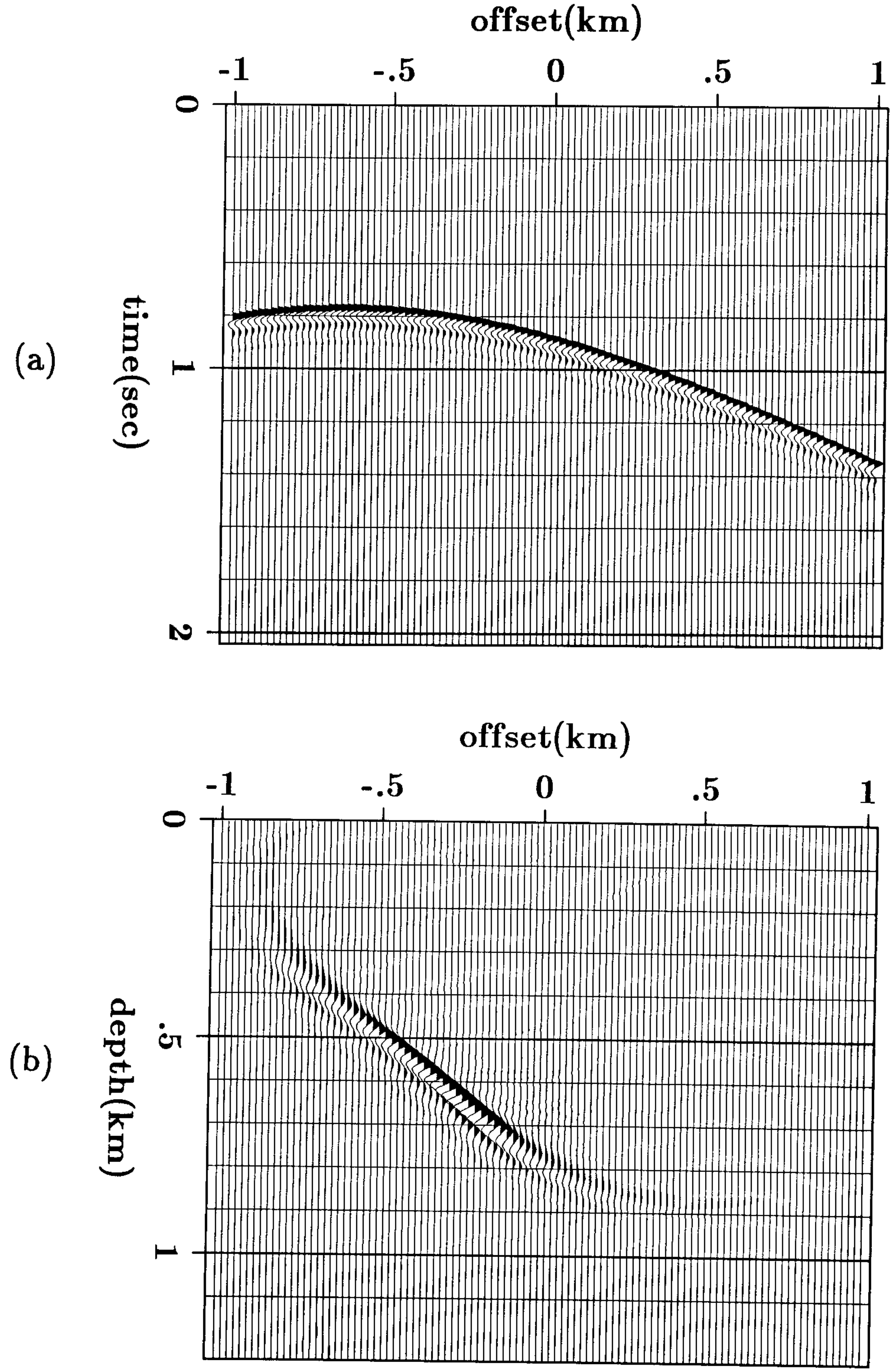

FIG. 1.4. (a) A Split-spread synthetic profile for a reflector dipping 30°. The velocity used in modeling is 1.5 km/sec. (b) The result of migrating the profile in (a). No zero-padding was done.

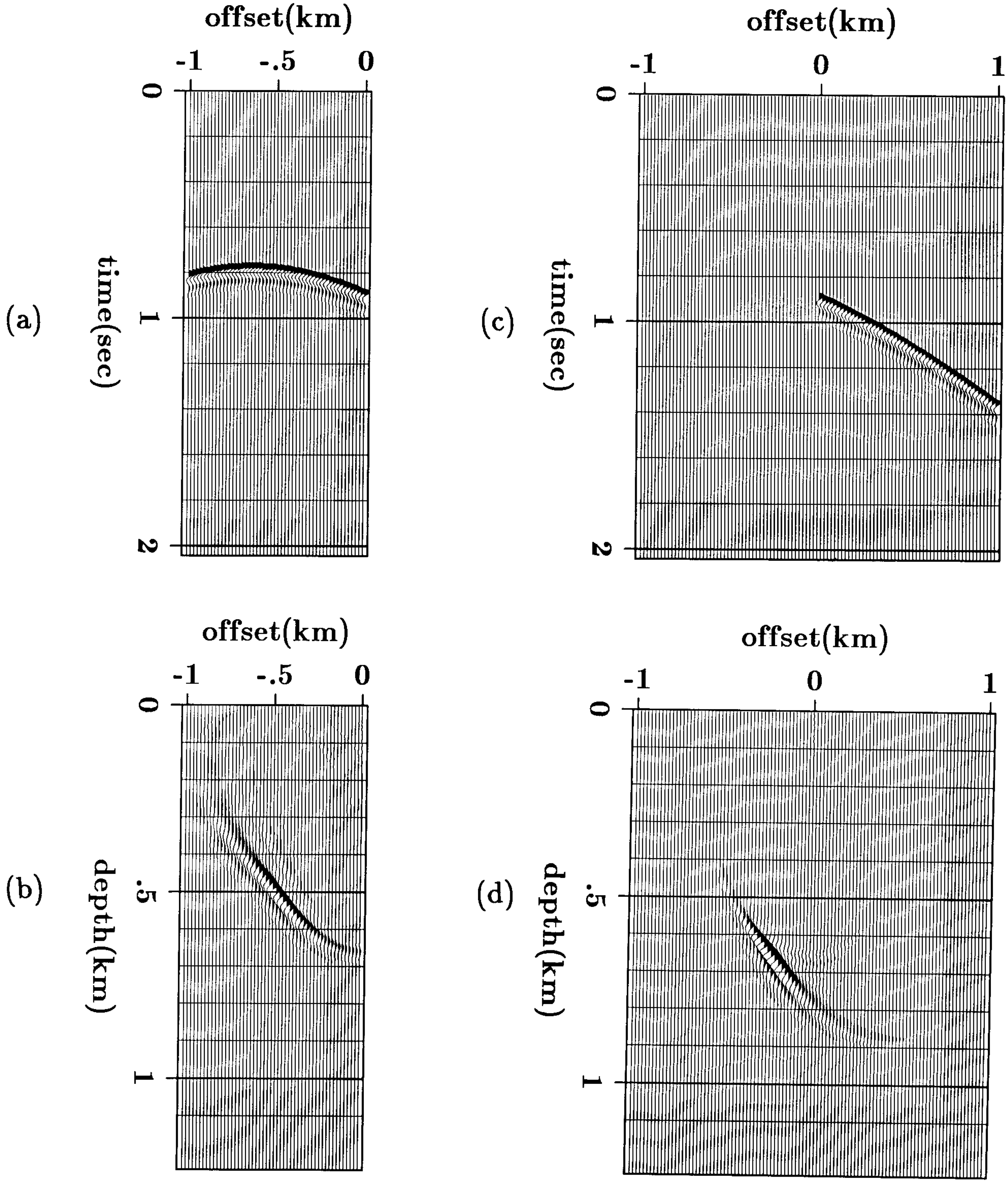

FIG. 1.5. (a) The left half of the profile in Figure 1.4. (b) The result of migrating the profile in (a); no zero padding was done. (c) The right half of the profile in Figure 1.4. (d) The result of migrating the profile in (c). Note that the image is captured in the area that was zero-padded.

1.6 Model assumptions

In this thesis, the earth is assumed to be represented by a two-dimensional, acoustic, and isotropic model. Assuming isotropy amounts to interpreting the error in velocity as being caused by heterogeneity and not by anisotropy. If the earth cannot be represented by a two-dimensional model, then out-of-plane reflections will not be imaged correctly; they will be part of the coherent noise. Extending the method proposed here to a three-dimensional model seems possible, though the analysis becomes more complicated. It is far more complicated to extend it to an elastic or anisotropic model, because more than one component of the recorded wavefield need to be analyzed.