CHAPTER 1

Introduction

1.1. Migration Processing

The goal of migration processing is to obtain a picture of reflectivity and velocity beneath the earth's surface from seismic data recorded at the earth's surface. Specifically, migration converts the temporal pattern of reflections into the spatial geometry of reflectors. At the same time it consolidates redundant and scattered reflections, thereby increasing signal over noise. These actions are interwoven with the estimation and use of a sub-surface velocity model.

Migration processing can be implemented in several ways. Conventionally, it includes stacking and migration of stacked sections. Other algorithms migrate the unstacked seismic data to do better than conventional processing. This thesis introduces several new methods of migrating the unstacked data, characterized by special coordinate systems, that overcome the limitations of other migration methods.

1.2. Conventional Processing

Conventional migration processing consists of three main processing steps: (Figure 1.1)

(1) The first step is to *estimate velocity* from common midpoint (CMP) gathers. A *CMP gather* is the set of all seismograms that have the same midpoint between source and receiver. The same part of a flat reflector is recorded by each seismogram. The difference in reflection travel time is a function of velocity.

(2) The second step is to *stack* CMP gathers. During stacking, redundant reflections on a CMP gather are summed together after taking account of

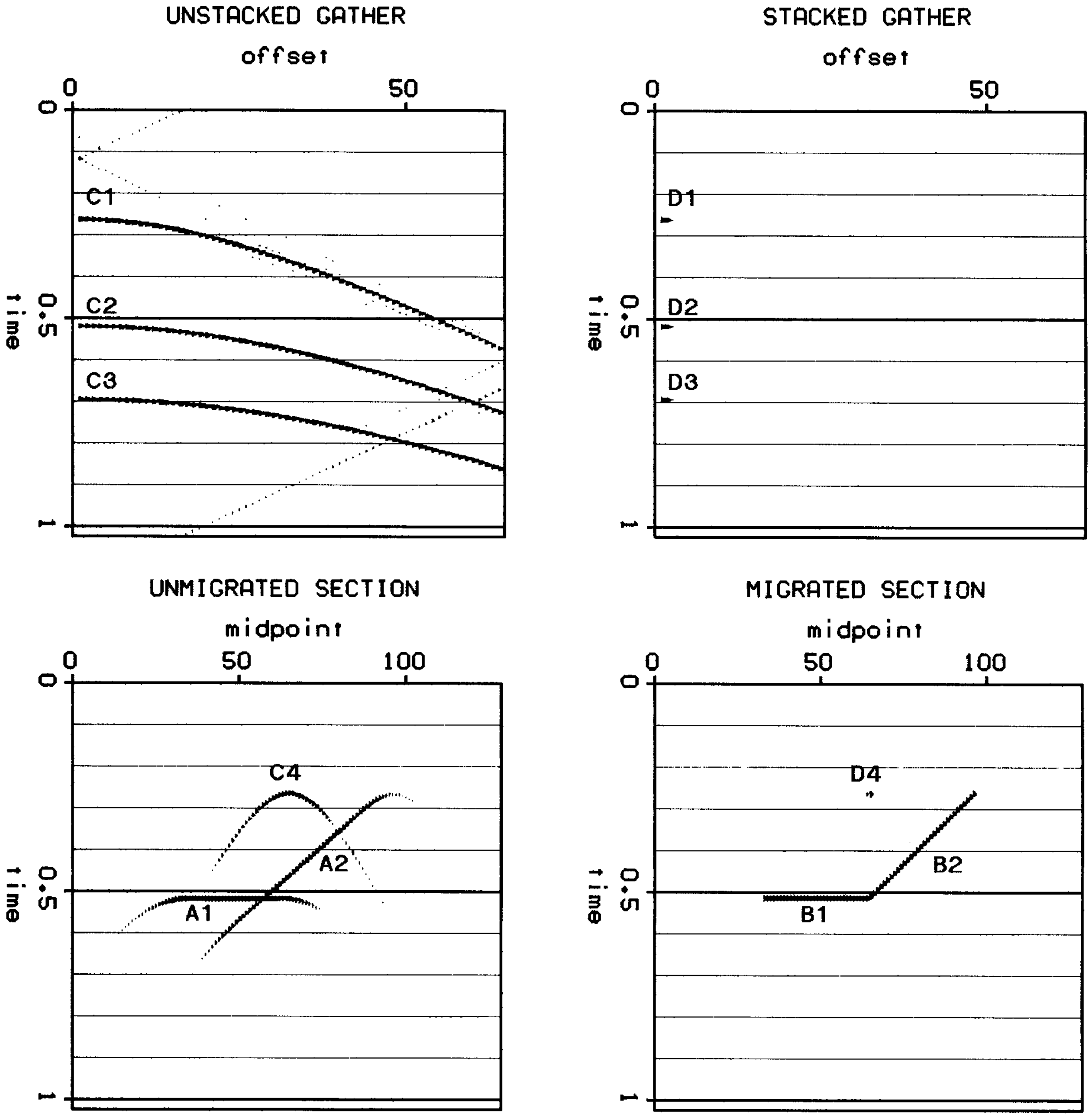

FIGURE 1.1: Migration processing. These figures illustrate migration processing in its conventional form. (1) Effects of migration processing: migration converts temporal reflector patterns (A1-2) into their spatial geometries (B1-2). Migration processing collapses scattered reflections (C1-4) into point reflectors (D1-4). (2) Conventional processing begins by determining media velocity from the curvature rate of hyperbolic reflections (C1-4). Then stacking sums together redundant offset reflections (top two figures) into the zero offset trace. Finally, the section composed of these zero offset traces is migrated (bottom two figures).

changes in travel time. The stacked trace is approximately a *zero offset trace*, or what would be recorded by a source and receiver together.

(3) The third step is to *migrate* the section composed of these stacked traces. It usually is the implementation of some solution to the wave equation.

These three operations are grouped together as migration processing for two reasons. First, they behave in similar ways. For example, in each case hyperbolic

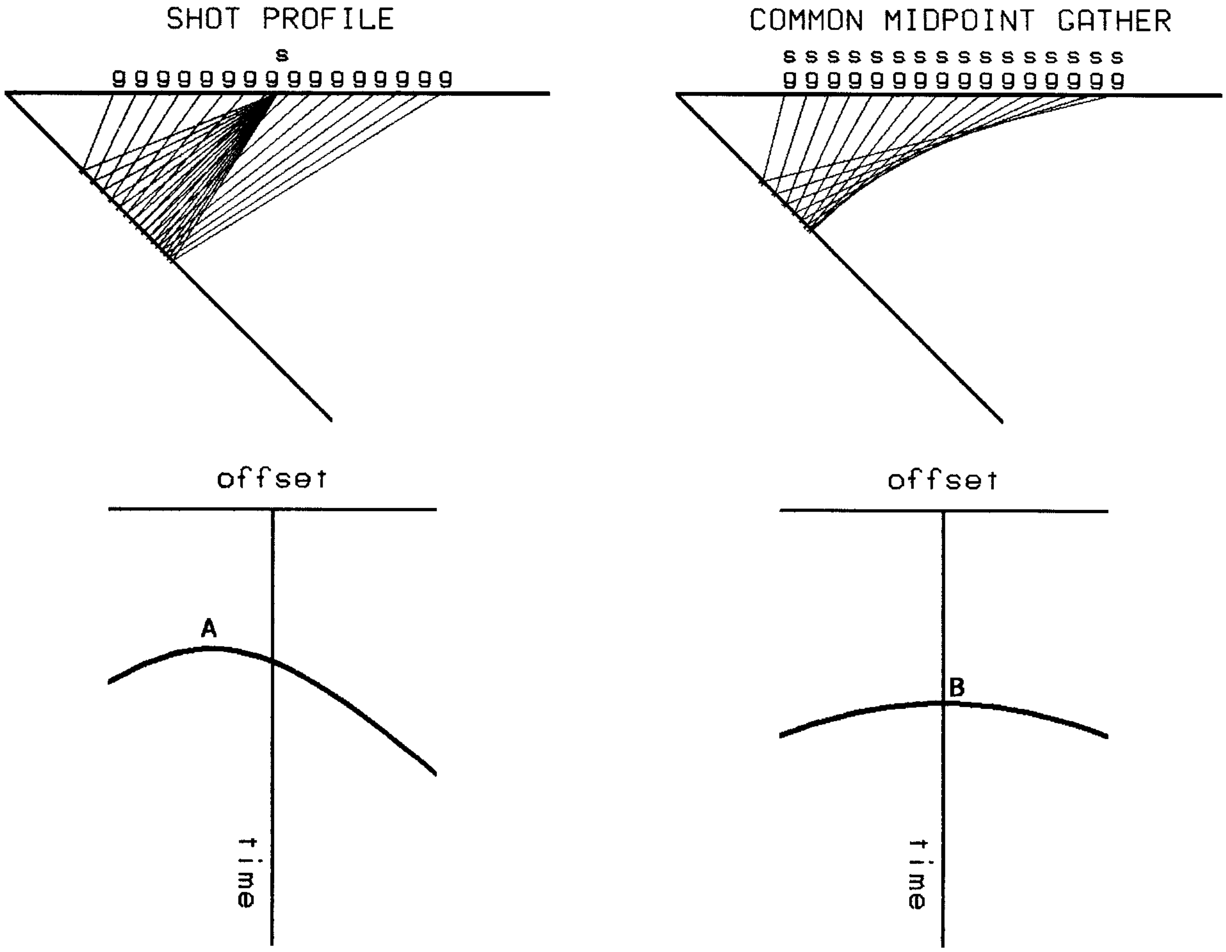

FIGURE 1.2: Dip sensitivity. The travel time curve of a dipping reflector on a CMP gather (B) is less sensitive to dip than on a shot profile (A). The apex of such a curve is always at zero offset (for vertically varying velocity). This can be deduced from the raypath geometry shown on the two upper figures.

shapes collapse to a point at the apex of the hyperbola. Second, these processes can be tied together by a comprehensive mathematical model for imaging raw seismic data presented in appendix F. It turns out that conventional processing are sub-operations within this general model.

Common midpoint stacking is the most widely used imaging process for many reasons. Any alternative to conventional processing should retain or supercede as many of these advantages as possible.

(1) Foremost, stacking often dramatically improves the signal to noise level, bringing out weak reflectors. Besides random noise, stacking discriminates to some degree against multiple reflections, refractions, shear conversions, and out of plane reflections.

(2) Stacking is a tool for velocity estimation. The best focused of several stacks made for different velocity functions selects the best velocity.

(3) Common midpoint gathers are relatively insensitive to dip as compared to shot profiles. (A *shot profile* is the set of all geophone recordings from the same shot source.) Reflector time always increases with offset on a CMP gather no matter the dip if velocity is laterally invariant. (Figure 1.2)

(4) Stacking compresses the dataset into a more manageable size.

(5) Last, but not least, stacking approximates a zero offset section. A zero offset section is more true to the sub-surface reflector geometry than raw field data. Furthermore, there is a well developed theory for migrating zero offset sections.

1.3. The Problem with Conventional Processing

Conventional stacking assumes flat dips. Levin (1971) introduced a correction term that handles dipping events. The correction is to increase the stacking velocity by the secant of the dip angle. This correction term, however, runs into several

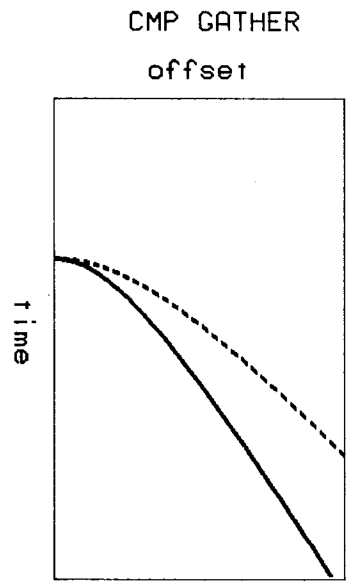

FIGURE 1.3: CMP gather velocity ambiguity. Is the dashed line a steeper dipping event or higher velocity event than the solid line? One can sum along the dashed or solid line, but can't image both clearly.

problems.

(1) This correction is only exact for constant velocity. It worsens at wide offsets, steep dips, and depth velocity variations.

(2) This type of correction introduces an ambiguity into velocity analysis. For example, a high velocity measured by stacking may be real or indicates a dipping reflector (Figure 1.3).

(3) This correction leads to a contradiction when there are several reflectors with dips in the same vicinity (such as a dipping fault plane in a layered medium; see Figure 1.4). Then the stacking velocity would have to be a somehow multi-valued function to capture all the reflections.

(4) CMP stacking fails to recognize certain information present in unstacked data. Some information is useful for geologic interpretation, such as reflectivity as a function of incidence angle.

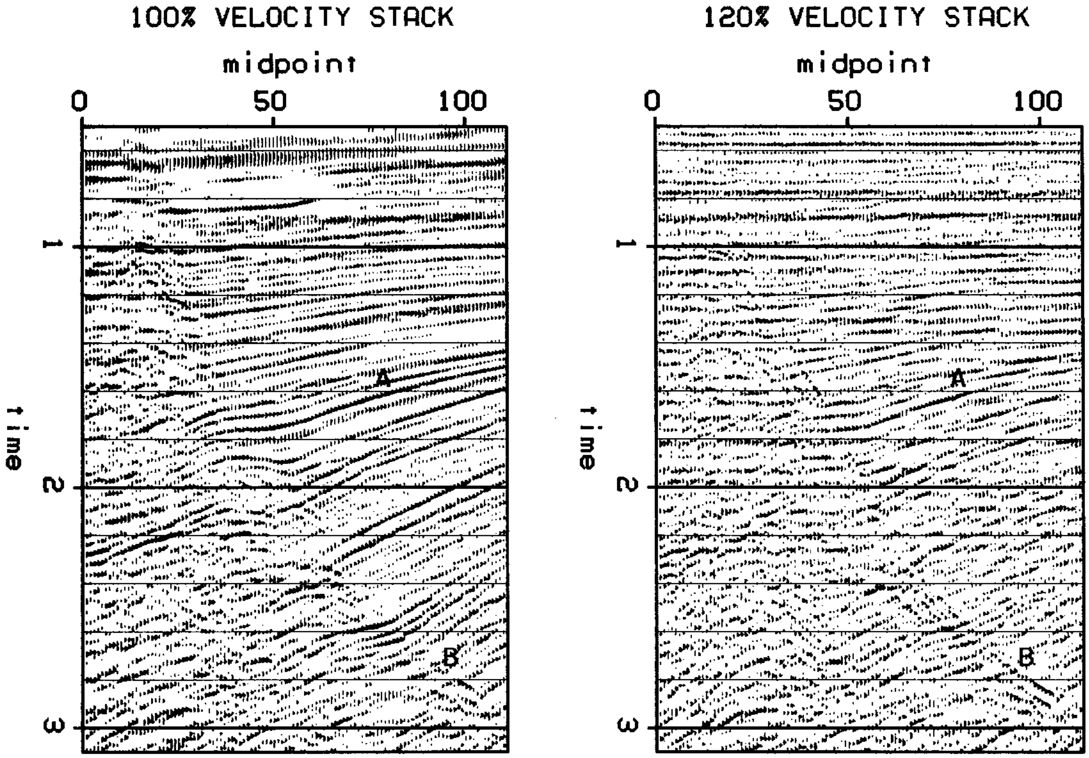

FIGURE 1.4: Stacking different intersecting dips. This figure demonstrates the problems of velocity ambiguity and intersecting reflectors of different dips. The section on the left was stacked at the flat dip velocity. It images shallow dipping events well (A). The section on the right was stacked at an inflated velocity. It images a fault plane (B) at the expense of the flat layers (A).

(5) CMP stacking does not account for lateral velocity variations. Significant errors occur when the variation is comparable to the scale of a geophone cable length (Lynn and Claerbout, 1982).

1.4. Migration of Unstacked Data

The main alternative to conventional processing is to migrate unstacked data. There are a dozen or so different ways to do this. They may be classified by that coordinate system the data is processed in: *field coordinates*, *offset-midpoint coordinates*, *angle-midpoint coordinates*, and other possibilities. Migration

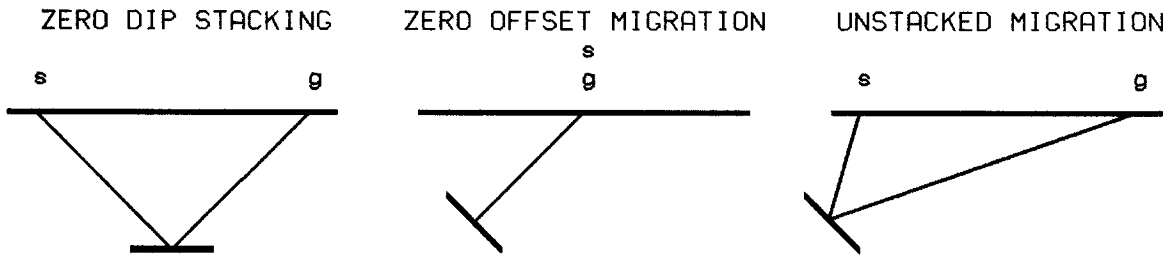

FIGURE 1.5: Dip range of migration methods. These diagrams summarize the dip and offset ranges of various migration methods. The migration of unstacked data best handles both non-zero dip and non-zero offset reflectors.

processing in these coordinate systems is described in the following sections.

A qualitative overview of the various coordinate systems is given by Figure 1.6. Field coordinates and offset-midpoint coordinates include the migration methods in greatest industrial use. Field coordinate methods are generally the most theoretically sound, while offset-midpoint coordinate methods are more workable. The angle-

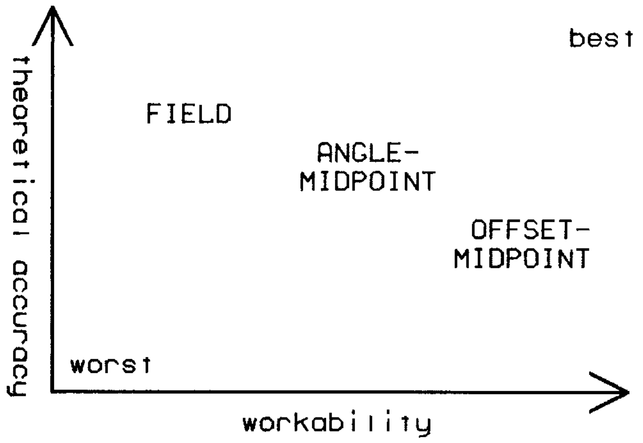

FIGURE 1.6: Comparison of unstacked migration methods. Various migration coordinate systems are plotted as to their accuracy and workability. Accuracy factors include lateral velocity inhomogeneities, wide offsets, steep dips, and depth velocity variations. Workability factors include truncation, aliasing, dip sensitivity, and velocity sensitivity. This graph is highly generalized and qualitative.

midpoint coordinate methods introduced in this thesis increase the accuracy of offset-midpoint coordinate methods while retaining their practical advantages.

1.5. Field Coordinate Methods

Field coordinate methods operate on seismic data that remains organized as it was collected: a set of shot profiles (Figure 1.7). Field coordinate methods are accurate in the presence of dipping reflectors, wide offsets, and velocity inhomogeneities. Theoretically, processing data in their original coordinate system is straight forward, especially when trying to deal with lateral velocity inhomogeneities.

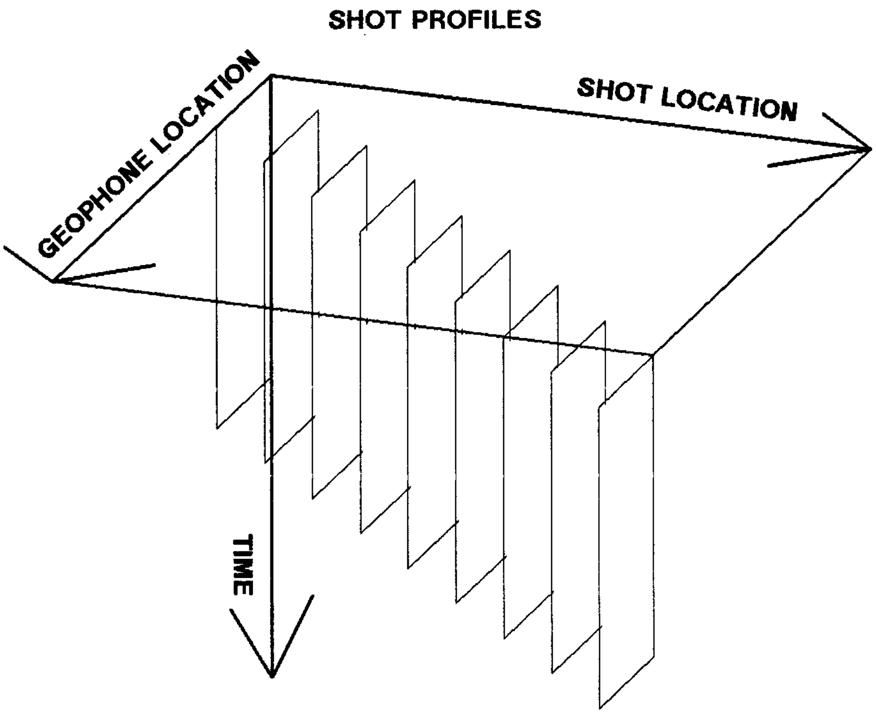

FIGURE 1.7: Field coordinates. Data may be migrated as a set of shot profiles. The geophone coordinate axis follows the seismic survey direction across the earth's surface. The shot coordinate axis also follows the seismic survey direction. However, it is a useful mathematical construction to plot the shot coordinate as a third dimension. This coordinate system is called *field coordinates*.

The problems with field coordinate methods seem to be of a practical nature. This may be why they are not used as often as the more practical midpoint coordinate methods. The problems include:

(1) Edge effects tend to dominate the migrated shot profiles. The distance spanned by the geophones recording a shot profile is short compared to the total length of the survey. Near offset and wide offset seismic traces are absent.

(2) Reflectors on shot profiles are often dip aliased. Aliasing degrades processing methods based on differential wave equations. Aliasing occurs at wide offsets where the reflection hyperbola has steepest dips. The problem is worst for flat reflectors that have the steepest hyperbola slopes.

(3) Velocity estimation is based on measuring reflection travel time differences between seismic traces as a function of offset. However, as shown earlier in Figure 1.2, travel time variations on a shot profile are more sensitive to dip than a CMP gather.

(4) A good knowledge of the velocity model is required before migration. Some midpoint coordinate migration methods do not require this.

1.6. Offset-Midpoint Coordinate Methods

Offset-midpoint coordinate methods migrate *constant offset sections* (Figure 1.8). In a constant offset section each seismogram trace has the same source-receiver offset. Constant offset sections are aligned so that the *nth* trace on each section has the same source-receiver midpoint. The set of the traces with the same midpoint can be processed as a CMP gather. Velocity analysis can be performed before or after migration on these CMP gathers. Migrated constant offset sections can be stacked together to increase the reflector signal strength over background

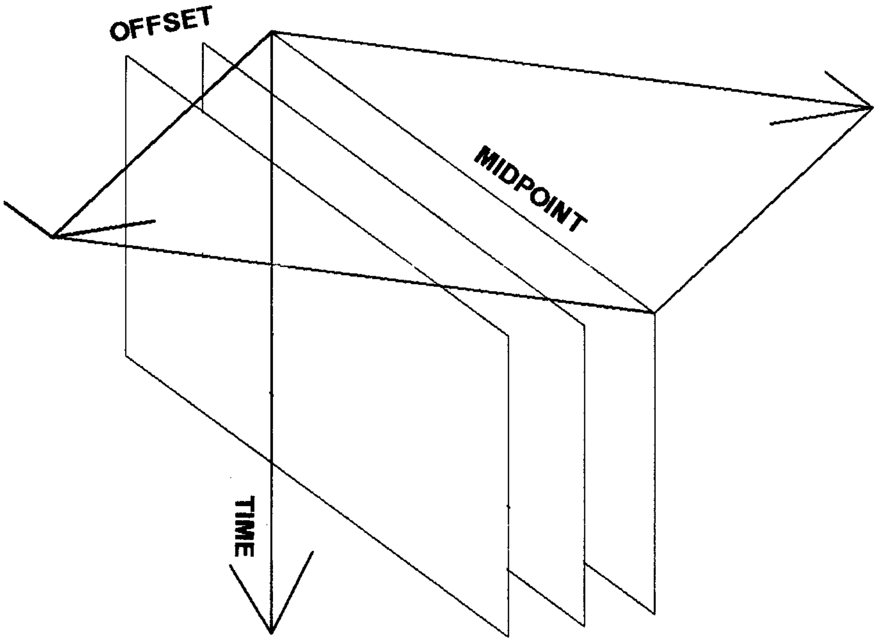
CONSTANT OFFSET SECTIONS

FIGURE 1.8: Offset-midpoint coordinates. The same seismic survey as in Figure 1.7 but considered as a set of constant offset sections. In field coordinate space, the data from a typical seismic survey lies mostly near the diagonal between the shot and geophone axes. This diagonal is called the *midpoint axis* because it is the midpoint between the shot and geophones. An assemblage of traces parallel to the midpoint axis is called a *constant offset section.* Such an assemblage is typically much longer than any that could be constructed parallel to the shot or geophone axes. The coordinate system, consisting of the midpoint axis and its perpendicular, offset, is called *offset-midpoint coordinates.*

noise.

The reason migration in offset-midpoint coordinates is more popular in industry than using field coordinates may be that it is more workable, in spite of being less accurate. Constant offset sections are much longer than shot profiles, so the edge artifacts do not dominate the migration results. The more geologically common flat events are not dip aliased on constant offset sections whereas they inherently have steep slopes on shot profiles. Velocity analysis on CMP gathers are less sensitive to dipping events for reasons shown in Figure 1.2. Migration schemes that are relatively velocity insensitive, such as discussed in the next section, can be devised in offset-midpoint coordinates. This defers velocity estimation or having to use a velocity model to when migration processing has improved the raw data.

A difficulty with migrating constant offset sections is in deriving a migration equation that is accurate for steep dips, wide offsets, and vertical velocity variations. Some approximations must be made, but they are generally not as bad as those assumed by conventional processing.

1.7. Partial Migration

A small bit of migration can be applied to the seismic data before conventional processing to improve conventional processing (Judson and Sherwood, 1977; Yilmaz and Claerbout, 1980; Bolondi et. al., 1981). Partial migration is usually done on constant offset sections and benefits from the practical advantages of this coordinate system. Furthermore, because partial migration makes relatively little change to the data, it tends to be efficient and velocity insensitive. However, such methods often make dip, offset, or velocity approximations. But since partial migration makes little change to the data, accuracy problems also have a less serious effect than a full migration.

This thesis introduces a method of partial migration in angle-midpoint coordinates (Chapter 3). This method has greater dip and offset accuracy than other partial migration methods and is more computationally efficient and stable.

1.8. Angle-Midpoint Coordinate Methods

The offset coordinate on a shot profile or CMP gather can be transformed into an angle coordinate. The angle coordinate is related to the fixed parameter in Snell's law of wave propagation. The effect is to select the parts of the seismic wavefield traveling at the specified angle.

ANGLE-MIDPOINT SECTIONS

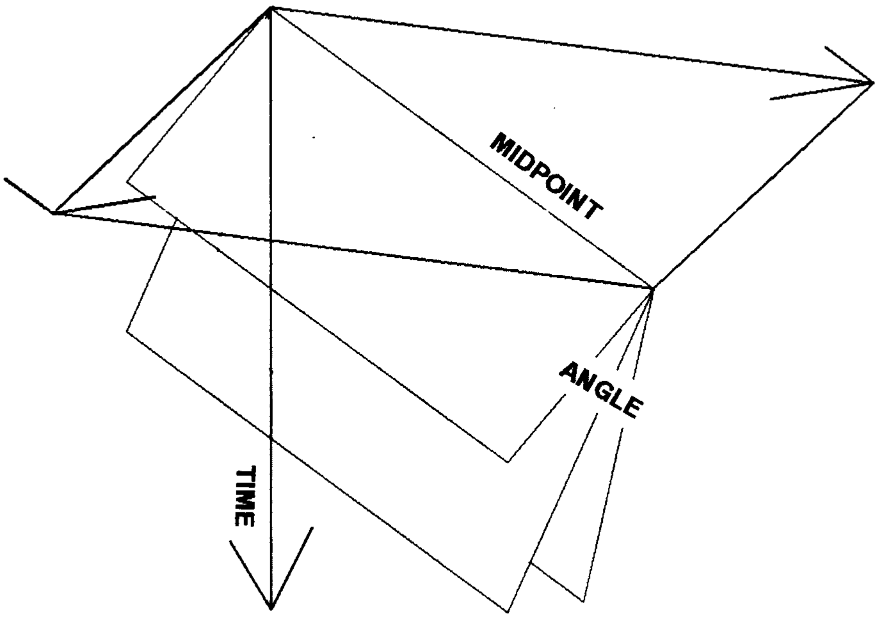

FIGURE 1.9: Angle-midpoint coordinates. Angle-midpoint sections are extracted diagonally across offset by methods shown in Figure 1.10. The angle is related to a ray parameter-like invariant of wave propagation. Such coordinate systems are called *angle-midpoint coordinates.*

This thesis introduces three angle-midpoint coordinate methods. They are:

(1) *Common midpoint slant stacks.* (Chapter 2) A slant stack sums along a slanted linear trajectory across a CMP gather (Figure 1.10). Earlier investigators (Ryabinkin, et. al., 1962; Taner, 1977; Phinney and Jurdy, 1979; Schultz and Claerbout, 1979; Garotta, 1980; Treitel et. al., 1982) have slant stacked shot profiles instead of CMP gathers. However, common midpoint slant stacks enjoy the practical advantages of midpoint coordinates. In addition, midpoint slant stacks are accurate for steep dips, wide offsets, and vertical velocity variations. The primary disadvantage is that common midpoint slant stacks are not as accurate as field coordinate methods in handling lateral velocity variations.

(2) *Common midpoint radial traces.* (Chapter 3) A radial trace maps seismic traces from CMP gathers along diagonal lines radiating from the origin (Figure 1.10). It approximates a slant stack. The motivation for radial traces is to avoid the practical problems of slant stacking that include truncation and aliasing. However, the migration equations developed in this thesis migrate radial traces inaccurately in the presence of variable velocity. To avoid this

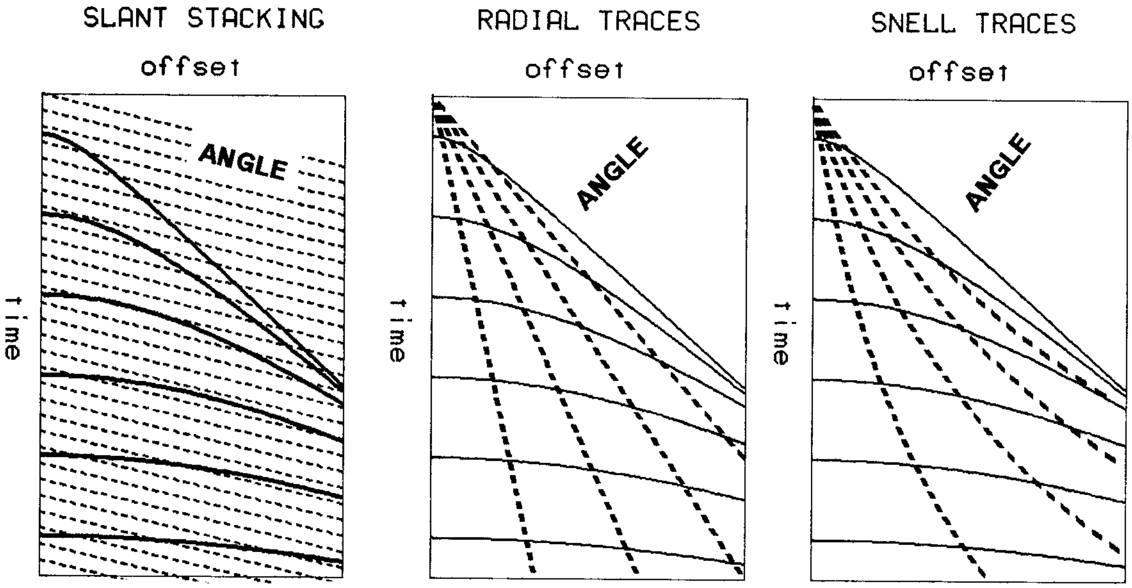

FIGURE 1.10: Three angle coordinate transformations. Three methods of transforming CMP gathers into angle-midpoint coordinates are: slant stacking, radial traces, and Snell traces. The solid lines in each diagram are reflections from flat events in a media where velocity increases with depth. A slant stack (left) sums along a slanted linear trajectory (dashed lines) to produce a slant stack trace. If the dashed lines were horizontal, then the resulting slant stack would resemble the vertical plane shown in Figure 1.9. A radial trace (middle) extracts the planes of Figure 1.9 from the data directly. A Snell trace (right) is extracted where each reflector has the same time slope on the CMP gather. In a media where velocity changes with depth, such as in this example, the Snell trace trajectories bend.

problem, this thesis introduces a partial migration scheme based on radial traces that is insensitive to velocity variations.

(3) *Common midpoint Snell traces.* (Chapter 4) A Snell trace is a radial trace generalized to vertical velocity variations. They map seismic traces from CMP gathers along curved lines (Figure 1.10). Snell traces incorporate components of both slant stack and radial trace migration methods. They are more accurate than radial traces and more practical than slant stacks.

1.9. Summary

There are several different methods of migration processing. Migrating the unstacked data attempts to cure the defects of conventional processing, particularly stacking problems dealing with dip. The three angle coordinate methods introduced in this thesis seek to overcome limitations of other methods of migrating unstacked data by combining accuracy with workability.