Chapter 2

Structural interpretation and velocity estimation

2.1 INTRODUCTION

In this chapter I describe structural interpretation of seismic data after migration, the process that provides the key data information for velocity analysis. Structural interpretation involves recognizing the main geological structures in the subsurface, and identifying the corresponding reflection events in the seismic data.

Traditionally, interpretation has been carried out after the data have been stacked. However, to obtain velocity information, one must interpret prestack data. Although the signal-to-noise ratio is much lower in prestack data than in poststack data, and prestack events can be hard to identify, I show in this chapter that the analysis of prestack data is feasible, especially if the data is presented to the interpreter in a form that represents interpretable geology.

I start the chapter by defining what a seismic event is and how it is affected by seismic velocity. I then demonstrate with field data examples how complex structure complicates velocity estimation, and show that migrating and interpreting the data can remedy these complications.

2.2 WHAT IS A SEISMIC EVENT?

A first glance at seismic data reveals distinct features, called seismic events (see for example Figures 1.1 and 1.2). Sheriff and Geldart (1982, ch.4) define a seismic event on the basis of five characteristics: (a) coherence, (b) amplitude standout, (c) character, (d) dip moveout, and (e) normal moveout. Coherency, the similarity in appearance of neighboring traces, is the strongest distinguishing feature. Amplitude standout and character refer to the distinctive shape of the waveform that identifies a particular event. Finally, moveout describes the systematic difference from trace to trace in the arrival time of an event.

Seismic events are associated with different types of seismic waves that travel from source to receiver through different parts of the Earth. Identifying the different wavetypes and their relation with the subsurface is called interpretation. In this thesis I limit the interpretation to primary reflection events. A major advantage of interpretation is that the interpreter can discard any unwanted events, such as multiples, refraction events, etc.

I concern myself only with the moveout of the primaries. Although some inversion methods use the complete seismic waveform to determine velocities (Tarantola, 1984; Mora, 1987; Woodward, 1989), traveltimes of events are by far the most robust measure of velocity. Traveltimes are integral measures of slowness (the reciprocal of velocity), and therefore more stable to invert than waveform information. Full-waveform inversion methods, on the other hand, have higher resolution; traveltime inversion methods can resolve only the low-wavenumber component of the velocity field (Claerbout, 1985, Fig.1.4-3).

In the next two sections I describe the two different types of moveout and their relation with the velocity and shape of structures in the Earth.

2.2.1 Normal moveout

The simplest reflection event is that arising from a flat reflector in a constant-velocity medium. The traveltimes of such an event satisfy a hyperbolic equation,

$$t^2 = t_0^2 + s^2 h^2, \tag{2.1}$$

where t is the two-way traveltime, h is the offset (the distance between shot and receiver), s is the medium slowness (the reciprocal of velocity), and t_0 is the two-way traveltime for zero offset (coincident shot and receiver). The difference between the traveltime at offset h and the zero-offset traveltime is called normal moveout (NMO), and equation (2.1) is called the NMO equation. This equation serves as the basis for most conventional velocity analysis methods. The most common of these methods, stacking-velocity analysis, sums data in common-midpoint gathers along different hyperbolas, where each hyperbola is defined by a different $t_0 - s$ pair. The result is displayed in so-called velocity panels that show semblance, the normalized sum, as a function of t_0 and s. I showed an example of such a panel in the previous chapter (Figure 1.3).

2.2.2 Dip moveout

The structure of reflectors in the Earth gives rise to a different kind of moveout, called dip moveout. Consider a dipping reflector in a constant-velocity medium. In the zero-offset section, the arrival time of the event varies linearly with midpoint y, where the slope of the event is given by (Claerbout, 1985, p.8):

$$p_y = \frac{dt}{dy} = 2s \sin\theta. \tag{2.2}$$

The quantity p_y is called stepout or dip moveout, and θ is the dip angle of the layer (measured with respect to the horizontal). The influence of structure on stepout can be seen in Figure 2.1, which shows the near-offset section of the salt data set. The dip of the sea bottom, which is covered by a constant-velocity water layer, can for example be calculated with the above equation.

2.2.3 Kinematics of an event point

For a particular shot-receiver pair, the two types of moveout uniquely determine the kinematics of an event. Therefore, I define an event point $\mathbf{d}$ by its arrival time and stepout:

$$\mathbf{d}(y,h) = (t, p_y;\ y, h), \tag{2.3}$$

or, simply,

$$\mathbf{d} = (t, p_y), \tag{2.4}$$

with y and h the midpoint and offset of the shot-receiver pair. p_y now is the stepout in the constant-offset section. The analysis of these event points plays an important role in the event migration and velocity estimation (Chapters 4 and 5). In the velocity inversion, event points are reconstructed from the migrated data, and are kept fixed; as the velocity model changes during the inversion, event migration then images these fixed event points at different depth points for each update of the velocity model.

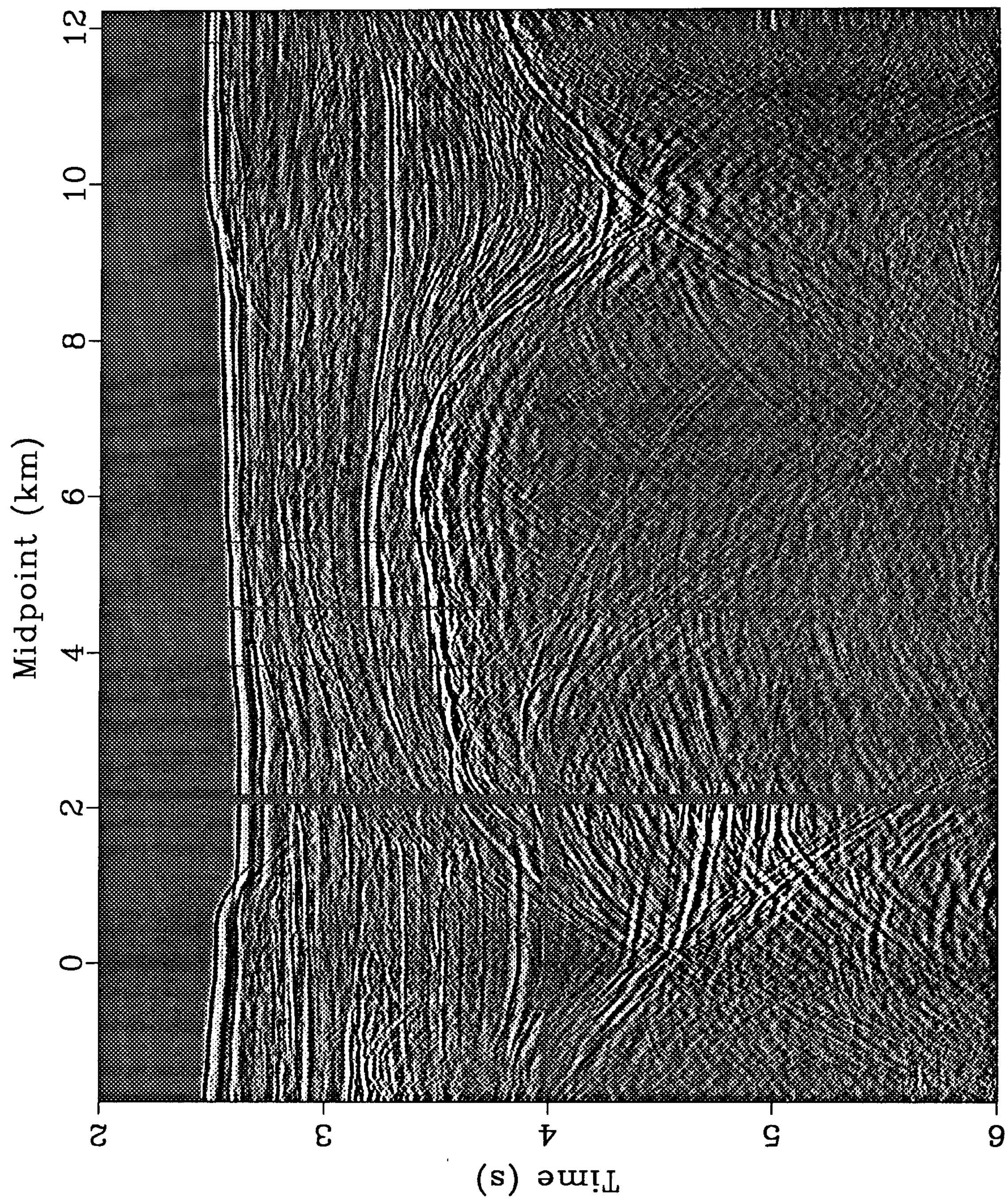

FIG. 2.1. Near-offset section of the Arco data set. Note the decrease in amplitude and pull-up in the sediment reflections below the salt. The near-offset distance is .2 km. Apart from the amplitude decay caused by the salt, an additional decrease in amplitude is apparent after 4 s. This decrease, which extends across the whole section, is caused by a filter used to eliminate water-bottom multiples.

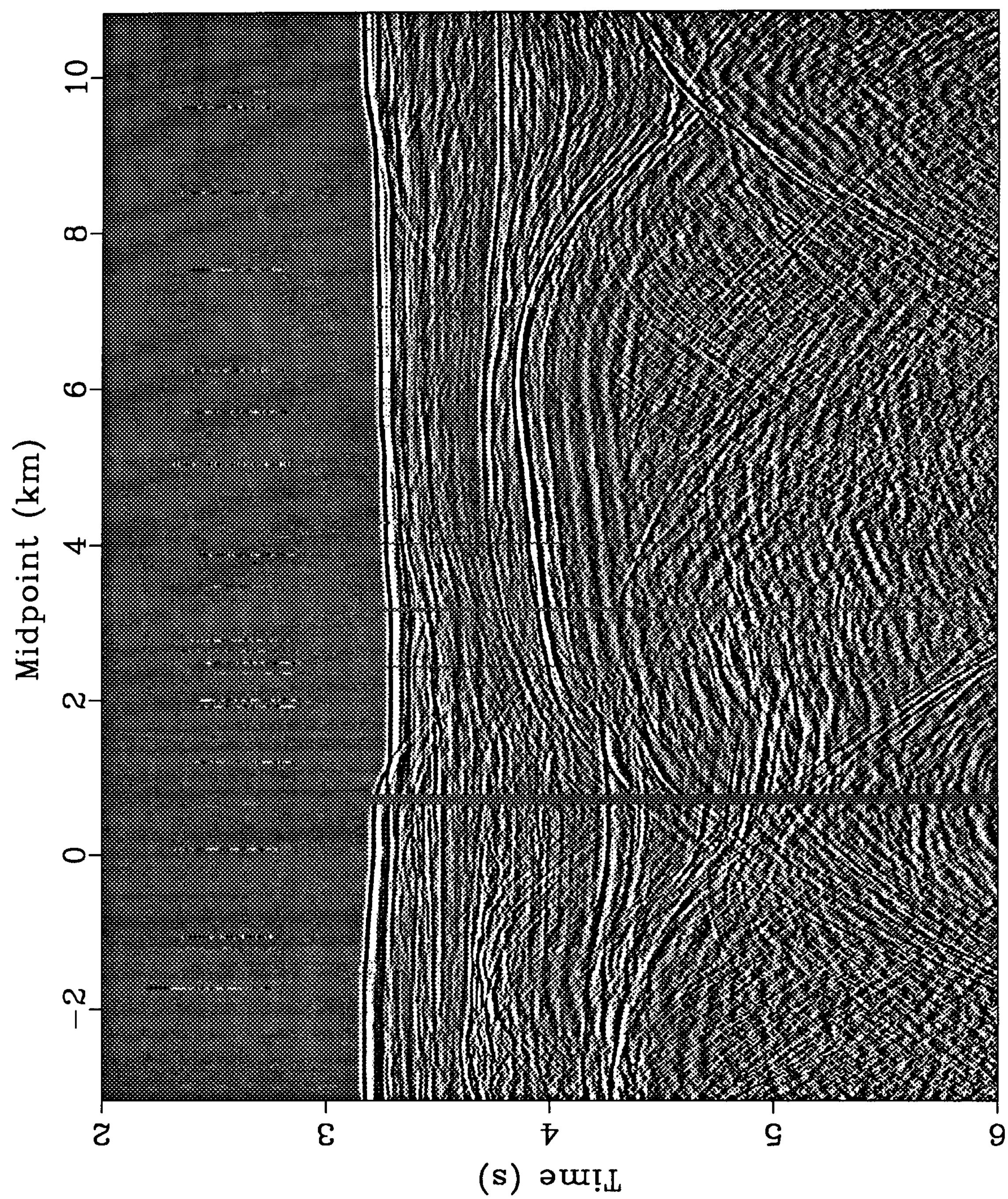

FIG. 2.2. Far-offset section of the Arco data set. As in the near-offset section, sediment reflections below the salt structure are pulled up. The offset of this section is 3 km.

2.3 COMPLEX STRUCTURE

As described above, in homogeneous media, velocity determines the normal moveout of events and structure defines their stepout. Even when the velocity is not constant but slowly varying, the effects of dip tend to show up mainly in constant-offset sections, whereas the effects of velocity are mostly distinguishable in common-midpoint gathers (Claerbout, 1985, p.340). This is why many velocity-estimation methods analyze moveout as a function of offset to determine seismic velocities.

However, in structurally complex regions, the separation of velocity and structural effects in the two domains is less clear. For example, I already discussed the difficulties in analyzing the moveout in events below the salt structure in the CMP gather of Figure 1.2a: structural effects severely distort event moveout. Similarly, the near-offset section in Figure 2.1 reveals velocity effects in the stepout of reflection events below the salt: events are pulled up by the high salt velocity. The same applies to the far-offset section shown in Figure 2.2.

Velocity analysis is greatly complicated by this confusion of structural and velocity effects. A solution to this problem is to migrate the data. Migration again separates dip and velocity effects in the two different domains; indeed, if the correct velocity is used for migrating the data, the events in different migrated constant-offset sections will be identical, and their "stepout" is determined solely by earth dip. Even if the velocity is incorrect, residual velocity effects are mainly detected across offset, just as before with unmigrated data recorded in regions with mild velocity variations. In other words, migration reduces the velocity-analysis problem to the familiar one of determining moveout as a function of offset.

Another problem with data recorded in areas with complex structure, the problem of poor data quality, is addressed by interpreting the migrated data. Structural interpretation helps in identifying events that are weak or contaminated by other events. I illustrate these two points—migration and interpretation of the data—in the next two sections.

2.3.1 Migrating the prestack data

Figures 2.3 and 2.4 show the result of migrating the near- and far-offset sections in Figures 2.1 and 2.2, respectively. The migration method is a depth-migration method that I describe in more detail in Chapter 4 (section 4.2). The velocity model used for migrating

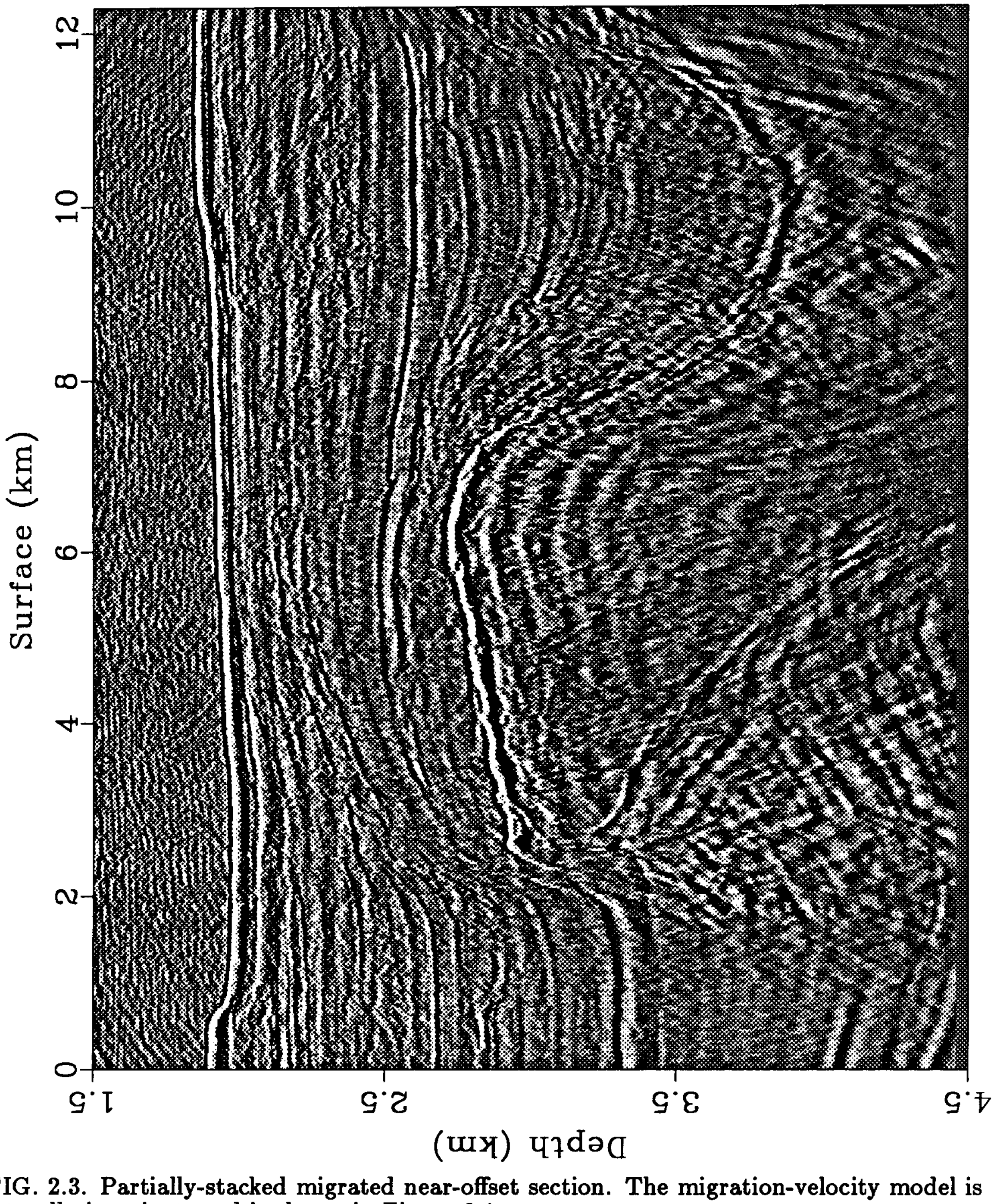

FIG. 2.3. Partially-stacked migrated near-offset section. The migration-velocity model is laterally invariant, and is shown in Figure 6.1.

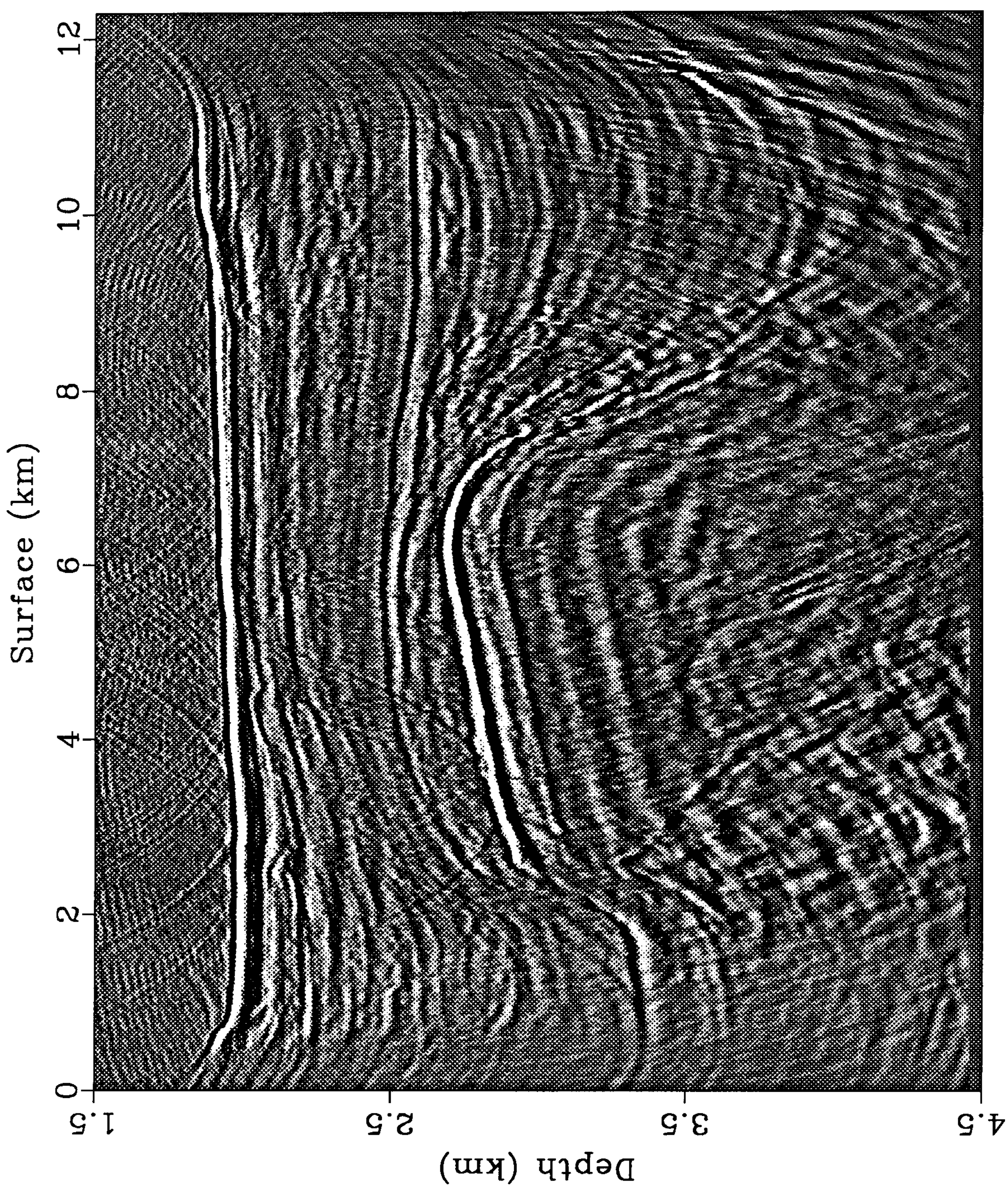

FIG. 2.4. Partially-stacked migrated far-offset section (same offset as constant-offset section shown in Figure 2.2). The migration velocity is the same as the one used in the migration of the near-offset section (Figure 2.3).

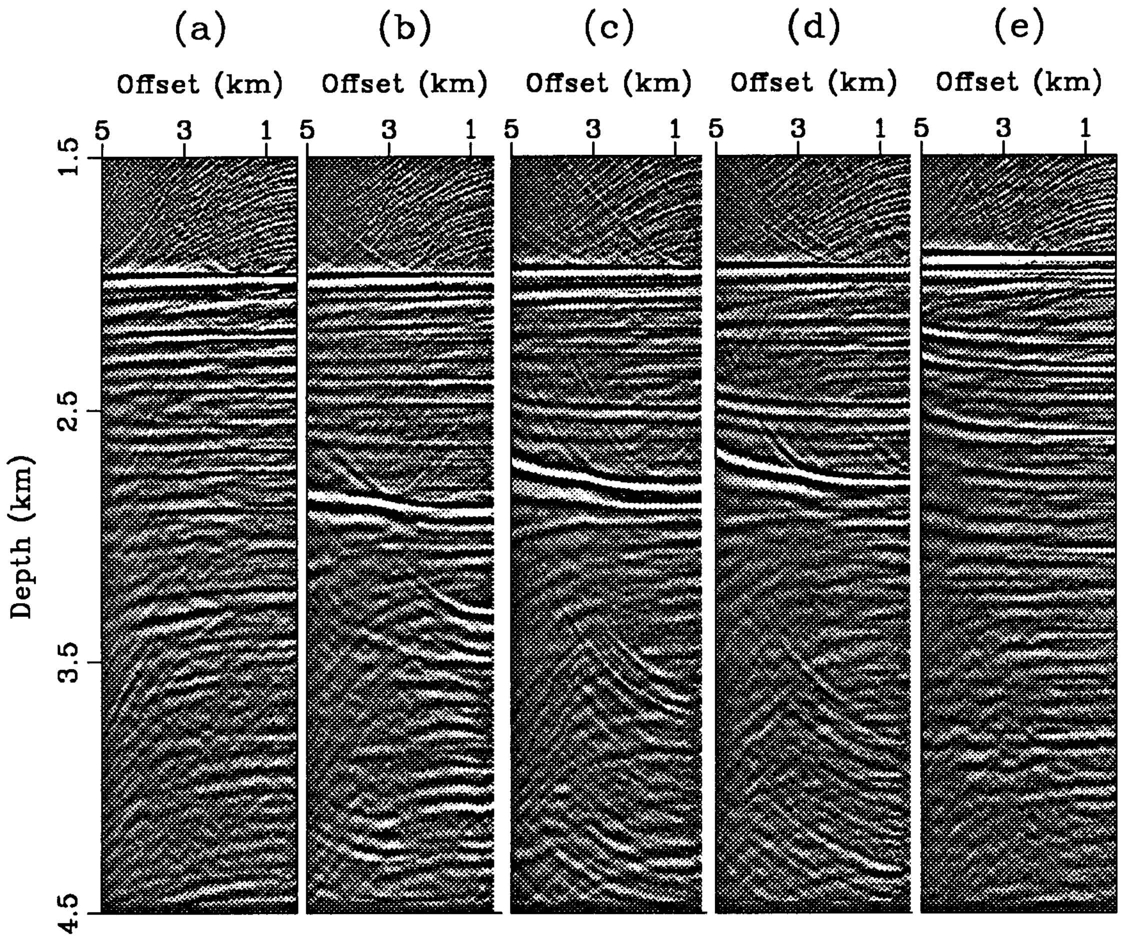

FIG. 2.5. CRP gathers at surface locations (a) 1.5 km, (b) 3 km, (c) 4.5 km, (d) 5 km, and (e) 9 km. The 3 middle gathers are located above the salt, and clearly show the strong salt top reflection (recognizable by the refraction event at the outer offsets). The migrated dipping reflectors below the salt show strong residual moveout.

the data is laterally invariant, and is shown in Figure 6.1. The sections in Figures 2.3 and 2.4 are obtained by stacking several migrated constant-offset sections surrounding the offset under consideration. These partially-stacked sections have a better signal-to-noise ratio than the individually migrated sections. Note that partially stacking the data works well after migration: residual moveout in the data is generally small, and does not impair the local stacks. The large moveouts in unmigrated data, on the other hand, require that the data are transformed before stacking. Two examples of such local-stacking methods are slant stack (Claerbout, 1975) and beam stack (Biondi and Kostov, 1989).

Both migrated sections clearly show the dipping reflector that was interpreted as the salt boundary in the preliminary interpretation of Chapter 1. The other steeply dipping reflector (which is imaged inside the salt, above the first reflector) is visible in the near-offset section, but does not show up in the far-offset section.

Figure 2.5 shows several subsets of the prestack migrated data at different surface locations. These gathers are often called constant-surface location (CSL), or common-reflector-point (CRP) gathers. In the upper part of the gathers most events are flat (no residual moveout) and well-determined, indicating that the linear velocity gradient used in the sediments above the salt is more or less correct. Similarly, moveout in migrated reflectors alongside the salt body is small, or even curving downward (meaning that the migration-velocity is too high; see Figure 2.5a).

Below the salt, the story is quite different: even after migration, sediment reflections are not very clear in the CRP gathers. The same applies to the two dipping events: they disappear at some offsets and are distorted by the sediment reflections. The top event does not extend beyond an offset of about 2.5 km; this explains why it is not visible in the migrated far-offset section (Figure 2.4). Nevertheless, in contrast to the reflections from the fractured sediments below the salt, which are discontinuous and do not have a distinct moveout, the dipping events extend over a large area below the salt and their residual moveout is consistent from surface location to surface location. Furthermore, the upward curvature in their moveout confirms the idea that the migration velocity must be increased to allow for the high velocity of the salt body. Therefore, these dipping events are prime targets for interpretation. Note that the same events are not easy to determine in the unmigrated data, neither in the constant-offset sections (Figures 2.1 and 2.2), nor in a CMP or shot gather (Figure 1.2). To illustrate this point, Figure 2.6 shows a detail of a constant-offset section containing the reflections from the steeply dipping reflectors.

2.3.2 Interpreting the migrated data

An interpretation of the prestack migrated data helps in the identification of events. To identify structural coherency, the interpreter must analyze the data in the constant-offset sections; to study residual moveout, the interpreter must use CRP gathers. I have designed an interactive interface to perform this analysis. The interface is described in detail in Appendix B.

Although picks can be verified in CRP gathers, event picking itself is done on constant-offset sections for several reasons. First, the migrated sections resemble the geology, so that the interpreter can pick structure, instead of moveout. Thus, knowledge of the structural

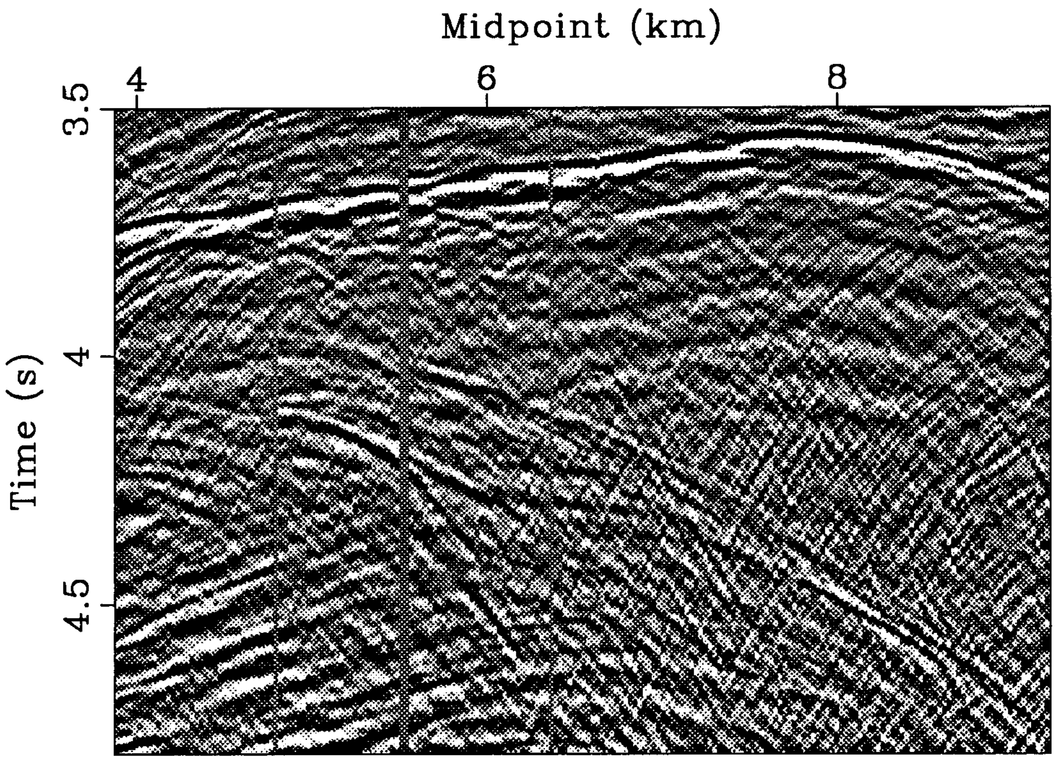

FIG. 2.6. Detail of a constant-offset section at offset 1.75 km. Can you identify the reflection events corresponding to the steeply dipping reflectors? (See Figure 4.6 for a hint.)

setting and geology of the region guides the picking, and, vice versa, the study of the migrated sections helps the interpreter gain insight into the geology. Second, only a limited number of sections have to be picked because the residual moveout in migrated data is small. Residual moveout curves at each surface location can then easily be found by interpolation of the picked events in the offset direction (see Appendix B). Picking a few constant-offset sections is less cumbersome than picking hundreds of CRP gathers. Finally, both the event migration (Chapter 4) and the velocity estimation (Chapter 5) analyze continuous reflection events at constant offsets. The picked constant-offset reflectors can be used directly as input to these processes.

Figure 2.7 displays the result of an interactive interpretation of the migrated data shown above (Figures 2.3-2.5). The figure plots several picked reflectors as a function of offset; Appendix B demonstrates that the picks indeed correspond to events in the data. I have picked the major reflectors above the salt, the two dipping reflectors below the

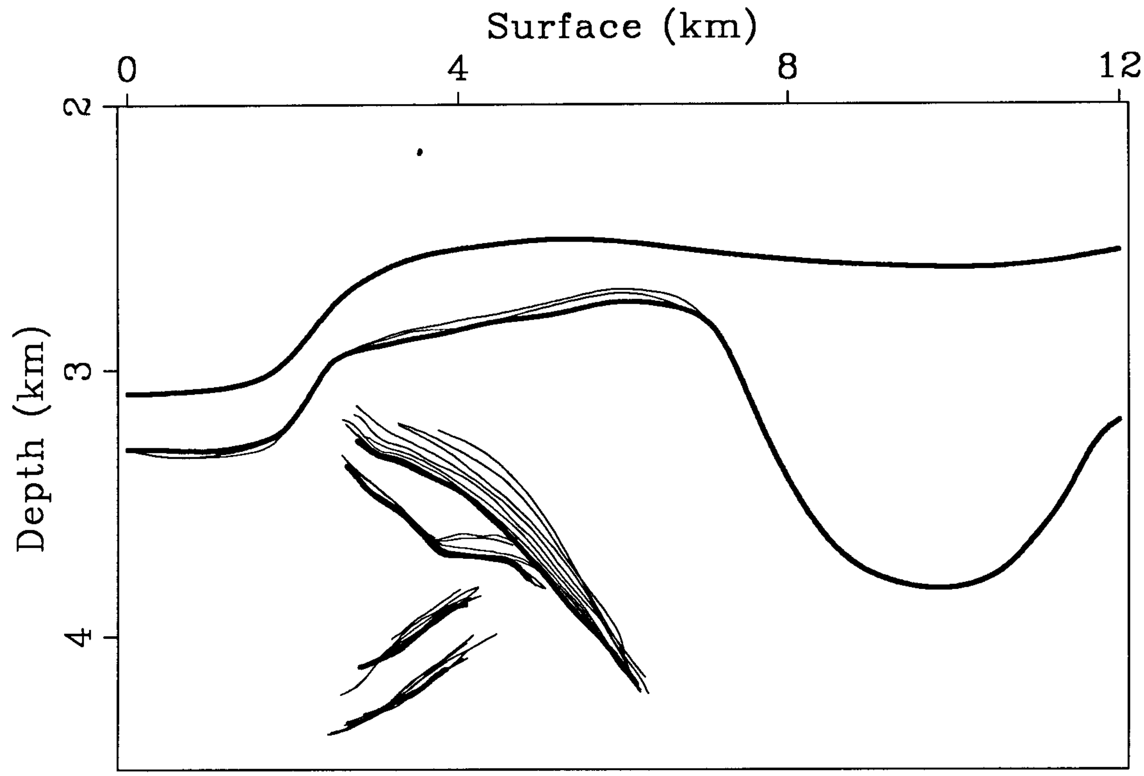

FIG. 2.7. Picked reflectors in the migrated constant-offset sections. The fat lines show the picked reflectors at near offset.

salt, and the two most continuous sediment reflectors to the left of the salt. As expected, the largest residual moveout occurs in the events below the salt, and residual moveout increases as the salt thickness increases.

The top dipping reflector is probably the salt boundary, in contrast to the initial interpretation that identified the bottom dipping reflector as the salt boundary (section 1.1). The bottom reflector is presumably a fault branching off from the salt boundary at a depth of about 3.8 km. (The depth depends of course on the migration velocity.) This interpretation is consistent with the notion that faulting occurred mostly in the sediments alongside the salt; the sediments above the salt are mostly continuous.

2.4 PITFALLS

Of course, one potential danger with picking events is that errors can be made in the picking, either by picking the wrong event, or by interpreting events that are not really there. Picking prestack data is generally less robust than analyzing stacked data. However, as I discussed in the previous section, migrated constant-offset sections are easier to pick than unmigrated gathers, especially if several of these sections from neighboring offsets are stacked to improve signal-to-noise ratio.

A general problem with data recorded in areas with complex structure is that a two-dimensional image will frequently fail to explain three-dimensional effects in the data. Salt data, in particular, are notorious for this problem. To reduce this difficulty from the outset, the salt data set that I analyze in this thesis is shot in the regional dip direction, reducing the chance of recording out-of-plane reflections. Nevertheless, there is no guarantee that all the events are genuinely in-line; a detailed analysis of event moveout is needed to confirm this assumption. The method of residual event migration that I describe in Chapter 4 performs such an analysis: reflector position and moveout are verified when the picked reflectors are residually migrated with some trial velocity models. The residual event migration is computionally cheap, and can be run interactively.