Chapter 2

Observations of elastic waves

2.1 Is the earth elastic?

This chapter is intended to give the observational perspective and motivation for choosing to derive inversion equations for elastic wavefields. After all, people have assumed that the Earth is acoustic for a long time. What waves cannot be well modeled by the acoustic theory? Is elastic wave theory really necessary?

2.2 Primary reflections and mode conversions

The most important seismic waves in geophysical prospecting for oil are the primary reflections. These are waves, generated by a seismic source on the Earth's surface, that travel downwards into the Earth and are reflected back upwards by discontinuities. When these reflected waves reach the Earth's surface, they are recorded as ground motions. Acoustic theory predicts only compressional waves. However, elastic theory also predicts shear waves. A downgoing wave mode (say compressional) is reflected back upwards as two different wave types, compressional and shear. The case when the upgoing wave type is different to the downgoing wave type is called mode conversion. Theoretically, the amplitudes of the reflected compressional and shear waves determine the P- and S-wave velocity and density perturbations at the boundary. The traveltime curves of reflections determines the velocity felt by the seismic waves between the Earth's surface and the reflector. Thus, wavefields containing reflection traveltime shapes and amplitudes should resolve gross velocity variations as well as velocity and density jumps at discontinuities.

There are four different primary reflections, P-P, P-S, S-P and S-S. How important are these in practice? Should effort be put into an elastic theory to account for the P-S, S-P and S-S events? This chapter shows some mode converted waves and illustrates that they are first order effects and are as important as the P-P primaries.

A two component shot gather due to a vertical vibrator is shown in Figure 2.1. It is representative of good quality reflection seismic data recorded over land in oil exploration surveys. The identified events are:

1. P-P primary reflection.
2. P-S primary reflection from the same discontinuity that produced event 1.
3. Other P-S events.
4. High amplitude reflections near the critical angle.
5. Head waves related to event 4.

Note that the P-S modes are more evident on Figure 2.1 than on the bulk of seismic data recorded in oil exploration. This is because oil exploration surveys typically have smaller offset ranges of about 2.5 km. This implies smaller incidence angles of reflected waves and hence less mode conversion. Another reason that mode converted waves have not been routinely observed in the past is that most surveys recorded only the vertical component of displacement. This component measures mainly P-waves because seismic waves tend be refracted to an almost vertical propagation direction at the Earth's surface by the low near surface seismic wave velocities (vertical propagating P-waves and S-waves respectively have vertical and horizontal particle displacements). Therefore, P-S reflections which have nearly horizontal displacements at the Earth's surface are usually strong on the horizontal component seismic records and weak on the vertical component records.

A 1D model was obtained from the data shown in Figure 2.1 (a) by linearly interpolating a P-wave RMS velocity function from an NMO velocity analysis and applying the Dix equation to convert to interval velocity every 20 meters (see Figure 2.3). The S-wave velocity shown in Figure 2.3 is half of the P-wave velocity as is typical for sedimentary rocks (the shot gather in Figure 2.1 was recorded in a sedimentary basin and the reflections are due to discontinuities in the elastic properties at boundaries between the sedimentary rocks). Figure 2.2 shows a synthetic gather generated using elastic finite differences from the velocity model shown in Figure 2.3 (the density model was constant).

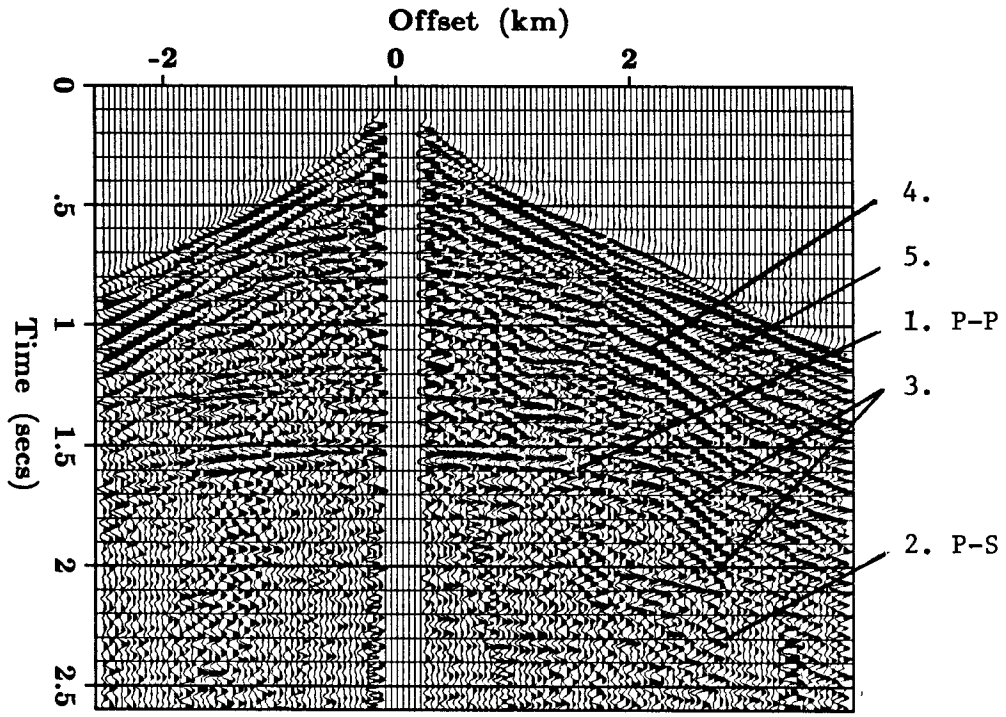

Figure 2.1: (a). Vertical component field shot gather from a vertical vibrator source (supplied by C.G.G. through Henry Brysk).

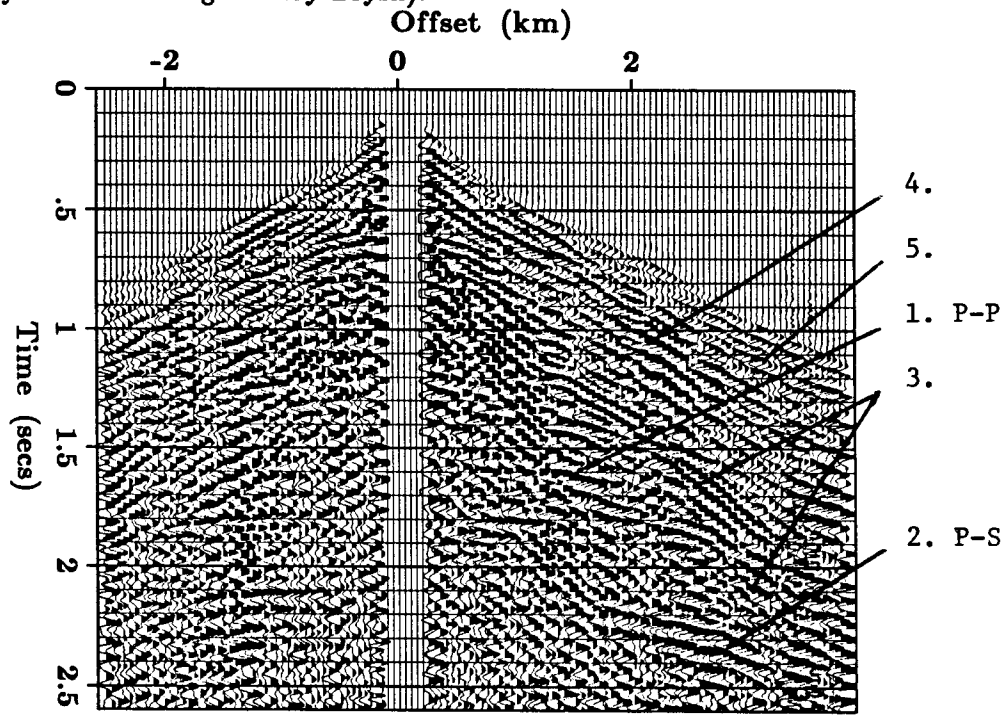

Figure 2.1: (b). Horizontal component field shot gather from a vertical vibrator source (supplied by C.G.G. through Henry Brysk).

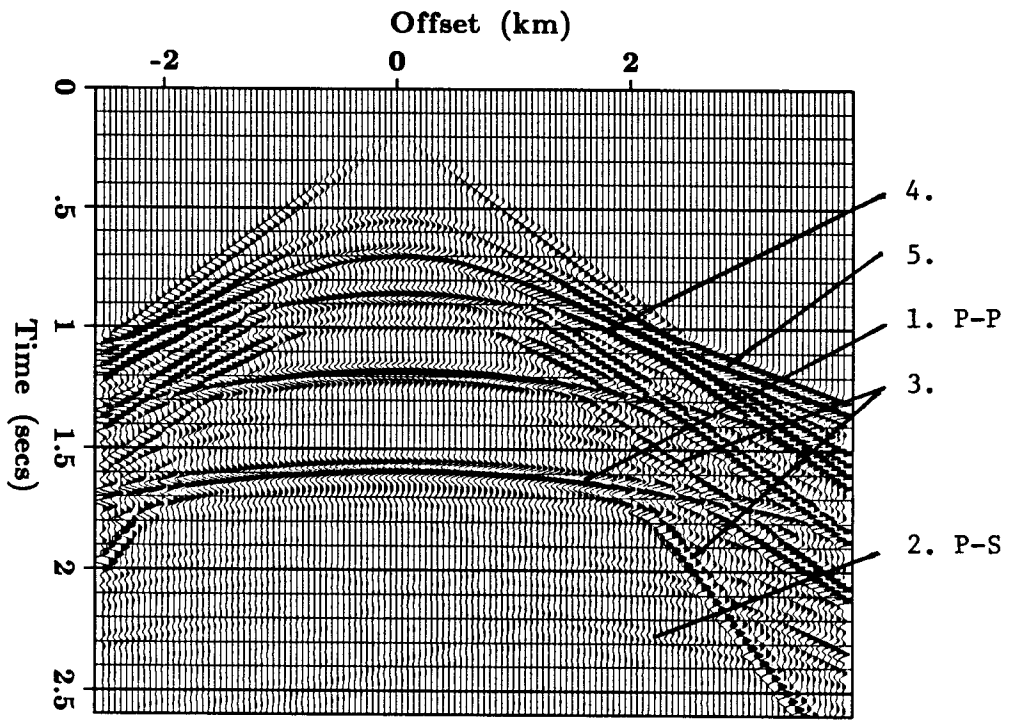

Figure 2.2: (a). Synthetic vertical component shot gather generated by elastic theory.

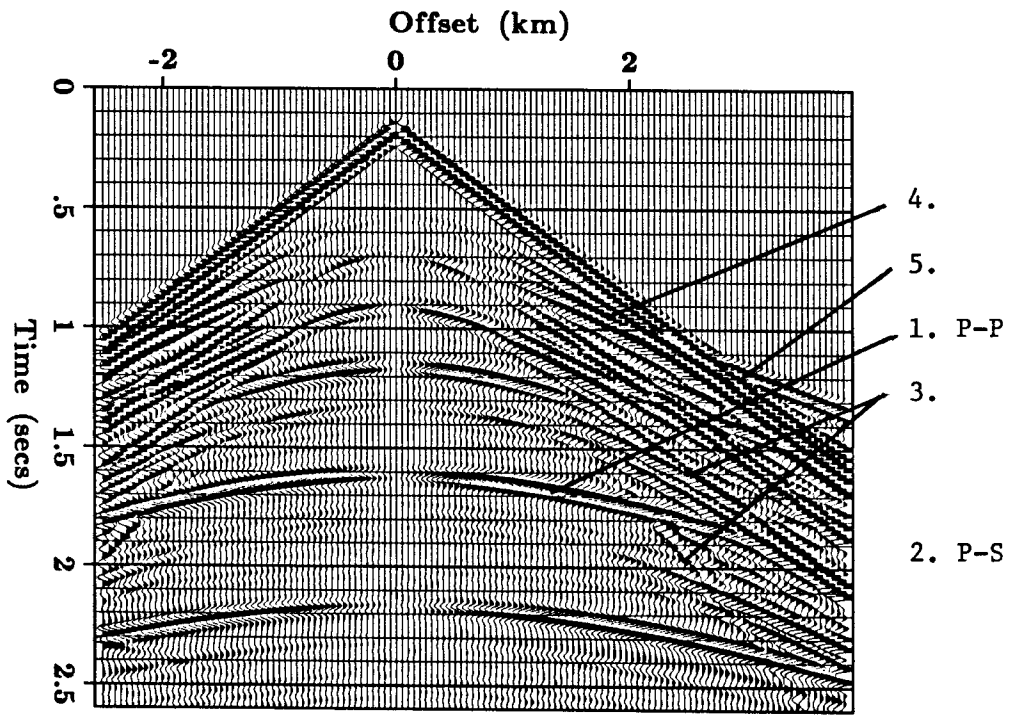

Figure 2.2: (b). Synthetic horizontal component shot gather generated by elastic theory.

The synthetic data in Figure 2.2 was generated using a compressional source and with an absorbing boundary condition applied at the Earth's surface. The same five events that were identified on Figure 2.1 can be seen on Figure 2.2. The P-P and P-S reflections (events 1 and 2) were both produced by a discontinuity in elastic parameters at a depth of about 3.1 km (the deepest reflector in Figure 2.3). This was verified by modeling with and without the 3.1 km reflector of Figure 2.3 and plotting the difference between these two modeling runs (Figure 2.4) leaving only the P-P and P-S reflections identified as events 1 and 2.

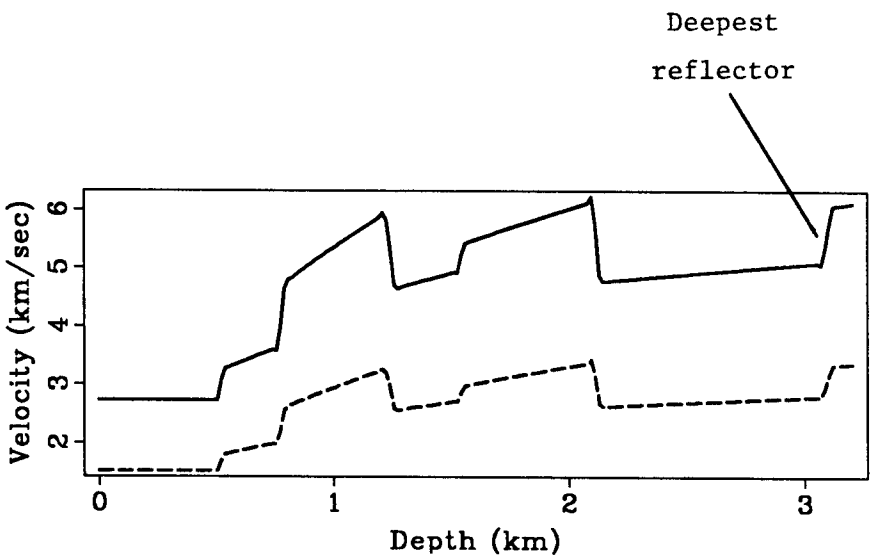

Figure 2.3: P-wave velocity model (solid line) and S-wave velocity model (broken line).

For comparison, an acoustic modeling run was performed with the same P-wave velocity model (Figure 2.5). The synthetic acoustic data does not contain any P-S events so it matches the field data much more poorly than does the synthetic elastic data.

The P-S events are about the same strength as the P-P events on the two component data shown in Figure 2.1. These strong events are ignored if the Earth is assumed to be a liquid but are well modeled using elastic theory.

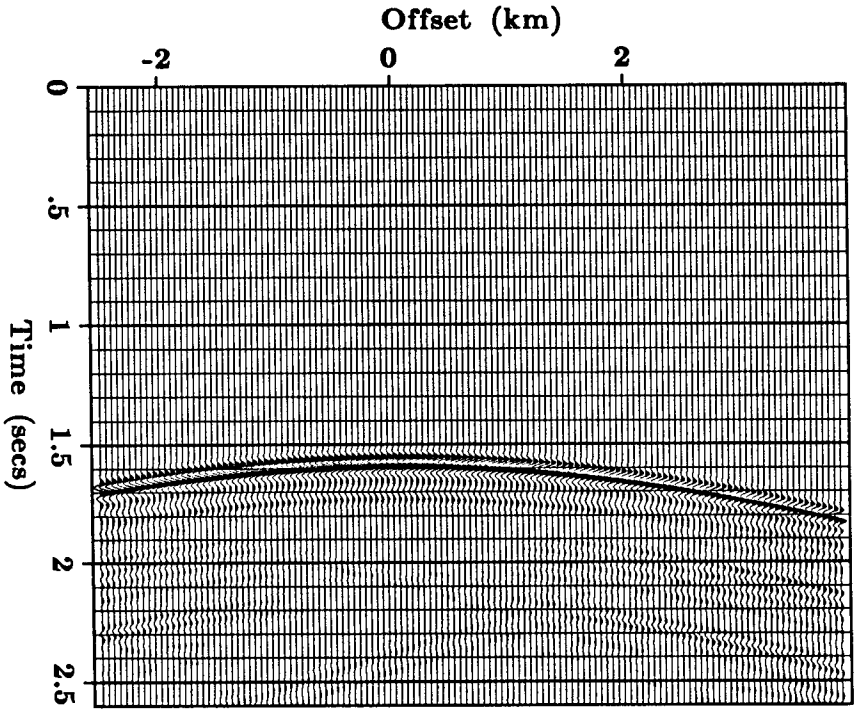

Figure 2.4: (a). Difference between synthetic vertical component shot gathers generated with and without the identified reflector.

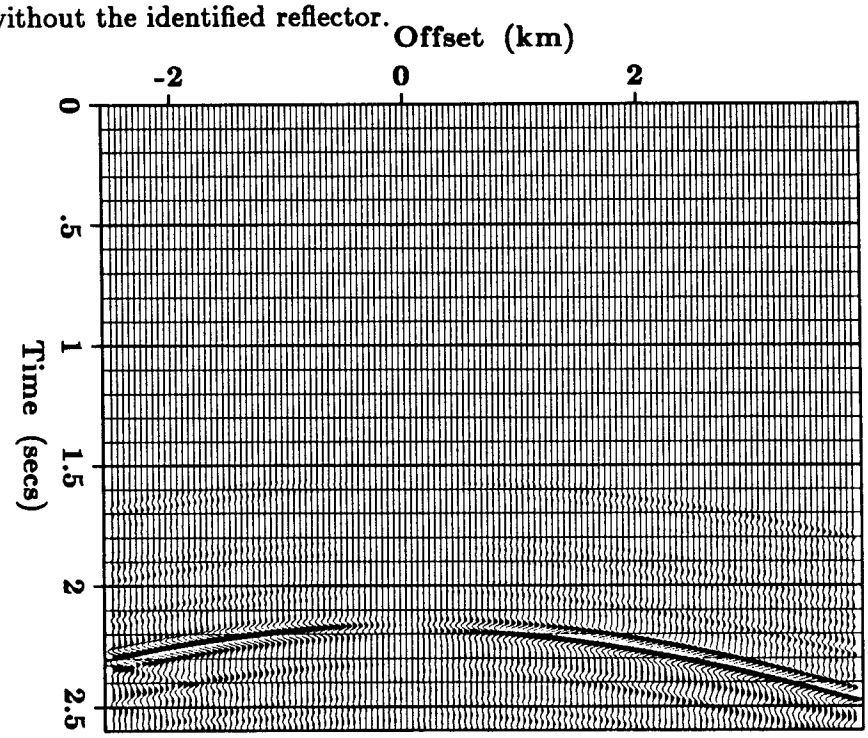

Figure 2.4: (b). Difference between synthetic horizontal component shot gathers generated with and without the identified reflector.

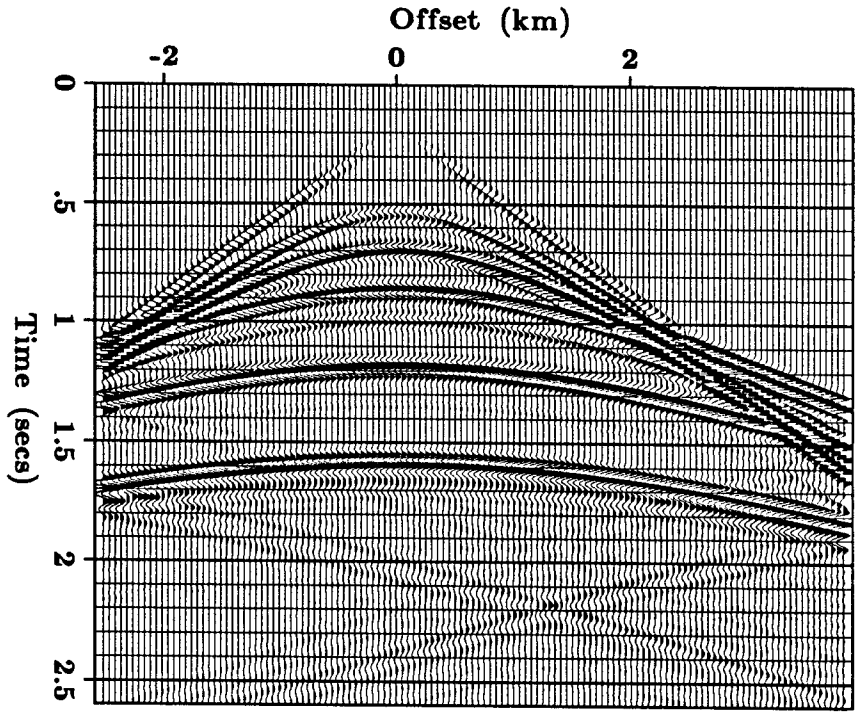

Figure 2.5: (a). Synthetic vertical component shot gather generated using acoustic theory.

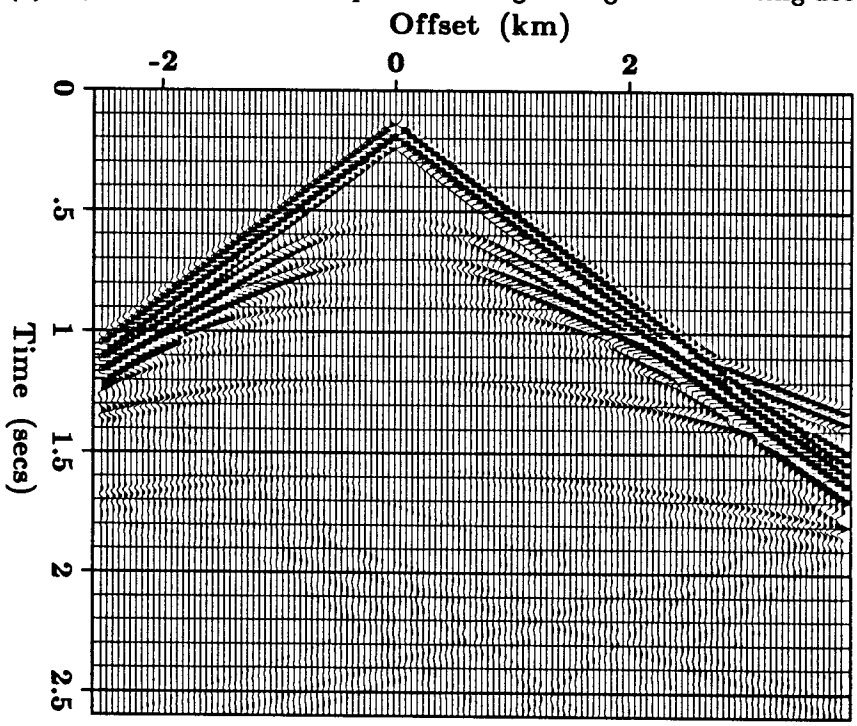

Figure 2.5: (b). Synthetic horizontal component shot gather generated using acoustic theory.

2.3 Other elastic phenomena

Other elastic phenomena are surface waves such as Rayleigh and Love waves, interface waves such as Stoneley waves and mode converted multiple reflections. These are also seen on seismic data, especially, Rayleigh waves (see Figure 2.6).

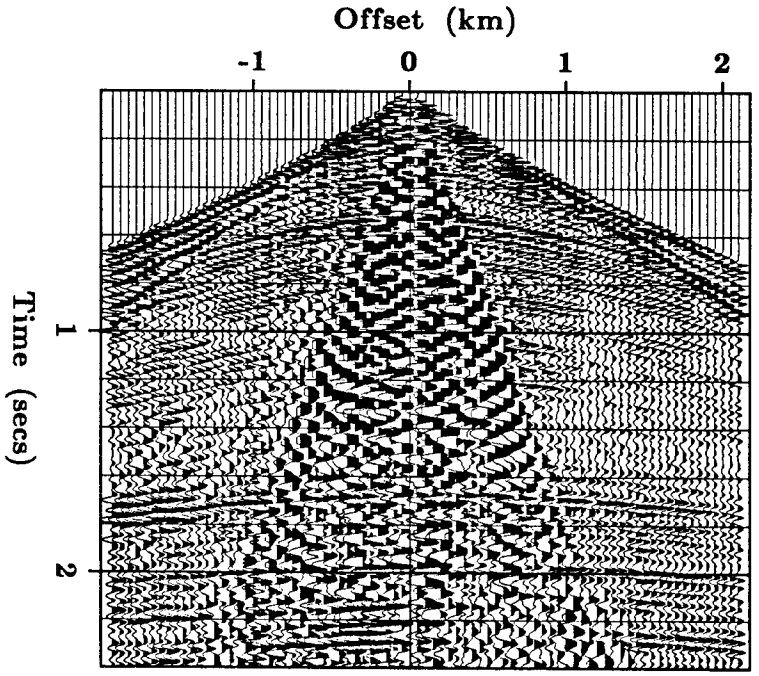

Figure 2.6: Field shot gather with Rayleigh waves (from Yilmaz and Cumro (1983)).

Although I will derive a method that accounts for all these additional wave types in the next chapter, I will later focus attention on the case when primary reflections dominate. The reason is that these events see, and hence resolve, the deeper geology that is so interesting to reflection seismologists.

2.4 Conclusions

P-S mode converted waves are the strongest events on vertical-component source to horizontal-component geophone seismic data. They are clearly visible on wide-offset vertical-component source to vertical-component geophone data. Data containing both P-P and P-S events are not well modeled using the acoustic wave equation but are well modeled using the

elastic wave equation. Therefore, when interpreting and processing wide-offset or multi-component seismic data, account should be taken of the mode converted waves. Interpreters should identify these events and theorists should assume the elastic wave equation.