Chapter 1

Introduction

Traditionally, seismic imaging techniques have only accounted for primary reflections. When strong reflectors are present (e.g, air-water interface, hard water bottom or salt bodies), multiples can significantly degrade the images and make their interpretation ambiguous. Multiples have been considered as noise, therefore, much effort in the past few decades has been devoted to developing multiple suppression techniques.

Well-known demultiple tools such as deconvolution (in time, frequency, and slant-stack domains), Radon-transform demultiple, and frequency-wavenumber (f-k) demultiple are limited to cases where the subsurface geology is simple. When the geology is complex multiples are not easily separated from primaries by criteria such as periodicity, moveout velocity, and spectra. Model-based techniques predict multiples with wavefield extrapolation (Morley, 1982; Berryhill and Kim, 1986; Wiggins, 1988; Lu et al., 1999). The accuracy of the predicted multiples strongly depends on the model used. Convolution-based techniques, such as surface-related multiple elimination (SRME) (Riley and Claerbout, 1976; Tsai, 1985; Verschuur et al., 1992), are in principle capable of suppressing multiples in complex geology. However, these methods require an overlap of source and receiver locations that is not realistic for many practical acquisition geometries and are limited to surface-related multiple suppression. Despite substantial progress in multiple elimination, complete removal of surface-related and internal multiples without distorting primary signals remains a challenge.

Motivations

The need to image areas with increasingly complex subsurface geology has driven the advancement of seismic acquisition geometry. Substantial improvement in seismic imaging is observed when the acquisition geometry goes from 2D to 3D, or from narrow azimuth to wide azimuth. Recently, coil shooting and ocean bottom node (OBN) acquisition provide rich- and full-azimuthal coverage.

Multiples can be treated as signal. One motivation to image with multiples is that they can supplement subsurface illumination that is not found in primary signals. Figure 1.1 illustrates the increase in illumination when surface-related multiples are used as signal. A figure extracted from Lu et al. (2013) compares two time slices at 120 ms two-way traveltime (TWT). The time slices were produced by a marine survey conducted in an area with a water depth of 70m. The left image shows a pronounced cross-line acquisition footprint. Using surface-related multiples yields an image (Figure 1.1 right-panel) that allows shallow geohazard interpretation.

I will discuss the benefit of imaging with higher-order surface-related multiples in terms of source and receiver arrangement. In ocean bottom node imaging, processing are sorted by common receiver gathers. Computationally, we treat each OBN receiver as a source and the physical sources as receivers. The first-order down-going reflection is also known as the mirror reflection. When we try to image a mirror reflection (Figure 1.2a), the sources are injected at location 1 and recorded at location 2. However, on top of the mirror reflection, we are also recording higher-order surface-related multiple reflections . The energy from the first-order reflection will then be reflected off the sea-surface and travel downward through the water column a second time (Figure 1.2b). In this sense ,the higher-order reflection effectively has energy originating from the sea-surface (location 2) and is recorded again at the sea-surface (location 2). The physical sources (location 2) are well populated at the sea

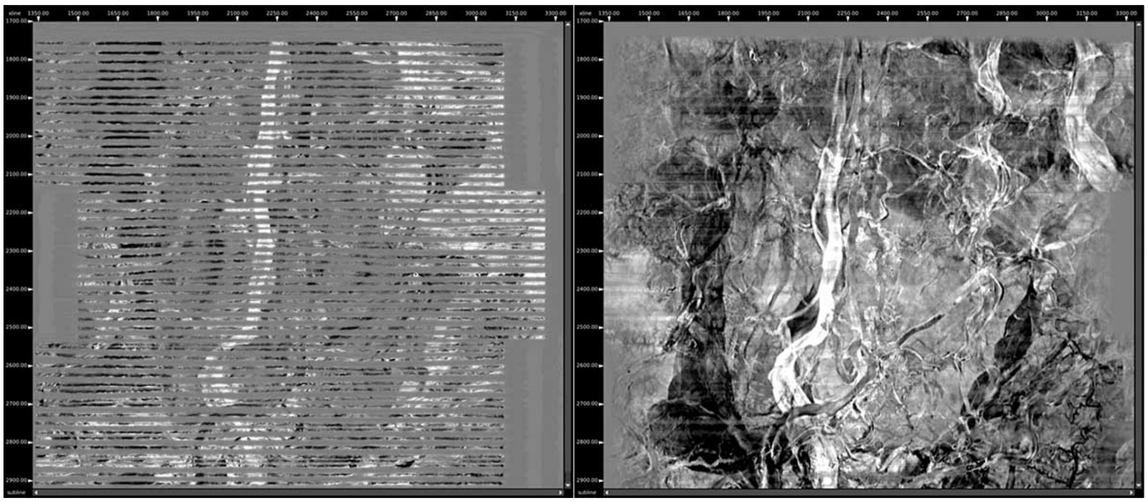

Figure 1.1: This is a comparison between primary-only (left) and surface-related multiples (right) imaging. The comparison is of two time slices at 120 ms TWT. There is an increase in illumination when surface-related multiples are used. This figure is extracted from Lu et al. (2013). [**NR**] chap1/. PGSSWIM

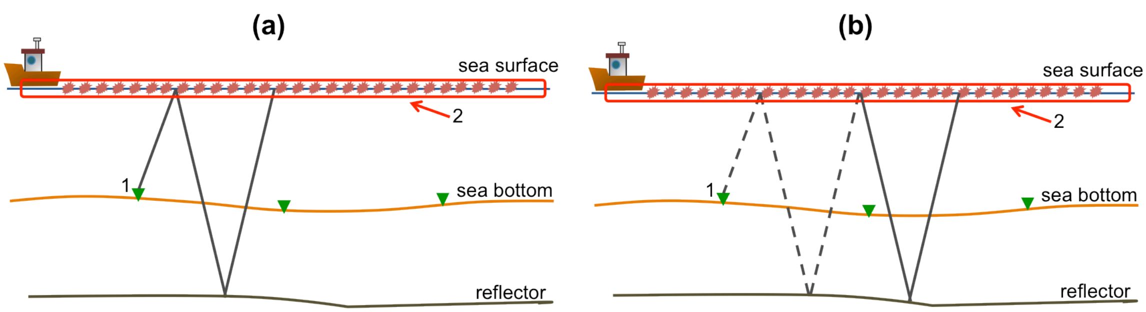

Figure 1.2: (a) Computationally, the mirror reflection has a source at the sea-bottom (location 1) and receiver at the sea-surface (location 2). (b) A surface-related multiple reflection effectively has energy originating from the sea-surface (location 2) and is recorded again at the sea-surface (location 2). The surface-related multiple reflection has a much denser source and receiver grid. [**NR**] chap1/. chap1fig2v2

surface. Using the surface-related multiples can provide information equivalent to a well-populated grid of sources and receivers While the illustrations only highlight the differences in 2D, the benefit in 3D is greater with better azimuthal coverage.

We anticipate several types of illumination when including multiple events. In general, we expect to see a wider subsurface illumination. This is more apparent in shallower regions than in deeper regions. Figure 1.2 illustrates that using surface-related multiples simulates a well-populated source and receiver grid. Using the multiples will not provide much improvement when the subsurface is relatively simple. However, multiples can be useful in subsalt imaging. Due to the rugosity of the salt, energy that enters the salt is often bent at different angles. Frequently, that energy does not return to the receivers. Figure 1.3 shows a ray tracing plot of the Sigsbee model with rays shooting from the location within the shadow zone of the subsalt region. Rays at various incident angles are often bent and fail to return to the surface. Treating the multiples as signals provide more opportunities to record energy that has reached the poorly illuminated areas. In chapter 4, we will discuss more about the illuminate gain that multiples can provide.

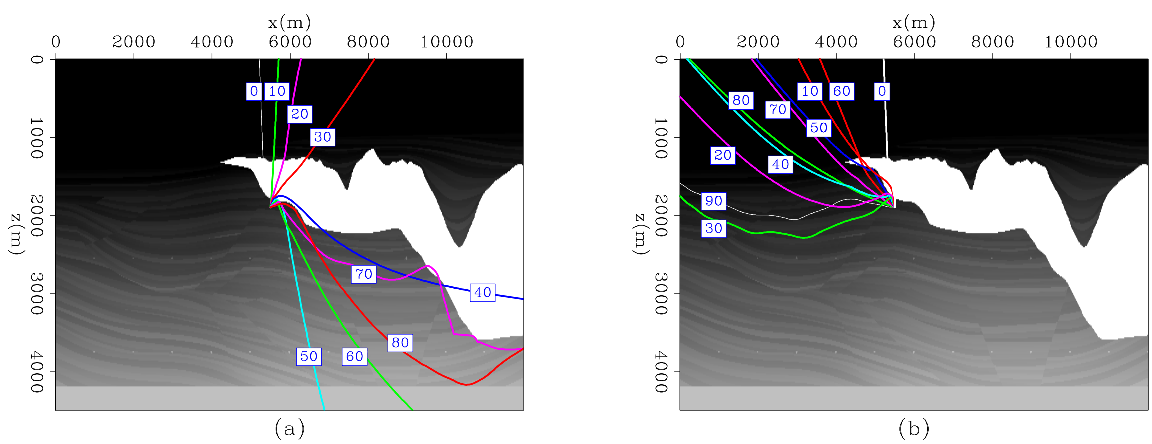

Figure 1.3: Ray tracing of the Sigsbee velocity model with rays shooting out from location within the shadow zones. (a) rays shooting from the negative x-axis direction up to the vertical direction at 10-degree intervals; (b) rays shooting from the vertical direction to the positive horizontal axis at 10-degree intervals. The complexity of the salt has bend the rays at various angles. Only a select few returns to the surface. [**ER**] chap1/. Vraytotal

Despite the advancement of multiple suppression techniques, complete removal of all multiples from the primaries still remains a challenge. Migrating such signals would result in crosstalk artifacts. Figure 1.4 and Figure 1.5 show a synthetic example when surface-related multiples are not completely removed from the data. A simplified version of the Sigsbee model is used to generate two sets of synthetic data. Figure 1.4a shows a shot gather with both primary- and surface-related multiple energy. Each order of surface-related multiple reflections arrives roughly one second apart. To simulate the situation of incomplete removal of all multiples, I also generated data with 20 percent of the surface-related multiple energy (Figure 1.4b). When migrating the data without multiple removal, multiples become noise in the migration image as highlighted by the circle in Figure 1.5a. Even with 80 percent of the surface-related multiple energy removed from the data, some unwanted noise remains in the migration image. In particular, the arrows in Figure 1.5 point to a bright spot region that is degraded by the noise. In this thesis, I explicitly tackle the problem of imperfect separation and aim to derive a solution that can remove such crosstalk artifacts in imaging. Instead of using migration, the imaging problem can be reformulated as an inversion problem. The basic idea is to estimate a seismic image by enforcing the consistency between the modeled data and the observed data. This consistency requirement can gradually push out unwanted noise such as crosstalk artifacts from the image. Such an inversion technique, commonly known as least-squares migration, will be discussed in the next chapter.

History of multiple imaging

Reiter et al. (1991) attempted to capitalize on the potential of multiples by formulating a prestack Kirchhoff time-migration method that includes the first-order water-layer reverberation in the migration operator. Because ocean bottom cable data could not be decomposed into up- and down-going components at the time, such work was limited to deep water datasets.

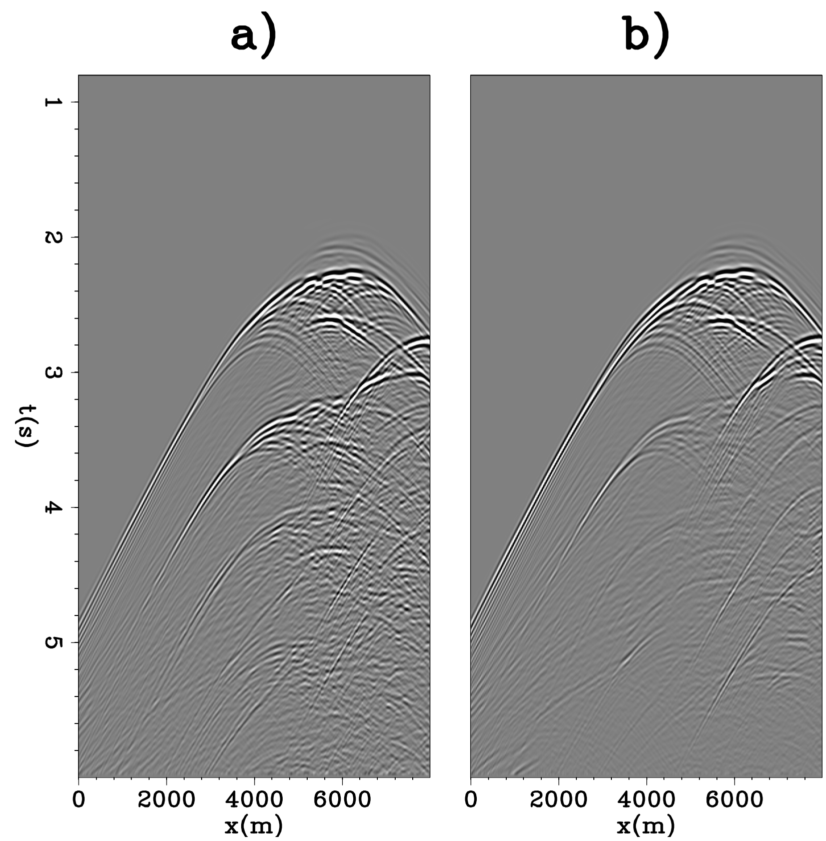

Figure 1.4: A shot gather displaying (a) both primary and multiple energy, and (b) primary data with 20 percent of surface-related multiple energy remaining to simulate incomplete multiple suppression. [**CR**] $\boxed{\text{chap1/. chap1dataCom}}$

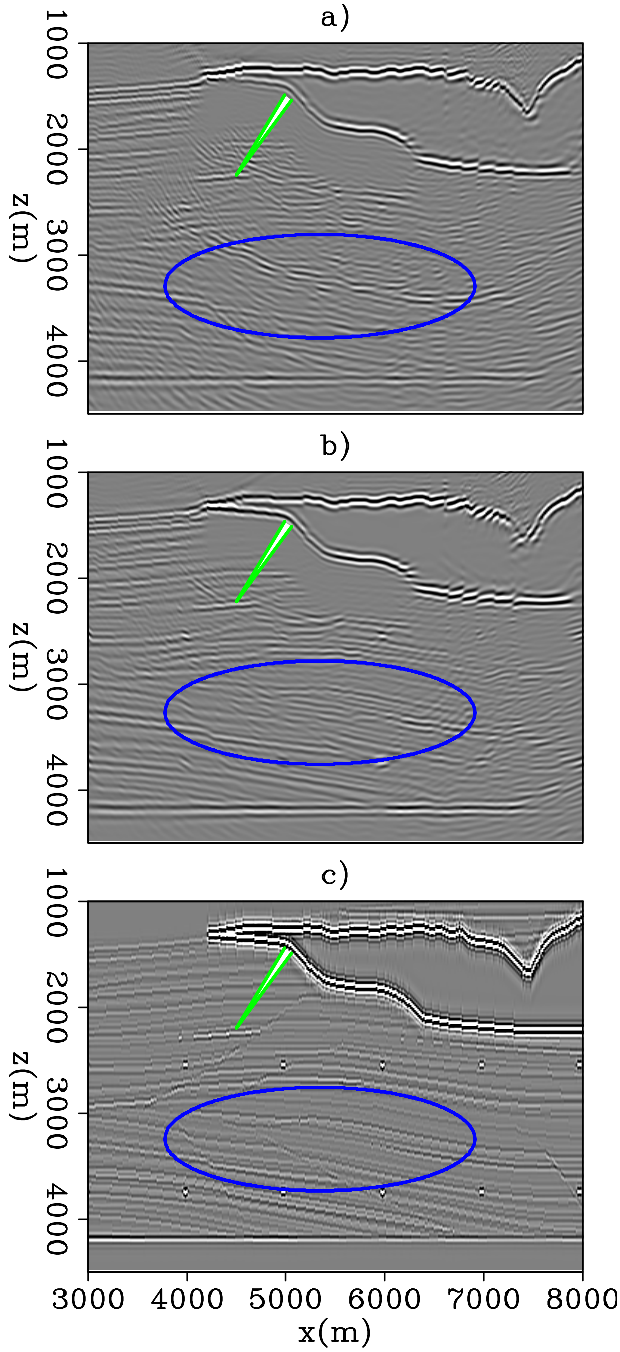

Figure 1.5: Migrated image from the synthetic data in Figure 1.4 (a) using both primary and multiple signal and (b) using a primary signal with 20 percent of the surface-related multiple energy. The true image is displayed in (c). The crosstalk noise is highlighted by the circle. The arrow indicates a bright spot region that is being degraded by the noise. Even with 80 percent of the multiple removed, the image is compromised. [**CR**] chap1/. chap1Zoom

When surface-related multiples are explicitly separated from the primary reflections (e.g., using SRME), they can be imaged independently from the primary reflections by using shot-profile (Guitton, 2002) or source-receiver (Shan, 2003) depth migration. Muijs et al. (2007a) imaged primary and free-surface multiples for OBS data by decomposing data into up-going and down-going constituents followed by downward extrapolation and a 2D deconvolution-based imaging condition. All of these techniques image the surface-related multiples by transforming the primary signal into a pseudo-source for migration with the multiple signals using the one-way wave equation (Artman, 2007). Recently, Liu et al. (2011) extended the technique to the two-way wave equation. These methods image a certain mode of multiples by treating all other modes, including the primaries, as noise. While these techniques are computationally efficient, current migration algorithms would leave crosstalk artifacts in the image. Migration algorithms such as reverse-time migration use the cross-correlation imaging condition to produce an image $I(\mathbf{x})$.

$$I(\mathbf{x}) = \sum_{\mathbf{x_s},t} S(\mathbf{x},t;\mathbf{x_s})R(\mathbf{x},t;\mathbf{x_s}), \tag{1.1}$$

where $S(\mathbf{x},t;\mathbf{x_s})$ is the source wavefield and $R(\mathbf{x},t;\mathbf{x_s})$ is the receiver wavefield. When multiples are used in the imaging condition, the source and receiver wavefields can be broken down into different order of reflections.

$$S(\mathbf{x},t;\mathbf{x_s}) = S_1(\mathbf{x},t;\mathbf{x_s}) + S_2(\mathbf{x},t;\mathbf{x_s}) + S_3(\mathbf{x},t;\mathbf{x_s}) + ..., \tag{1.2}$$

$$R(\mathbf{x},t;\mathbf{x_s}) = R_1(\mathbf{x},t;\mathbf{x_s}) + R_2(\mathbf{x},t;\mathbf{x_s}) + R_3(\mathbf{x},t;\mathbf{x_s}) + ..., \tag{1.3}$$

where the subscript number refers to an order number that scales with an additional pass through the water-column. When cross-correlation imaging condition is applied, the final image can be classified into two parts: the signal image and the noise image. The signal image, $I_{\text{signal}}(\mathbf{x})$, is from the interference of wavefields corresponded to the same order of reflections. The noise image, $I_{\text{noise}}(\mathbf{x})$, are caused by the interference of wavefields not associated with the same order of reflections.

$$I(\mathbf{x}) = I_{\text{signal}}(\mathbf{x}) + I_{\text{noise}}(\mathbf{x}), \tag{1.4}$$

$$I_{\text{signal}}(\mathbf{x}) = \sum_{\mathbf{x_s},t}(S_1R_1 + S_2R_2 + S_3R_3 + S_4R_4 + ...), \tag{1.5}$$

$$I_{\text{noise}}(\mathbf{x}) = \sum_{\mathbf{x_s},t}(S_1R_2 + S_2R_1 + S_1R_3 + S_3R_1 + ...), \tag{1.6}$$

A robust technique is needed to gain the benefit of multiple imaging without compromising its quality.

Brown (2004) approached the multiple imaging problem with linearized inversions. Using the NMO-based operator and assuming a relatively simple subsurface, Brown was able to construct operators that image with all types of peg-leg multiples. I propose using least-squares reverse time migration to show that multiples can add values, even for a complex subsurface.

DISSERTATION OVERVIEW AND CONTRIBUTIONS

The remaining chapters in this dissertation are organized according to the following outline:

Chapter 2 ***Joint imaging of up- and down-going signal*****:** In this chapter, I discuss joint imaging of up- and down-going signal for an ocean bottom dataset. The benefits and characteristics of imaging with either type of signal will be highlighted. I apply a data-domain linearized inversion technique, known as least-squares reverse-time migration, to optimally combine the information from both the up- and down-going signals. I demonstrate how high quality images can be obtained with results from a 2D synthetic and the 2D Cascadia field datasets.

Chapter 3 ***3D field data examples - Deimos Dataset*****:** In this chapter, I apply the inversion method in Chapter 2 onto the 3D Deimos ocean bottom field dataset from the Gulf of Mexico. Several challenges arose when I applied this method to a 3D field dataset. One challenge was imperfect separation between up-going and down-going signals in the dataset. I will discuss how this affected regular migration images. I propose a way to handle this problem by manipulating the properties in the extended image space. I show that the joint imaging result can provide a better image than migrating either of the signals alone. Using least-squares migration also gives fewer migration artifacts and better amplitude information underneath complex overburdens.

Chapter 4 *Imaging with multiples using linearized inversion*: In this chapter, I discuss the theory for imaging beyond the first-order of surface-related multiples using least-squares reverse-time migration. The procedure for constructing the modeling and migration operator for the higher-order surface-related multiples involves using the data as an areal source. I demonstrate the improvement in illumination and noise suppression with results from a 2D synthetic dataset.

Chapter 5 *3D Gulf of Mexico data example*: In this chapter, I apply the method developed in Chapter 4 onto a 3D Gulf of Mexico ocean bottom node dataset to image with the mirror and double-mirror reflection energy. I will incorporate some of the technqiues discussed in Chapter 3 to improve the robustness of the joint LSRTM method. The result from the 3D Gulf of Mexico example shows that there are crosstalk reduction and illumination improvement in the image. In particular, I will highlight improvements in areas near and underneath a complex salt structure.

Chapter 6 *Conclusions*: In this chapter, I first summarize the most important results in this dissertation. I then discuss some possible directions for future research.