Chapter

1

Introduction

The word *migration* as it applies to seismic imaging is definitely a misnomer. It is believed to have arisen because oil migrates up dip since it is less dense than water. This knowledge proved to be exploration dynamite. Once understood, explorationists exploited it by looking for anticlines rather than synclines—and the California fields around the Brea tar pits became history. Analogously, dipping events on unmigrated seismic sections move up-dip on the final imaged or migrated section, so using the term migration in place of the more accurate imaging terms was quite natural.

It is also quite natural to think of seismic migration as being somewhat akin to photographic imagery. An image is captured, either digitally or on film, by recording the result of passing a *reflected* source of light (the sun or artificial light) through a properly focused lens on a photographic plate, film, or charge coupled device (CCD). This works because light travels in a straight line at a known constant speed and the lens, when focused, refracts the light to collect it in the proper place on the plate or CCD. We can think of this process in three steps. First, the light wavefield travels out from the source in all directions until it strikes a non-transparent reflector. Second, the reflected wavefield passes through the lens to form the image. Third, the camera's shutter captures an instant in time to record the final image. It is safe to say that radar imagery operates in much the same way and the only real difference lies in the construction of the "lens."

However, seismic migration differs from the photographic process in many ways. Sound replaces light (or radar or electro-magnetic sources) as the imaging source, and the speed of sound in subsurface rocks is definitely not constant, and it cannot be assumed to travel in a straight line. Moreover, as we will see later, each and every sound source, regardless of type, may generate three different, but coupled, wavefields as the energy spreads. As far as the author knows, there is no simple seismic analogy to the photographic lens.

Perhaps a better way to say this is that the lens for each seismic imaging effort is essentially unique to that effort. In a sense, this observation is the most crucial difference between imaging with sound and imaging with light. In the former case, we must somehow estimate the lens during the seismic imaging process. This lens is called the Earth model. In its simplest form, an Earth model is a three-dimensional velocity field that describes the subsurface speed of a compressional sound wavefield. In simple terms, a compressional wave is one wherein the particle motion occurs along the direction of propagation and represents a compression followed by a rarefraction of the particles. In its most complex form, an Earth model also includes the sound speeds of two additional waves called *shear* waves because the particle motion is perpendicular to the direction of propagation. An Earth model may also include other rock properties that influence the way in which sound propagates through the earth, but those will be of little interest here.

Seismic imaging can be considered to be a data-processing technique that creates an image of the earth's structure from the data recorded by a seismic reflection survey.

Target audience

This book and the complementary course are intended for an audience that requires a less mathematical understanding of migration and modeling than what might be required of advanced graduate students and researchers in the field. In the author's mind, this includes geophysicists and geologists who desire a fundamental principles understanding of these topics as well as a practical perspective as to where and how they may be applied for exploration advantage. We hope that, in spite of this objective, you come away with a much broader understanding of both modeling and migration as well as their application in the development and estimation of the Earth model.

Overview

Because modeling, as highlighted in this book, is so central to our ability to image, we emphasize our reasons why we believe it should become a key component to any and all exploration projects. For this, we rely on early (1936) modeling work by F. Rieber, as well as recent work by Carl Regone, J.T. Etgen, and others from British Petroleum, and the 2005 SEG Summer Research Workshop in Salt Lake City, Utah.

Three types of Earth models characterize the propagation of sound waves in the Earth. Such models range from an overly simple *acoustic* model, which only supports compressional waves, to anisotropic models that also support two coupled shear waves. Acoustic models are sometimes also referred to as isotropic models, but we will reserve that designation for isotropic elastic models. An isotropic elastic model supports both compressional and shear waves, but the velocity of these waves is independent of the propagation angle. When the propagation velocity varies as a function of angle, the Earth model is said to be *anisotropic*. Anisotropic Earth models support one compressional and two shear waves. Thus, anisotropic Earth models contain three velocity models: one for the compressional wave, and one for each of the shear waves. Although we can think of anisotropic models in terms of three velocity fields, you should be aware that connections between the three propagation fields can be extremely complex.

The book will briefly consider sources other than sound, but since they focus on seismic migration, we ultimately are only interested in acoustic sources.

Defining the sound source and explaining its utilization to measure a synthetic seismic experiment may be the most important component of this book. We use Newton's second law in conjunction with Hooke's law to produce simple propagation equations that allow us to explain a significant percentage of the rather large number of migration algorithms that exist today.

At its best, the current ad-hoc approach for developing an acceptable seismic Earth model for imaging purposes rarely provides the necessary reflectivity required by modeling. What appears to be lacking is an understanding of how the seismic image relates to this reflectivity, so we emphasize how the needed reflectivity might be obtained.

The mathematics underlying modeling also underlies migration and, consequently, has a major impact on the acquisition geometry. The kind of data we should acquire versus the kind of data we have historically acquired is discussed in terms of optimizing migration quality.

In the belief that understanding migration is facilitated by first focusing on the simplest forms of migration, we briefly review rather quaint stacking and dip correction approaches for the production of so-called zero offset sections. We then use poststack imaging methods as they apply to stacked data sets to compare several algorithms from what we define as the migration hierarchy, and finally we move on to more modern prestack methods. These methods are applied to a wide variety of real and synthetic data in a visual, subjective attempt to evaluate the migration hierarchy's ability to produce high quality images.

Because of its clear importance, modern velocity analysis is explored in some detail. We review three different approaches producing the kinds of migration output that facilitate velocity analysis and estimation of Earth models. We provide a short review of tomographic updating. Finally, we demonstrate the conditions under which full waveform inversion might be expected to produce high quality results.

The book ends with a series of case studies designed to demonstrate the relative accuracy of the various algorithms comprising what we call the migration hierarchy.

Inversion

Estimating the appropriate lens for seismic migration is an exercise in *inversion*. This is a mathematical process by which data are used to generate a model that is consistent with the data. The most desirable outcome of a seismic inversion process would be an Earth model with sufficient detail to describe all information necessary to optimize the exploration workflow. The most comprehensive mathematical formulation of inversion provides a complete platform for estimating this information. The inversion technique iteratively combines modeling with migration to directly estimate the Earth model. At each step of what may be many iterations, the difference (the residual) between the modeled data and the recorded data is migrated to estimate a new model. When the migrated residual is zero, synthetic data generated using the estimated Earth model perfectly matches the recorded data and consequently the model is considered optimal.

One of the earliest practical tests of this so-called full-waveform inversion was an abysmal failure. Nevertheless, today, the good news is that, in a perfect setting, this process really does work. The bad news is that currently available seismic data do not entirely satisfy the mathematical requirements necessary for success.

Until recently, the modeling piece of this inversion process was by itself considered far too computationally intensive to be practical. It may also be true that the actual concept of synthesizing data over some perceived geologic model was considered to be of little practical use. However, computer power is rapidly approaching the point where modeling may not only be practical, but may even be of use in providing empirical answers to questions that are difficult to answer in any other way. While it may not be computationally possible to perform the iterative inversion described in the previous paragraph, computer power is quickly reaching the point where we may be able to consider doing the inversion for carefully selected projects.

Velocity Analysis

When concise mathematical recipes for optimal estimation of the Earth model are not practical, other more practical methods must be devised and exploited. In the last twenty-five years, a wide variety of somewhat ad-hoc velocity estimation methods have emerged and are currently used to provide reasonable estimates of the seismic lens. The importance of migration as a tool in this approach cannot be overestimated. But traditional, normal-moveout based methods applied after migration, together with tomographic techniques, have proven to be quite useful when the more optimum and concise methods fail.

How well these human-intensive techniques work are somewhat dependent on how the input data is processed. Thus, the person actually attempting to estimate the Earth model must recognize that some so-called “best practices” approaches are not amenable to the production of high quality results.

Modeling

A superficial glance at the inversion process seems to imply that we need two pieces of machinery to make it work; that is, we need to understand how to synthesize the kind of data we record (modeling), and we need to understand how to migrate it. What is really true, however, is that the only thing we really need to understand completely is how to perform the modeling, since migration is actually just two independent modeling exercises. To fully appreciate how modeling appears in the imaging process requires considerable mathematical theory and physical principles. However, there are just two fundamental principles on which modeling is based. The first, Newton's second law, is easily understood from a purely physical point of view. You experience it every time you accelerate in a car. The second, Hooke's law, is somewhat more difficult to understand, but is still quite easy to explain in simple one-dimensional terms. The combination of these two principles effectively provides us with a simple propagation methodology that is easily explained graphically and that provides the basis for making modeling and migration accessible with minimal mathematical symbolism.

Given that modeling is fundamental to seismic imaging, we obviously must put considerable emphasis on understanding how it works and the many variations of how it is implemented. In addition, it is of considerable interest to understand the types and style of Earth models that we may wish to investigate.