Chapter 1

Introduction

1.1 Imaging beyond structures

The primary motivation for the work developed in this thesis is the need to improve the estimation of local perturbations in the elastic parameters of subsurface rocks from surface seismic data. These perturbations in the elastic properties can be related to lithological factors, like fluid saturation (Domenico, 1976, Ostrander, 1984), relative shale content (Han et al., 1986; Hornby and Murphy, 1987), and porosity (Cheng and Toksöz, 1979; Domenico, 1984). Any improvement in the estimation of these physical properties can have a considerable impact in areas that include litho-stratigraphic interpretation, direct hydrocarbon detection, and reservoir characterization. This thesis focuses on the development of tools to improve the elastic inversion of marine seismic data; nevertheless many of these tools can also be applied to land data.

There are many ways to estimate model parameters from data. Although the term inversion can be generally applied to all the different formulations of the estimation process, some formulations are often included in the group of data processing methods rather than data inversion methods. Processing can also be considered as the first step towards inversion (Claerbout, 1992a), and many times the success of the latter depends on the correctness of the former. I begin by discussing the different approaches to the elastic inversion of surface seismic data in order to show how the processes developed in this work relate to those approaches and what improvements are obtained with their application.

1.1.1 Different approaches to seismic inversion

In a series of three papers, Backus and Gilbert (1967, 1968, and 1970) gave a theoretical formulation for the geophysical inverse problem and discussed its intrinsic limitations, such as non-uniqueness and restricted resolving power. Since then, both linear and nonlinear inversion methods have been extensively applied to reflection seismic data (under the acoustic or elastic assumption) to reconstruct the density and acoustic/elastic velocity models. Early work concentrated in the inversion of the acoustic wave equation. Cohen and Bleistein (1977, 1979) used a closed form of the inverse parabolic wave equation to derive an inversion algorithm for compressional velocity. A similar approach was used by Clayton (1981) to retrieve the high-frequency changes in both the density and the bulk modulus; Tarantola (1984) described a method conceptually similar to prestack migration, also using the density and bulk modulus as the model parameters. Extensions to the elastic assumption were introduced by Tarantola (1986), Mora (1987), and Snieder et al (1988) among others.

All these approaches involved direct inversion of the data using the wave equation as the forward operator. By the time an elastic formulation for the wave-equation-based inversion problem started to be developed, an alternative approach for the estimation of elastic properties from surface seismic data had also been introduced. With this alternative approach the data were first preprocessed to obtain the relevant information loosely referred to as *amplitude versus offset* (AVO), and then an inversion scheme using the Zoeppritz-Knot's equations as the forward operator was applied to these reduced data.

A problem with this early formulation of the AVO method is that instead of using a wave-equation-based method to obtain this data reduction, it was usual to apply a sequence of processes, each of them related to the correction or removal of a particular effect. Several authors have pointed out the required processes: O'Doherty and Anstey (1971), Sheriff (1975), Ostrander (1984), and Yu (1985). Some of these processes are the same as those applied in standard processing of reflection seismic data: removal of all events except primary PP reflections (e.g., multiples, converted waves, and refractions), deconvolution of the source-receiver-instrument signature, correction of geometrical-kinematical effects (either by prestack migration or spherical-divergence and NMO corrections), compensation of transmission and absorption losses, and array response.

The linearized inversion method described by Demirbag and Coruh (1989) applies these steps, keeping the data in the vertical-time-offset domain. The elastic parameters of the upper layer are considered to be known and the inversion is done in a layer-by-layer scheme from the shallowest to the deepest, which results in the accumulation of errors with depth. To obtain the angle-dependent reflectivity at each iteration they use ray-tracing through the upper layers. Other approaches, however, replace the angle dependence in the equations with the horizontal slowness p, and obtain the reflectivity matrix (in terms of p) from the data. Kolb et al. (1989) used slant-stack transforms, followed by a moveout correction to obtain the reflectivity matrix, but their method was limited to cases in which it is valid to assume that the earth is horizontally layered within the range of a CMP gather. Despite this limitation, using slant-stack is advantageous because it represents a plane-wave decomposition of the data, which results in a retrieved reflectivity that is more consistent with the Zoeppritz equations (Claerbout, 1985).

The migration method described in chapter 4 reduces the recorded data to a form that can be directly described by Zoeppritz-Knot equations. The solutions of these equations correspond to the response of a plane-wave scattered at a plane interface separating two homogeneous-isotropic elastic media, as a function of the elastic parameters and density of both media, and the angle of incidence of the original wave.

1.1.2 Comparing direct inversion with data reduction before inversion

It is important to distinguish between *global inversion* methods usually referred to as *full waveform inversion*, and *focused inversion* methods, mostly known as *amplitude versus offset* (AVO) methods[1]. Global approaches use the direct inversion approach. The objective function represents a measure of the difference between the recorded data (in the original form), and the data predicted by a particular choice of model parameters[2]. To be

[1]Although the term AVO is appealing because of the direct intuitive link with the basic information used in the inversion (amplitude as a function of the source-receiver separation), it is also misleading because many other factors not related to the inversion parameters can be responsible for the AVO behavior. Even if all these factors are compensated for, the AVO function is not directly related to Zoeppritz-Knot's equations because it does not represent the plane-wave response of the medium.

[2]In fact, the difference between the model and the a priori model is also included in order to constrain the inversion, and both differences are usually weighted by the respective inverse covariance matrices.

able to describe all the features in the data, the model space must assume its most complex form for the particular formulation of the forward problem. In focused approaches the data is first reduced to a form that contains only relevant information, that is, information which depends only on the subset of the model space that we want to invert for. The objective function measures only the misfit between a particular attribute of the data and the attribute predicted by a particular choice of parameters in the associated subset of the model space.

It is important to note that the data reduction involved in the focused approach assumes that the complementary part of the model space necessary to perform the data reduction has already been estimated, also using an appropriate focused approach. On the other hand, global inversion approaches make no distinction between low- and high-wavenumber components of the model. As pointed out by Claerbout (1985), this distinction is important because of the band limitation of surface seismic data. While only low-wavenumber part of the velocity field can be reliably obtained (usually by velocity analysis and/or well-log information), the retrieval of the reflectivity (impedance contrasts) is restricted to the high-wavenumber components. The independence between the two parts of the impedance spectrum provides a theoretical justification for the separability of the estimation process of the two parts of the model (low and high wavelengths). One difficulty that arises from the simultaneous inversion of velocities and reflectivities is that, whereas the effect of reflectivity perturbations can be partly linearized, the effect of velocity perturbations is highly nonlinear (Hindlet and Kolb, 1988). Another disadvantage of the direct inversion approach is its high cost; the complete physical process must be simulated at each new iteration.

The wavefield-decomposition and modeling methods described, respectively, in chapters 2 and 3 can be applied to both inversion approaches, while the migration method defined in chapter 4 is specifically designed for the focused approach.

1.1.3 Limitations of the Zoeppritz inversion

In addition to the data-bandwidth limitations, the inversion of elastic parameters is also constrained by the physical limitations inherent to surface seismic data (Jannane et al., 1989). Furthermore, the small-period changes in the lithology observed in *in situ* measurements (sonic log, gamma ray log, etc.) are far beyond the typical resolution of surface seismic data. The implications of this long wavelength characteristic of the data, compared to the usual stratification period, were presented by Backus (1962); he showed that, in the long-wavelength limit, a stack of isotropic thin layers is dynamically equivalent to a homogeneous transversely isotropic medium. Consequently, a reflectivity matrix retrieved from surface seismic data might be better described by a transversely isotropic model than by the simple isotropic model. The group theory introduced by Schoenberg and Muir (1989) connects the finely stratified media with their long-wave equivalent homogeneous medium. To implement a reflectivity-based inversion with a transversely isotropic model it is necessary to use the corresponding reflection coefficient. Keith and Crampin (1977) derived the equivalent of Zoeppritz equations for a general anisotropic medium and Shoenberg and Protazio (1990) rationalized the solution for media with monoclinic (or higher) symmetry and with a mirror plane of symmetry parallel to the reflecting plane. However, the introduction of extra elastic parameters in the inversion process can only be feasible, after the development of more accurate and reliable methods for estimating the angle-dependent reflectivities.

1.2 An overview of the tools developed for this thesis

1.2.1 Multicomponent acquisition simulation for elastic migration and inversion of marine data

There are several approaches to performing elastic migration or inversion in fluid-solid layered media. In one approach, the media are divided into fluid and solid zones, and the wavefields in each zone are propagated independently, except for the explicit dependence through the stress-strain continuity relations at the boundary between zones, introduced as time dependent boundary conditions. A different approach makes no explicit distinction between liquid and solid media (except for their different stiffness components) and uses a single elastic equation to propagate the wavefield. A third approach (for the specific case of source-receivers located in a fluid layer) neglects mode-conversion and propagates only the scalar compressional field using a scalar equation. These three approaches were cited in decreasing order of accuracy, complexity, and cost in the implementation. The method described in chapter 4 uses the second approach which combines accuracy with feasibility of implementation.

The first step in migrating marine data by solving a single elastic equation is the transformation of the recorded scalar pressure field into a vector particle-displacement field. This transformation can be done in a very straightforward way if the recording geometry samples the wavefield in both the horizontal and the vertical directions. However, only recently have multiple cables located at different depths begun to be used in experimental off-shore surveys. Chapter 2 describes a method for transforming the recorded pressure data into an elastic vector field that is applicable in standard one-cable marine surveys. The transformation is performed in the ω-κ_x domain and requires only a few assumptions to validate its application. The assumptions are that the water surface is smooth, that the cable is nearly parallel to the water surface, and that the water surface is a perfect mirror for seismic waves. Results obtained in a realistic example, in which these assumptions are only partially fulfilled, demonstrate the robustness of the method.

1.2.2 Finite-difference wave-equation modeling in layered media

Since the introduction of the finite-difference method for solving the acoustic and elastic wave equations in layered media (Alterman and Karal, 1968; Boore, 1970; Ottaviani, 1971), many alternative forms of discretization have been incorporated in the method to improve numerical stability and accuracy, and decrease numerical dispersion and numerical anisotropy (Alford et al, 1974; Kelly et al, 1976; Virieux, 1984 and 1986; Kosloff et al, 1984). I show in chapter 3 that for a medium with sharp, discontinuous boundaries between layers, some dynamic-accuracy and numerical-dispersion problems still exist, even when high-order differential operators and a staggered grid scheme are used in the discretization process. The chapter also describes an alternative finite-difference scheme (the dual-operator method) that uses operators of different size when differentiating elastic constants (discontinuous functions), or wavefield components (continuous functions). Comparison with traditional finite-differences, a propagator-matrix scheme, and the analytical solution for a simple three-layer model illustrate the improvements obtained with the dual-operator method. The dual-operator method produces accurate and stable results for both solid and fluid layers. Figure 1.1 shows a small window of the vertical component of the wavefield simulated by the three schemes. While the results from the dual-operator and the propagator-matrix schemes have a very similar behavior, the result from the traditional finite-difference scheme has an abrupt phase transition which is not in agreement with the analytical solution.

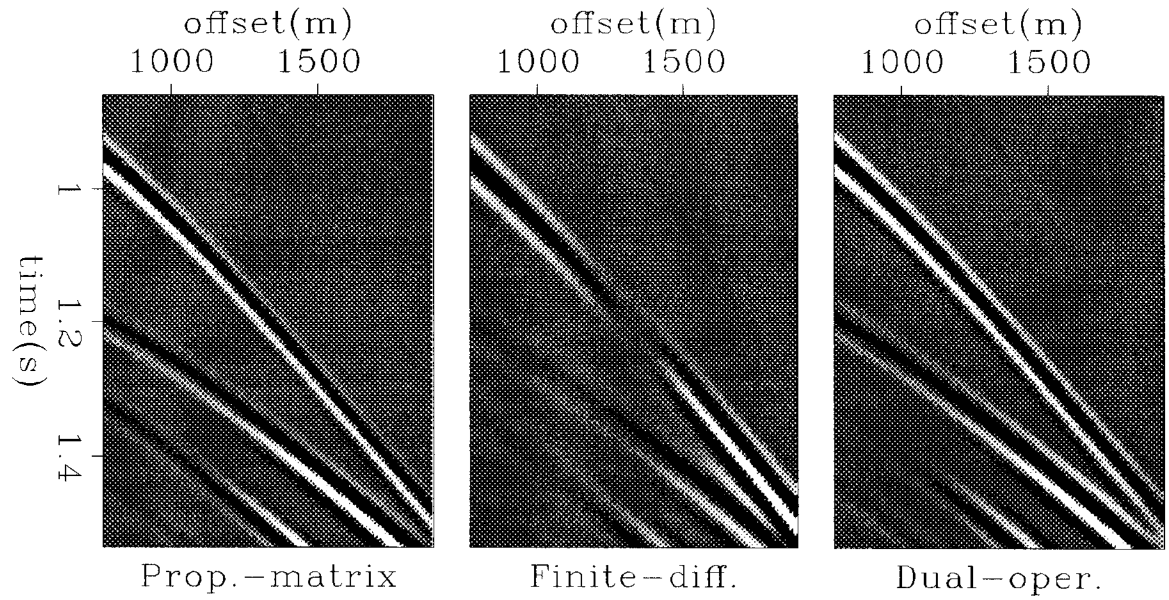

FIG. 1.1. Vertical components of the wavefields simulated by three different modeling schemes. **Left** Propagator-matrix. **Center** Traditional finite-differences. **Right** Dual-operator.

1.2.3 Amplitude recovery by elastic migration: approaches and limitations

Migration is usually defined as a process that transforms reflection seismic data recorded at the earth's surface into an image of the subsurface geologic structures. Although concise and comprehensive, this definition includes a large diversity of processes that generate different structural images, each of them associated with a distinct geological characteristic. Waves propagating through the overburden rocks are affected differently, and in a different degree, by each physical property of the rock, although only a few of these properties produce measurable changes in the wavefield recorded at the surface. Wavefield inversion methods try to obtain the images of a limited number of physical properties that, within the framework of a simplified physical system, better explain the data. Compared to inversion, migration is a midway process that tries to reduce the complex information present in the original data to a form that can be directly related to a limited set of physical attributes. In particular, amplitude-oriented, elastic migration methods attempt to reduce the data to a form that can be directly related to the Zoeppritz equations, that is, the in-depth, angle-dependent, plane-wave reflection coefficient images.

The first half of chapter 4 discusses some of the possible approaches and options that can be used to implement each of the stages of elastic reverse-time migration in the space-time domain. The extrapolation stage can be implemented under a one-experiment or two-experiment approach, with a smoothed or unsmoothed stiffness model, using a full wavefield or hybrid ray-wave extrapolation method, and operating in a scalar or vector wavefield. Two different aspects of the imaging condition are considered: the choice of the imaging attribute, and the implementation criteria for obtaining the image. The discussion focuses on the choice of in-depth (local) PP, SS, SP, and PS reflection coefficients and on three implementation criteria: the standard zero-lag cross-correlation criterion, the "V-stack" criterion, and the plane-wave-response criterion.

The positive and negative aspects of each approach and choice are considered in the light of event-reliability and accuracy in the amplitude-recovery process. Conventional migration schemes require that the velocity model be a smooth function of space to avoid the imaging of false events caused by the reflections of the extrapolated wavefields at the interfaces of the model. The drawback of model smoothing is that transmission/conversion losses are not corrected during the extrapolation. Using a nonreflecting wave-equation does not solve the problem, because amplitudes are still not correctly handled at the interfaces.

The second part of chapter 4 proposes an alternative one-experiment approach to reverse-time migration. Reverse-time migration like many other migration schemes, is traditionally defined as the "interaction" between two wave-extrapolation experiments, one describing the forward propagation of the source term and the other describing the backward propagation of the recorded wavefield. The first stage of the one-experiment approach simulates the time-dependent boundary conditions and the wavefield at the final time. The second stage replaces, at the positions where the receivers are located, the upper boundary condition by the recorded wavefield and backward propagates in time the single wavefield. This approach requires a different definition for the imaging condition.

1.2.4 Plane-wave decomposition of downward-extrapolated data

Although conceptually independent, the plane-wave-response imaging condition is defined in conjunction with the one-experiment approach because this approach cannot be used with conventional imaging conditions. The formulation of this imaging condition aims to estimate the in-depth (local) plane-wave response as a function of the angle of incidence relative to the normal to the local reflector-plane. The implementation includes the following stages: downward extrapolation of the recorded wavefield (performed by reverse-time propagation); separation of the downward extrapolated wavefield into P and S waves, which are then separated into upward and downward propagating waves; plane-wave decomposition of the four wavefields and integration over time to obtain four image-cubes. These cube-images correspond to the PP, SS, PS, and SP plane-wave reflection coefficients for each model position, as a function of the local angle of incidence. The method is referred to as the plane-wave-response (PWR) migration. Because of the limitations imposed by the memory-intensive implementation of the method and the present state of the available hardware resources, the angular discretization used in the examples was excessively sparse. Nevertheless, results obtained with the application of the PWR migration to synthetic data were in good agreement with the theoretical expectations.

1.2.5 Application of the PWR migration to field data

To illustrate the method, the PWR migration was applied to a standard off-shore dataset. Prior to the migration, a few preprocessing steps were necessary to precondition the data to the assumptions of the method. These assumptions are that the data share the same spectral bandwidth imposed by the specific choice of discretization parameters, that the experiment involves a line-source in a 2D-structured subsurface, and that a vector displacement field is recorded.

The spectral conditioning included two parts: application of a least-squares shaping filter to deconvolve the instrument signature into a short-period estimation of the source signature. The second step involved the predictive deconvolution of the data to suppress the long-period part of the source. The transformation of point-source data into line-source data can be done by a properly weighted integration along the offset direction (Wapenaar et al, 1990) of the data resorted into common midpoint gathers. For simplicity, this more elaborated procedure was replaced by a simple scaling of the data by a power of time. A theoretical justification for this approximation can be found in Mora (1987). Finally, the transformation of the pressure data into a vector wavefield was performed by the method described in chapter 2.

An important part of field data application involves building the stiffness-density model using information from the data, from nearby well-logs, and applying empirical relations between the physical parameters. All this information was integrated, under the assumption of a stratified model, to construct the background (macro) model.