Chapter 1

Introduction

The effect of velocity anisotropy on wave propagation in homogeneous and heterogeneous media has been the subject of numerous publications. Careful forward modeling has helped interpreters understand how velocity anisotropy manifests itself in field data. Fewer attempts have been made, however, to solve the inverse problem, namely, the estimation of the parameters that describe the complexity of velocity anisotropy. These parameters are the elastic constants. The estimation of elastic constants is important because it can aid lithologic discrimination and fracture orientation, reveal anisotropic properties of the medium not obvious in the data, and provide further imaging or full waveform inversion algorithms with background models that can be refined iteratively. This dissertation will focus on one solution to the inverse problem, namely, the estimation of elastic constants from seismic measurements.

1.1 Anisotropy or heterogeneity?

Rocks can be anisotropic for a variety of reasons. Some rocks, minerals for example, can be inherently anisotropic depending on how their molecules arrange themselves in an orderly way to form a crystalline structure. Other rocks can become anisotropic after a sufficiently large stress has altered the crystalline structure of their constituents. Sufficiently large stresses can also cause preferentially oriented cracks in isotropic rocks or in rocks with otherwise randomly oriented cracks to make them look anisotropic at seismic frequencies. Other types of rocks can be formed by arrangements of elongated grains or fine isotropic layers that make the rocks look anisotropic at seismic frequencies. A more detailed explanation of possible causes of rock anisotropy can be found in Crampin et al. (1984).

Backus (1962) showed that a region composed of thin isotropic layers is equivalent in the long wavelength limit to a homogeneous transversely isotropic medium. More recently, Schoenberg and Muir (1989) extended Backus's conclusion to arbitrary, anisotropic, thin layers. These results have two important implications. The first is that, for scales much smaller than the seismic wavelength, there is no way to distinguish intrinsically anisotropic materials from materials with preferentially oriented heterogeneities (e.g., fine layering), which means that, from seismic measurements alone, it is not possible to identify the causes of anisotropy. The second implication is that, for scales smaller than a fraction of the minimum wavelength in the data, there is no way to distinguish whether the medium is heterogeneous or homogeneous anisotropic. This fundamental equivalence between anisotropy and heterogeneity in the wave propagation problem has its counterpart in the inverse problem.

Both heterogeneity and anisotropy affect wave propagation. The goal of the inverse problem in heterogeneous anisotropic media is to transform this coupled effect in the data into a model that is simultaneously heterogeneous and anisotropic. At first glance, this problem may seem insoluble because of the fundamental equivalence between anisotropy and heterogeneity that I mentioned before. We should remember, however, that the equivalence in the forward problem occurs at scales that are small compared to the wavelength. At larger scales, the effects of heterogeneity and anisotropy are distinguishable, and therefore, as long as the scale of interest in the inverse problem is not too small, it should be possible to set up an inverse problem that separates such effects.

The problem of the equivalence between anisotropy and heterogeneity worsens when only a fraction of the information contained in the wavefield (e.g., first arrival traveltimes) is used for the inversion. In this case, anisotropy and heterogeneity may be equivalent every time they are described with the same number of parameters, or, even worse, with different combinations of parameters in anisotropy and heterogeneity that fit the data equally well. Figure 1.1 (taken from Babuska and Cara, 1991) illustrates this difficulty. In this example, two different models are used to fit the same pair of traveltimes: model (a) is heterogeneous isotropic and model (b) is homogeneous elliptically anisotropic. Since both sets of parameters can be used to explain the observations, there is a complete equivalence between anisotropy and heterogeneity in this case. Increasing the number (finite) of measurements and the angles of observation is one way to resolve the ambiguity by selecting the model that fits the particular data better. However, if the model is subdivided into smaller cells, it is always possible to find a scale where the equivalence occurs because only two rays cross the small-size cells. If the ambiguity remains after increasing the number of measurements, additional information is necessary to resolve it.

The additional information necessary to resolve the ambiguity comes from the prior information about the medium, which tells us what model to use. That information can be used in the example of Figure 1.1 to choose between models (a) or (b) and estimate only the corresponding pair of parameters. However, if the prior information is not correct, anisotropy in the real medium is transformed into heterogeneities that do not exist, or, conversely, heterogeneities in the real medium are explained by unreal anisotropic solutions. Therefore, the selection of the proper model is crucial.