Chapter 1

General Introduction

Summary

This thesis is about seismic wave propagation in 2-D and 3-D random media. Restricting to the weak wave field fluctuation regime, we obtain approximations of the scattering attenuation coefficient and the phase velocity dispersion of plane and spherical waves. Based on these wave field attributes, we construct the Green's function for primary wave fields. This novel wave field description can be understood as an extension of the generalized O'Doherty-Anstey theory, valid in 1-D heterogeneous media, to the case of 2-D and 3-D random heterogeneities.

We show how these results can be used in geophysical applications. The estimation of scattering attenuation in complex geological regions is an important issue for rock characterization. For the example of the German KTB borehole, we provide scattering attenuation estimates derived from the well-log statistics. The presented Green's functions can be also incorporated in standard seismic tools like true-amplitude migration and AVO techniques in order to compensate for the scattering losses due to small-scale heterogeneities of reflector overburdens. With help of synthetic data examples we demonstrate the performance of this correction method.

The thesis is organized as follows. In this chapter we review the basic problems which will be the subject of subsequent chapters. Chapter (2) gives an overview of the theory of waves in random media and presents the numerical experiments that allow to verify the analytical results. In chapter (3) we present the main results of this thesis. The O'Doherty-Anstey approach is extended to 2-D and 3-D random media in analogy to the 1-D case. Explicit results for the attenuation coefficient, the phase velocity dispersion and the Green's function for the primary wave field are presented. All results are numerically verified. Chapter (4) gives a brief discussion of characterizing not only the primary part of seismograms but also the early part of the coda. The aforementioned applications are presented in chapter (5). Finally, we conclude and discuss open problems in chapter (6). The appendices contain detailed derivations of used relations and explicit results.

1.1 Scattering of elastic waves in the Earth

In recent years, the effect of multi-scale heterogeneities in earth-models has been recognized as a vital aspect of the overall behavior of seismic waves. That scattering on multi-scale heterogeneities plays an important role in seismic wave propagation was recognized more than 30 years ago. Aki was one of the first seismologists who claimed that the coda, i.e., the long tail after the primary arrival is excited by multiple scattering (Aki, 1969, and Aki & Chouet, 1975). A comprehensive overview of scattering phenomena and their description in seismology is given in Wu and Aki (1988) and Sato and Fehler (1998). Also in exploration seismology, multiple scattering has been made responsible for the amplitude decrease with increasing travel-distance. The paper of O'Doherty and Anstey (1971) investigated the effect of stratigraphic filtering on reflection amplitudes.

Very much effort has been spent in the understanding of wave propagation in layered structures (Asch et al., 1990). Seismic waves propagating in randomly multi-layered media are subjected to stratigraphic filtering. The physical reason is the multiple scattering by 1-D inhomogeneities. In random statistically homogeneous media, explicit approximations for the transmissivities of obliquely incident P- and SV-plane waves have been found by applying the second-order Rytov approximation to the 1-D multiple scattering problem in the frequency domain. This description is known as the generalized O'Doherty-Anstey formalism (Shapiro et al., 1996a and Shapiro and Hubral, 1999).

However, the Earth, the lithosphere and hydrocarbon reservoirs may have a very complex structure including multi-scale 3-D heterogeneities. This becomes evident from geological surveys, vertical and horizontal well-log data, and seismic wave field analysis. Reported scales of heterogeneity range from several centimeters up to hundreds of kilometers (for a review we refer to chapter 2 in Sato and Fehler, 1998 and see also Figure 1.1). Laboratory measurements of rocks revealed that even on the microscopic scale there are heterogeneities due to varying grain sizes and fluid flow channels (Bourbié et al., 1987). Thus, any attempt to describe complex geological structures by deterministic models fails in the sense that the interaction between seismic wave fields and the heterogeneities is not correctly reproduced. In such cases the concept of random media is more suitable and more general. There are numerous studies that assume the earth as a realization of a random medium (see e.g., Frankel and Clayton, 1986, Holliger and Levander, 1992, and Wu et al., 1994). The random medium consists of a constant background of a certain medium parameter – the reference medium – and its corresponding fluctuations, that is a realization of a random process in space. The latter is statistically characterized by a spatial correlation function. Crustal heterogeneities are best explained using an exponential (or more generally von Kármán) correlation function which is rich in short-wavelength components (Sato and Fehler, 1998).

Amplitudes and phases of wave fields fluctuate in random media. Typically, one can observe a spatial decay of propagating modes that depend on the ratio of wavelength to the characteristic size of heterogeneity (for illustration see Figure 1.2). That is to say wave fields are characterized by scattering attenuation and dispersion; both are important parameters for rock characterization. A suitable description of the seismic wave field in random media enables the construction of the Green's function taking into account effects of randomly distributes small-scale heterogeneities. Small-scale heterogeneities refer to heterogeneities that are small compared with those of the macro-model.

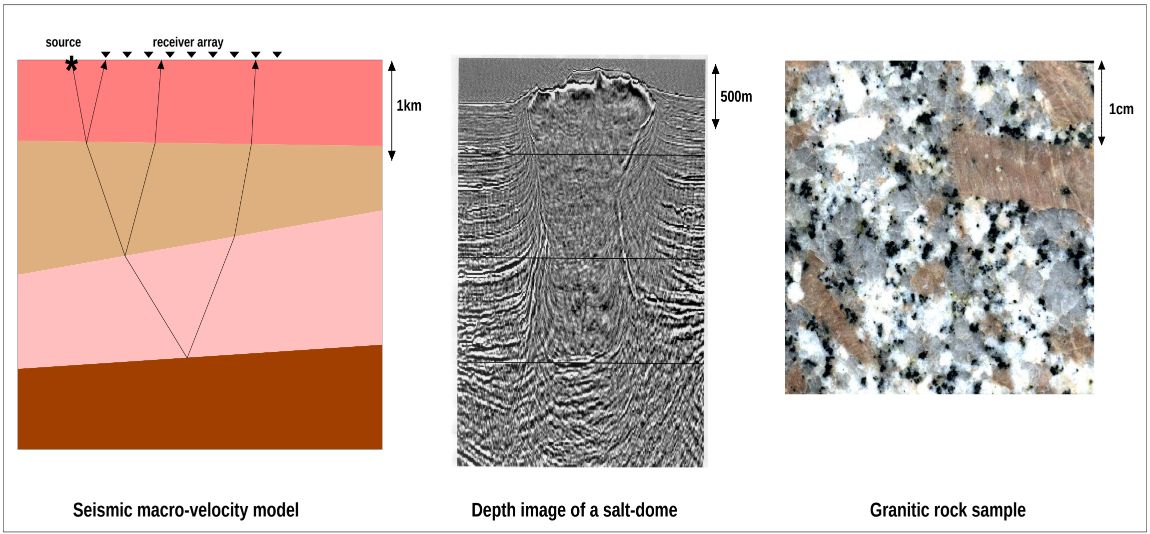

Figure 1.1: The seismic method and length scales of heterogeneities involved. The lefthand figure explains the principle of seismic reflection profiling. The scattering or reflection occurs on large-scale heterogeneities indicated by the four layers. The scale of heterogeneity is given by coarse lithologic units of the order of kilometers. The middle figure shows a prestack depth migrated section of a salt dome, revealing heterogeneous structures on a length scale of the wavelength ($\approx 60m$). Even the heterogeneous composition of rocks on the centimeter scale (righthand side) impacts the seismic wave field.

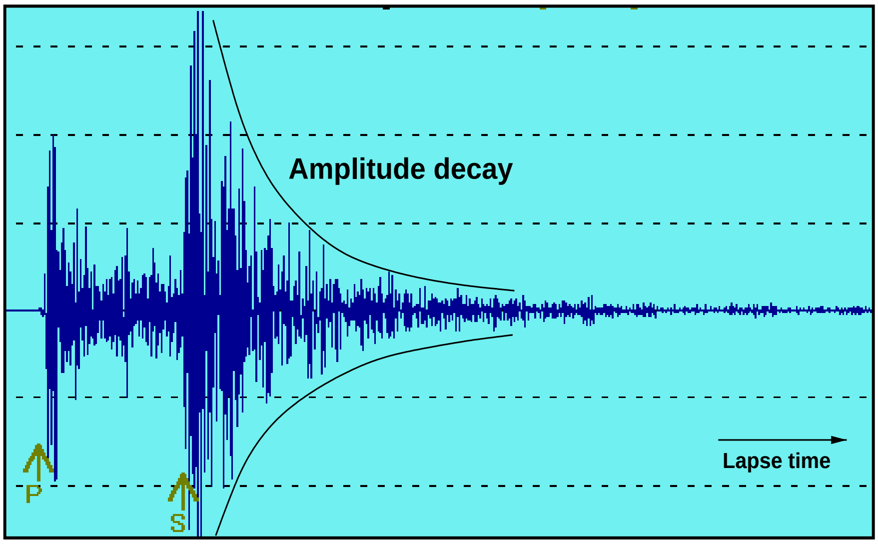

Figure 1.2: Seismogram from an earthquake in Northern Italy. The complex wave trains following the direct P- and S-waves arrivals (indicated by the arrows) are an evidence for scattering on randomly distributed heterogeneities located between the seismic source (earthquake hypocenter) and the receiver station. Typically, one can observe the amplitude decay with increasing lapse time. In the same way, the wave field amplitudes in the vicinity of the direct arrivals ('primaries') are also attenuated when the distance between source and receiver increases. These observations are related to the phenomenon of scattering attenuation.

This could be useful in order to apply – in combination with usual macro-models – any kind of imaging or inversion technique, a fundamental problem in exploration seismology. For example, taking into account the small-scale heterogeneities of reflector overburdens improves AVO-analysis; this was clearly demonstrated for 1-D heterogeneities by Widmaier et al. (1996).

Within the weak wave field fluctuation regime there exist several approaches to quantify scattering attenuation. They include the mean field theory based on the Born approximation yielding an estimator of the coherent wave field (Keller, 1964). That the mean field theory is not adequate to describe scattering attenuation of seismic waves is well-known (Wu, 1982). There is also the so-called traveltime-corrected mean field formalism which is successfully applied to interpret attenuation measurements in seismology (Sato and Fehler, 1998). The traveltime-corrected mean field formalism however is based on heuristic and not always justified assumptions. Stronger wave field fluctuations, visible through a longer and more complex coda, indicate that the process of multiple scattering becomes important. Then the radiative transfer theory and the diffusion approximation are adequate concepts to describe averaged wave field intensities (Ishimaru, 1978). In addition, numerous numerical studies characterized the scattering attenuation in heterogeneous structures (Frankel and Clayton, 1986, Frankel, 1989, Shapiro and Kneib, 1993, Roth and Korn, 1993, and Frenje and Juhlin, 2000).

1.2 Transient waves and self-averaging

In seismology and rock physics the measured seismograms (wave field registrations) usually consist of the so-called ballistic wave followed by the coda. The ballistic wave is the wave field in the vicinity of the first arrival and in geophysical literature known as the primary wave field. It can be understood as a superposition of a wave field part which is not scattered at all and of multiply forward scattered waves. In seismograms it can be identified as the early well-defined pulse. Performing an average over all possible realizations of disorder one obtains the so-called coherent wave (for a recent review on this terminology we refer to Tourin et al. (2000) and references therein). The coda is the long complex tail of the seismograms and contains multiple scattering contributions. Sato and Fehler (1998) provide an overview of several approaches to characterize the coda in earthquake seismograms.

Several pulse propagation theories for random media already appeared in the literature. Wenzel (1975) describes the propagation of coherent transients with perturbation theory. Beltzer (1985, 1989) and Beltzer et al. (1990) investigated the pulse propagation in random media based on the causality principle. A combination of the traveltime-corrected mean field theory and the causality principle can be found in Fang and Müller (1996). The above mentioned wave field approximations describe the wave field for an ensemble of medium's realizations. This is because ensemble averaged wave field attributes are used. However, in seismology only one realization of the heterogenous medium exists. Then an ensemble averaged wave field attribute does only represent the measured one provided that it is a self-averaged wave field attribute as pointed out by Gredeskul and Freilikher (1990). That is to say it becomes averaged while propagating inside the random medium.

A pulse propagation theory valid for single realizations of 2-D and 3-D random media is not available. In the case of 1-D random media such a wave field description is known as the generalized O'Doherty-Anstey (ODA) formalism of Shapiro and Hubral (1999). It is a suitable wave field description of the primary wave field, i.e., the wave field in the vicinity of the first arrival. There are also recent efforts to generalize the ODA theory for so-called locally layered media, i.e., media with layered microstructure but a 3-D heterogeneous macroscopic background (Solna and Papanicolaou, 2000). However, the wave field in the background is described with help of ray theory and is therefore restricted to small wavelengths compared with the heterogeneities.

1.3 Motivation of this work

The purpose of this thesis is to develop a theory that allows to quantify scattering attenuation and phase velocity dispersion of the primary wave field in a broad frequency range and to describe pulse propagation in single realizations of 2-D and 3-D random media. Such a theory can be understood as a generalization of the ODA theory towards 2-D and 3-D random media. It is based on ensemble-averaged, logarithmic wave field attributes directly related to the scattering attenuation and phase velocity dispersion. These attributes are derived in the Rytov- and Bourret approximation which are only valid in the weak wave field fluctuation regime. Müller and Shapiro (2001a) numerically showed the partial self-averaging of logarithmic wave field attributes and constructed the medium's Green function for an incident plane wave. The same strategy, however using logarithmic wave field attributes that additionally fulfill the Kramers-Kronig dispersion relations extend this theory towards a full frequency range wave field description. Moreover, considerations on wave propagation in elastic media and waves radiating from a point-source supplement this theory.

From a practical point of view, the benefit of the aforementioned wave field description is twofold: First, a quantitative description of scattering attenuation may help in the interpretation of seismic attenuation measurements. Constraints on the magnitude of intrinsic and scattering attenuation can be formulated. Second, the combination of seismic imaging techniques with this theory of pulse propagation provides a recipe for imaging in random geological structures. Removing the effects of small-scale heterogeneities allows to investigate the nature of large-scale seismic reflectors and to estimate their reflection coefficients.