Summary

Within this work two main aspects are focused. One is the numerical modelling of seismic wave propagation in geological structures where guided waves are significant. The other one aims at finding a flexible unified approach to the seismic inverse problem in different environments using the Born approximation. The two topics are related since the Born approximation requires solutions for reference models which are obtained by numerical modelling.

The thesis presents numerical modellings of seismic wave propagation in two very different regimes. In coal seams of a few meters thickness wave propagation is modelled at wavelengths of about one to two meters and signal frequencies up to 1000 Hz. In the mantle wedge of a subduction zone modelling is done at wavelengths of a few kilometers and frequencies up to 2 Hz. The former case is approached in cartesian coordinates using a 2-D/3-D finite difference method, the latter case is treated in spherical coordinates in 2D and 3D using a spectral and a pseudospectral method. Common to both cases is the relevance of guided waves which propagate in the low-velocity coal seam or in the low-velocity zone inside the mantle wedge.

The intention of the research on wave propagation in coal seams (Chapter 2) is to find approaches to a reconnaissance method ahead of the faces of an advancing coal mine roadway. Such systems are already in use for tunnelling in hard rock and are described in chapters 1.1 and 2.2. This research was done in cooperation with DMT GmbH & Co. KG (Essen) and was funded by the Deutsche Steinkohle AG (DSK) and by the European Commission. Unknown disturbances within the rock ahead of a tunnel can delay or even interrupt a tunnelling operation. In tunnel seismics, mainly scattering from disturbances within the rock ahead of the advancing tunnel front is of interest. Disturbances that are likely to be found in the coal seams of the Ruhr area can be, for example, a seam ending, seam splitting, faults, pinches or washouts (Chapter 2.4). Since the coal seam is a layer of low velocity and density compared to the surrounding rock, guided waves are excited by seismic sources that are located within or close to the seam. Complicated layering or complex geological structures can essentially affect the propagation of seismic waves and make the analysis of measured data difficult or even incorrect. Thus, a detailed study on wave propagation in models with different disturbances can give an overview about wave propagation effects and is a prerequisite for the interpretation of measured data. It was shown, that amplitudes of reflected seam waves strongly depend on parameters like the fault throw or the degree of thinning or washout (Chapter 2.5). At specific disturbances conversion to higher modes can occur. Furthermore, modellings reveal, that higher frequency phases above the fundamental mode Airy phase are preferably reflected whilst lower frequency phases are preferably transmitted. These results give an indication, which
frequencies are required for the seismic source excitation. It was further obvious, that special kinds of disturbances like a seam splitting can hardly be detected by using reflected seam waves. Special attention was payed to the interaction of seam waves and tunnel waves propagating along the surface of the tunnel. Both wave types can be distinguished by their polarisation attributes (Chapter 2.5.3).

As a further aspect, wave propagation in the Aegean region is investigated (Chapter 3). The work is part of the Collaborative Research Centre 526 ‘Rheology of the Earth - From the Upper Crust to the Subduction Zone’ funded by the German Research Foundation (DFG). Motivation for this investigation comes from the hypothesis of a deep, low-viscosity subduction channel existing on top of the plate contact of the Hellenic Subduction Zone. Metamorphic rocks are expected to be exhumed by forced return flow within such a subduction channel. The existence of a subduction channel was proposed during the past years due to different indications. This is described in detail in chapters 1.2 and 3.2.5. Analysis of seismograms in this region is supposed to give further evidence for the validity of this concept. In this context, the wave propagation along the plate contact is calculated for models of the Hellenic Subduction Zone. The main focus lies on the propagation of waves from intermediate depth events in the vicinity of the low-velocity subducted crust or within the tail of the expected subduction channel. Thus, wave propagation is again dominated by guided waves propagating along the plate contact of the Hellenic Subduction Zone. A separation of the guided wave trains at surface receivers was shown, that is caused by the abruptly changing dip of the slab. This separation is inhibited for models with a subduction channel since radiation of guided waves at the slab bend is enhanced. It was further shown, that the propagation of guided waves depends on the location of the source with respect to the subduction channel or subducted low-velocity crust.

The basic intention of all measurements and investigations done in coal seams as well as in subduction zones is to find, locate and characterise structures, that deviate from the well-known and expected geological structure. In coal seams these deviations represent hazards for the mining process, while in subduction zones they may give hints on how material is exhumed, how water is channeled through the mantle wedge and how volcanoes are fed. Finding these anomalies means solving a geophysical inverse problem that uses waves scattered from anomalies to determine their properties. The Born approximation provides a very general approach to this intent. It allows to easily calculate the wave field scattered from anomalies in simple or complicated background media. The Born approximation method gives a linear relation between the perturbations of the model and the perturbations of the wave field. This approach gives an approximation of the scattered wave field, since it is assumed, that primary waves are unchanged during their propagation through the inhomogeneous region. It is only valid for small or weak scatterers. The advantage of the method is, that the integrand calculated for the Born scattering is identical to the sensitivity of the displacement field to changes of density and elastic constants and thus can be directly used for the inverse problem. Thus, the thesis allows a unified and flexible approach to seismic waveform inversion that can be applied to various background media in 2D and 3D cartesian or spherical domains.

Using the Born approximation, an algorithm for the modelling of scattered seismic wave fields is developed for cartesian as well as for spherical applications (Chapter 4). Modelling results of the
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formerly described investigations can be used to verify the new algorithm. Two different applications of the Born scattering approach are presented, one is the scattering of guided seam waves in a small-scale cartesian model (Chapter 4.4) and the other one is the scattering of seismic waves at heterogeneities in the earth’s mantle in a regional spherical model (Chapter 4.5). The results obtained with the Born scattering algorithm show good agreements with finite difference computations for cartesian models as well as with results obtained with a spectral method for spherical models especially for high amplitude scattered waves. It was shown, that a grid spacing of minimum 1/8 of the dominating wavelength of the signal is needed to obtain sound results. Low amplitude scattered waves agree in travel time but can disagree in waveform. This might be caused by inaccuracies of the Born approximation for strong perturbations of material properties or large scattering structures. However, scattered waves calculated with other numerical methods can also be erroneous especially for low amplitude signals, for example due to artifacts produced by reflections at the model boundaries or too large grid spacings. Finally, the code was parallelised and is running on multiple processors (Chapter 4.6). The parallel implementation of the code significantly reduces computation times and allows to compute scattered wave fields within a short time span even for large numbers of grid points.

Within the presented work requirements are connected to the described two main aspects of investigations. At first, models and model series needed to be designed and created for the numerical modelling of seismic wave propagation (Chapter 2 and Chapter 3). For the modelings, existing programs (2-D/3-D finite difference method and Chebyshev pseudospectral method) were used and modelings were instructed during the supervision of a master’s thesis (Chapter 3). Analysis, interpretation and illustration of modelling results were further requirements. Within this context, occurring waves were identified and their properties were described. The wave propagation characteristics of the different wave types, especially of the guided waves within the coal seam (Chapter 2) and within the subducted low-velocity crust and the subduction channel (Chapter 3), were investigated. Further requirements were to classify the results and the comparison to former studies. In addition, results needed to be evaluated with regard to their applicability for a reconnaissance method ahead of the faces of an advancing coal mine roadway (Chapter 2) and with regard to the detectability of a subduction channel (Chapter 3). As described in Chapter 4 an algorithm for the modelling of scattered seismic waves with the Born approximation was developed in Matlab using the program GEMINI that calculates the direct wave field. The developed algorithm was tested and verified by staggered variation of modelling parameters and comparison to results obtained with other modelling methods. A further requirement was the optimisation of the algorithm by a parallel implementation of the code.