Chapter 1

Introduction

1.1 Global Tomography

Knowledge of the Earth's interior is essential for the understanding of processes observed at the surface such as volcanism, seismicity, plate movements, vertical movements or variations of the geomagnetic field. But as direct probing of the deep interior remains impossible, indirect observations have to be used to gain information on the Earth's mantle and core. Mantle rocks, which were brought up to the surface give indications on the composition, temperature and pressure distribution of localized regions in the mantle. On a long wavelength scale, gravity measurements can provide information on the density distribution of mantle material and geomagnetic observations of the past and present field give insight into dynamic processes in the outer core. With magnetotelluric measurements, a long wavelength 3-D image of electric conductivity related to varying rock properties in the upper mantle can be determined. Finally, seismic tomography presents a powerful tool to image the present state of seismic velocity heterogeneities within the Earth's crust, mantle and core on a variety of scales as seismic wave propagation is influenced by the material along the waves' paths through the Earth.

Focussing now solely on seismology, velocity information can be obtained from various types of seismological data: P- and S-wave arrival times of phases traveling through the Earth's crust, mantle and core have been used by many authors to derive global compressional and shear velocity models (e.g. Zhou, 1996; Grand *et al.*, 1997; van der Hilst *et al.*, 1997; Obayashi and Fukao, 1997; Bijwaard *et al.*, 1998; Kennett *et al.*, 1998; Vasco and Johnson, 1998; Bijwaard and Spakman, 2000; Boschi and Dziewonski, 2000; Kárason and van der Hilst, 2001; Zhao, 2001; Grand, 2002; Kennett and Gorbatov, 2004; Lei and Zhao, 2006). Furthermore, a new class of travel time tomography models is evolving which takes into account the finite frequency of body waves by incorporating Fresnel kernels (Montelli *et al.*, 2004a, 2004b) as theory states that the infinite frequency approximation of ray theory can cause imaged velocity anomalies to be reduced in amplitude and laterally blurred in their extent (Dahlen, 2004). However, as this method requires knowledge of the frequency content of the picked phases and as travel time data sets of long period body waves are up to now comparatively small, resolution is lower (≈ 200 km / $1.8°$, Montelli *et al.*, 2004b) than can be reached with regular travel time tomography. Travel time tomography based on ray theory leads to highly detailed images of velocity structures in the Earth with a maximum lateral resolution of approximately $0.6°$ for global P models and $1.8°$ for global S models. Local tomography dealing with very small study volumes is able to produce even better resolved models but only for limited regions. However, the main shortcoming of travel time tomography is that ray coverage is particularly low where earthquakes and stations are sparse as in the upper mantle beneath oceans or cratons and therefore cannot provide good models of these areas.

In contrast, inversion of surface wave group and phase velocity measurements results in velocity models of the upper mantle (e.g., Shapiro and Ritzwoller, 2002; Boschi *et al.*, 2004) with a sufficient ray coverage also in other regions where only few earthquakes are observed or a sparse network exists. But the model resolution is only at best on the order of $3.0°$ which is too low for imaging, for example, the narrow outlines of subducted slabs.

Normal mode splitting functions contain structural information on very long wavelength features up to spherical harmonic degree 8 (lateral sensitivity comparable to $\approx 23° \times 23°$ cells) but unlike surface waves and most body wave phase types their informational content covers the entire Earth's interior. Global models with this type of data were amongst other authors produced by Resovsky and Ritzwoller (1999), Ishii and Tromp (2001) and Beghein *et al.* (2002).

Other researchers invert waveforms of body and surface waves (e.g., Li and Romanowicz, 1996; Mégnin and Romanowicz, 2000) to derive global shear velocity models up to degree 24 (comparable to $\approx 8° \times 8°$ cells).

To overcome the problem that different types of seismological data image only certain parts of the Earth many authors employ mixed data sets consisting of surface wave dispersion, normal mode splitting functions, long period waveforms and absolute as well as differential travel time data (Su *et al.*, 1994; Masters *et al.*, 1996; Ekström and Dziewonski, 1998; Liu and Dziewonski, 1998; Ritsema *et al.*, 1999; Masters *et al.*, 2000; Gu *et al.*, 2001). However, due to the amount and type of data, mainly long wavelength models are obtained with these data sets.

In this thesis, advantage is taken of the various types of seismological observations in a different approach: To obtain a model that shows the high-resolution features of travel time tomography, the data set is improved by adding new, accurate arrival times. Furthermore, the gaps in ray coverage are implicitly filled by applying reference velocity models based on different seismological data sets not used for inversion here.

Among problems that all types of tomographic inversions inherently have in common are a) that the reference model has to be close to the real Earth due to linearization of the mathematical problem and b) that model amplitudes are reduced due to regularization during inversion which is required because of the ill-posedness of the problem. The effect of the nonlinearity of the tomography equations has been addressed in global travel time tomography, for example, by Bijwaard and Spakman (2000) and Widiyantoro *et al.* (2000). These authors account for ray bending due to 3-D heterogeneities by alternating tomographic inversion steps with 3-D ray tracing to improve the prediction of travel times and 3-D raypaths. The decrease of model amplitudes due to regularization of the inversion can partly be remedied by avoiding

overparameterization of the model. Therefore earlier studies have either used mixed data sets as described in the previous paragraph resulting in sufficient sampling in all regions of interest or by using an irregular grid parameterization dependent on data sampling or model characteristics (e.g., Abers and Roecker, 1991; Bijwaard *et al.*, 1998; Kárason and van der Hilst, 2000; Sambridge and Faletič, 2003).
The aim of this thesis is to establish improved models of 3-D velocity structures within the crust and mantle by employing a more extensive data set and by using 3-D starting models based on complementary seismic data. Overall, improved tomography models of the Earth's crust and mantle may provide further insight into the tectonic/geodynamic evolution of the Earth and a better understanding of the geodynamic processes within it. Besides that, an improved velocity model allows for a better travel time prediction and therefore more accurate event locations, which is also a step towards creating a seismological reference model of the Earth.

1.2 Data Set

Travel time tomography models can be improved on a regional scale by incorporating accurate arrival times of body waves which have not been used before to fill, in particular, gaps in ray coverage in the upper mantle. Sources of such data sets are archives of data centers (e.g. ORFEUS[1], ANSS[2]) which store the waveforms but do not process them further, bulletins which contain arrival times that were not reported to the ISC[3] (e.g. Euro-Mediterranean bulletin, Godey *et al.*, 2006) or temporary experiments with spatially dense station arrays which mainly use either relative teleseismic travel time residuals or local absolute travel times (e.g. EIFEL (Ritter *et al.*, 2000), MIDSEA (van der Lee *et al.*, 2001), SVEKALAPKO (Bock and the SVEKALAPKO Seismic Tomography Working Group, 2001), TOR (Gregersen *et al.*, 2002)). As part of this thesis, such high-accuracy data sets were picked with a semi-automated picking software (Sandoval *et al.*, 2004a) and obtained from other groups for stations in Europe and North America and afterwards combined with the latest travel time data set of Engdahl et al. (1998) for subsequent usage in global travel time tomography. Additionally, to better constrain the lower mantle, core phases were employed as they were not used in previous studies which applied the same tomography algorithm. Core phases have also been used by other authors to investigate the lower mantle and core with global travel time tomography (e.g. Obayashi and Fukao, 1997; Vasco and Johnson, 1998; Boschi and Dziewonski, 2000; Kárason and van der Hilst, 2001; Lei and Zhao, 2006).

1.3 Method

Tomography models can be improved by starting from a velocity model that gives a more realistic representation of the Earth's crust and mantle instead of the commonly used 1-D spherically symmetric reference models. Therefore, in this study a 3-D reference model from

[1]Observatories and Research Facilities for European Seismology
[2]Advanced National Seismic System, U.S. Geological Survey
[3]International Seismological Centre

surface wave tomography is used for the uppermost mantle which contains also a detailed crustal model and a long wavelength shear velocity model based on a mixed data set as described above is incorporated for the rest of the mantle. The new reference model deviates significantly from the 1-D model in which the earthquakes were originally located. Therefore, the earthquakes are relocated prior to the tomographic inversion in the 3-D reference model to obtain consistency between the new reference model, travel time predictions and earthquake locations and to thereby also avoid baseline shifts in the residuals. In contrast, in previous studies working with 3-D reference models (e.g. Bijwaard and Spakman, 2000; Widiyantoro *et al.*, 2000) this step was omitted assuming that changes in event parameters are small enough to be neglected which may not be justified
To take into account the nonlinearity of the tomography problem and the underestimation of model amplitudes due to ill-posedness, the tomography with 3-D reference models is taken even further here. A modified 3-D reference model is set up that utilizes 3-D velocity models based on independent long period data sets in regions of low ray coverage with short period P-waves and replaces them by a tomography model based solely on P travel times otherwise. Before replacement with this travel time tomography model, the model amplitudes are enhanced to counteract their underestimation due to regularization. Yet in order not to affect the model misfit only the null space part of the model is used. By using this combined 3-D reference model, the nonlinearity of the problem is better taken into account as ray paths and travel times are adjusted according to this new model which gives a better representation of the Earth's velocity field as "seen" by short period P waves than the previous 3-D reference model.

1.4 Thesis Outline

In Chapter 2, the basic theory of travel time tomography based on ray theory and our implementation is reviewed. Furthermore, the parameterization used as well as the applied damping procedures are described. Chapter 3 contains a regional study of the uppermost mantle beneath Europe. It represents an orientation on the main theme of this thesis demonstrating the effect of 3-D reference models on a small data set and regionally restricted model. In Chapter 4, the picking of the new arrival times for Europe is described and the resulting picks are presented with a quality estimate. Chapter 5 deals with the extension of the tomographic method for the use of different 3-D reference models and accounting for the difference in source parameters due to the change of reference model. Furthermore, these models are compared to a global tomography model using a 1-D reference model. Chapter 6 provides a description of new details that could be derived from the improved tomography model also including the Euro-Mediterranean bulletins (Godey *et al.*, 2006) as additional data and Chapter 7 gives an interpretation of the new model beneath western North America including the additional data from stations in that region. In Chapter 8, the improvement of travel time prediction and earthquake location with the new tomography model is shown and differences to the relocations of Engdahl *et al.* (1998) are discussed. Finally, in Chapter 9 the main results of this study are summarized.