7. Discussion

This thesis focused on the viscosity structure of Northern and Central Europe. It was investigated with different modelling techniques, on the one hand 1D investigations with the pseudo-spectral method, on the other hand 1D and 3D investigations with the FE method. The load applied was either an ice-load model (RSES from Kurt Lambeck) or a water-load model (Hohenwarte reservoir). The results of the modelling obtained with the ice load were compared to RSL data and GPS data from the BIFROST campaign [Johansson et al., 2002]. The investigation concerning the Hohenwarte reservoir has predicted tilt and strain data, which up to now have not been compared to observed data from seismometers and strainmeters in the nearby Moxa observatory.

7.1 Results of the forward modellings

Chapters 2 and 3 employed a forward modelling strategy, on the one hand with RSL data from Scandinavia, the Barents Sea, and NW Europe, which cover the last deglaciation interval (21,400 years BP to present), as well as radial crustal velocities from the BIFROST project, and on the other hand with recently compiled RSL data from the NW European coast including the regions Belgium, the Netherlands, NW Germany, and the southern North Sea, which cover a time period from 11,500 years BP to present. The first investigation was used to infer the radial viscosity variation of the Earth's mantle underneath Scandinavia and NW Europe, and to possibly detect a low-viscosity zone underneath those regions, which was proposed in the literature. The second investigation focused on the comparison of modelling results to the sea-level curves of the RSL data.

The analysis in chapters 2 was twofold, first using the pseudo-spectral method to calculate the optimum values for lithospheric thickness and bulk upper- and lower-mantle viscosities for different subregions of the RSL data, and then using the Neighbourhood Algorithm, a global inverse procedure developed by Sambridge [1999a,b], to search for a low-viscosity asthenosphere.

The results in the former case show that differences arise for the thickness of the lithosphere, with thicker values underneath Scandinavia ($H_l \sim 120$ km), and thinner values underneath the British Isles and the Barents Sea ($H_l \sim$60-70 km). This agrees with the thickening of the crust and the lithosphere from the North Atlantic Mid-Ocean Ridge towards the Baltic Shield. While the values for bulk upper-mantle viscosities are similar for all three regional subsets with $\eta_{UM} \sim 4 \times 10^{20}$ Pa s, the lower-mantle viscosity is poorly constrained ($\eta_{LM} > 10^{22}$ Pa s), which indicates an insensitivity of these RSL data to the lower mantle.

The results from the NA inversion only indicate a low-viscosity zone underneath the subregion of the Barents Sea. Here, in a depth interval of 120 - 200 km, this zone is characterised by viscosities around 10^{19}-10^{20} Pa s. Then the lower part of the upper mantle (transition zone) becomes more viscous, with viscosities up to 10^{22} Pa s. However, underneath the subregion of Scandinavia no evidence for a low-viscosity zone was found from the inversion of RSL data, while underneath NW Europe no clear indication for such a zone is possible, as too much earth models reproduce these RSL data. Interestingly, the NA inversion of the BIFROST uplift data favours a thin low-viscosity layer between 160 - 200 km depth, which confirms an earlier inference by Milne et al. [2004], but which is actually not resolved by the data. In agreement with the pseudo-spectral method, the NA results also reveal that the thickness of the rheological lithosphere increases from 60 - 70 km underneath NW Europe and the Barents Sea towards values exceeding 120 km underneath Scandinavia.

The results of chapter 3 show that a broad range of Earth parameters can predict the Belgian RSL data, the ranges then becoming narrower towards the southern North Sea region. In fact, the Belgian data appear to simply trace the eustatic sea-level rise, confirming the stable behaviour of the Belgian crust (London-Brabant massif) during and after the last ice age [Kiden et al., 2002]. Hence, the data are not very sensitive to changes in the Earth's interior structure, and they are too far away from former ice sheets (British Isles and Scandinavia) to allow a better determination of the Earth's structure beneath Belgium with this method. In contrast, a narrow range of Earth parameters define the southern North Sea region, reflecting the greater influence of the GIA. The difference between the behaviour of the Belgian and the southern North Sea data is based on the time and depth range of the data. The North Sea data are deeper (up to -50 m) and older (up to 11,500 years BP) samples than the Belgian data (up to -20 m and up to 9500 years BP). The models which show a best fit with the RSL data from the other regions predict an average lithospheric thickness of ca. 90 km along the NW-European coast, although thicknesses decrease to values around 80 km beneath the Netherlands and 70 km below NW Germany. The upper-mantle viscosities for all regions except Belgium are well constrained at ca. 7×10^{20} Pa s, and cover a range between $\eta_{UM} \in [6.5\times10^{20}, 10\times10^{20}]$ Pa s. The lower-mantle viscosities are, however, almost unconstrained, confirming the low resolving power for the lower-mantle viscosity of RSL data with a small spatial distribution. These results confirm earlier findings for RSL data of Lambeck et al. [1998a] and Steffen and Kaufmann [2005, chapter 2]. Furthermore, the modelling results confirm visual comparisons of sea-level curves, e. g. they reveal a non-linear, glacio- and/or hydro-isostatic subsidence component, which is negligible on the Belgian coastal plain but increases significantly to a value of ca. 7.5 m (since 8000 years BP) along the NW German coast. This subsidence is at least in part related to the post-glacial collapse of the so-called peripheral forebulge, which developed around the Fennoscandian ice-load centre during the last glacial maximum. Nevertheless, the analyses show that neither the western Netherlands sea-level curve of van de Plassche [1982], nor the German sea-level curve of Behre [2003] can be viewed as optimally reflecting absolute sea-level rise in NW Europe (at least not during the early and middle Holocene). The results of chapter 3 confirm former investigations of Kiden et al. [2002] from the Belgian-Netherlands coastal plain and provide new evidence from the German and southern North Sea sectors for the post-glacial collapse of the peripheral forebulge.

7.2 Results of the FE modellings

Chapters 4 to 6 used the FE technique either with an ice load (4 and 5) or with a water load (6) for investigations of the Earth's structure in Northern and Central Europe. The results of the ice load were compared with the crustal velocities from the BIFROST project, while for the results of the water load no comparison was made, as it was a test of the sensitivity of the reservoir load to the mantle. In chapter 4, a 3D viscosity structure, derived from seismic shear-wave tomography models, was employed in the Earth's mantle to compare 1D and 3D models and also to investigate how the thermodynamic properties of the mantle affect the viscosity variations. In chapter 5, a sensitivity analysis of the BIFROST GPS data to the upper mantle was performed with a model subdivided into blocks of variable size. As the subdivisions yielded a huge number of sensitivity kernels to interpret, a new approach was introduced to calculate the kernel of a block by averaging the perturbed predictions of all surface nodes of this block to one value for this block.

The results of chapter 4 indicate significant differences between 3D and 1D modelling. The observed BIFROST crustal velocity data are best fit using a 1D earth model, as for the different 3D earth models observations and predictions can differ by 2-7 mm/yr. The horizontal crustal velocities are affected even stronger. The typical divergent motions of the 1D earth models is no longer dominating for 3D viscosity models. Instead, a regional velocity field with movements away from the Norwegian coast towards the old Baltic Shield is observed. The presence of lateral viscosity variations in the upper mantle with a strong horizontal flow component significantly influences the horizontal velocities. Again, horizontal velocities from the 3D earth model prediction cannot explain the BIFROST data well, the prediction from the 1D earth model scores better. The results of a sensitivity analysis show that the dramatic change in the horizontal flow pattern has its origin deeper in the upper mantle, between 450 and 670 km depth. The uplift is mainly influenced by the viscosity structure beneath the lithosphere. In general, only minor dependencies of the lower-mantle viscosity structure to RSL and crustal motion data can be established, confirming the results of Mitrovica [1996] and Steffen and Kaufmann [2005].

In chapter 5, the results show that the present-day uplift velocity is mostly sensitive to viscosity variations in upper-mantle layers between 220 and 540 km depth, independent of the block size. Viscosity changes in the blocks within the former ice sheet produce larger effects than the blocks with mainly parts outside the former ice sheet. The largest effects are found for the blocks located below the former ice maximum on the surface. The effect of a viscosity change in the neighbouring blocks to one block on the uplift rate is negligible. There is a clear influence of the block size on the results. The uplift velocity is more sensitive to the viscosity changes in smaller blocks than in larger blocks. A comparison of the results of smaller and larger blocks also indicates higher sensitivities for the horizontal velocities of the larger blocks, and the sensitivity depends on the location of this block in relation to the former ice sheet. For all block sizes, we establish the directed movement of the kernels out of the perturbed block induced by the higher viscosity in that block. In general, lateral viscosity variations in the transition zone of the mantle have a strong influence on the tangential motion. The sensitivity for the blocks with most parts located outside the former ice sheet is small. Concerning the sensitivity of a selected block to the surrounding blocks, the influence is large in the first and the fourth upper-mantle layer, and is mainly influenced by viscosity changes in the blocks with an ice load on the surface. The strongest influence results from the blocks which are located in the direction of the discussed horizontal component.

In view of the BIFROST stations, former results can be confirmed: For the uplift velocity, the sensitivity generally increases for the central BIFROST locations, and the lowest sensitivity is found for the stations in the far north and south. The maximum is resolved for the second and third upper-mantle layer. In contrast to the former results of the blocks, the horizontal velocities are mostly sensitive to viscosity changes in the second and third upper-mantle layer. This is in agreement with the investigations of Milne et al. [2004]. Furthermore, the difference between the third and the fourth upper-mantle layer is larger. Another fact is that the horizontal velocities are more affected by (i) the location of a station on a block in relation to the location of the block in the model, (ii) the distance of the station to the block border and (iii) the ice-sheet geometry, which confirms the results of Wu [2006].

Finally, in chapter 6 the FE method is used with a water load instead of an ice load. Two main questions were addressed: (i) is the water load of the Hohenwarte reservoir sensitive enough to mantle viscosity, and (ii) can the induced deformation effects be measured at the nearby Geodynamic Observatory Moxa? The deformation effects were explored both on a short-term seasonal time scale and a long-term decadal time scale. The questions can be answered simply: ”no” for the first question, ”yes” for the second. The vertical deformation is more affected by load changes than the tilt and the strain. For the viscoelastic case, the viscoelastic part is small compared to the elastic part and only observable over a long time period, if an irrealistic viscoelastic structure of the underlying upper mantle is used. For short-time lake-level fluctuations, the viscoelastic influence is less than 3%. Concerning tilt and strain, the seasonal effect is mainly induced by elastic deformation. They result at the location of the reservoir in the μrad and μstrain ranges, respectively. As for the vertical deformation, long-term decadal variations are only significant, if an irrealistic viscoelastic upper-mantle structure is included in the analysed model. In a distance of 4 km to the reservoir, where the observatory is located, the influence of seasonal lake-level fluctuations on tilt and strain is larger than the resolution of the used instruments. Here, differences of at most 48 nrad for the tilts and 6 nstrain for the strains are established, which should be observable at the Geodynamic Observatory Moxa independent of the model structure.

7.3 General conclusions

As already discussed above, the results of chapter 6 cannot be used for conclusions concerning the lithospheric thickness and / or the upper mantle. Thus, the conclusions focus on results from chapters 2 to 5. The results demonstrate the complexity of the GIA process and the search for a heterogeneous earth model reproducing observed physical quantities such as crustal motions and RSL data.

7.3.1 Lithospheric thickness

The lithospheric thickness increases from 60 - 70 km underneath NW Europe towards ca. 90 km underneath the North Sea area and finally to values exceeding 120 km underneath Scandinavia. From the Barents Sea the lithosphere increases from 60 - 70 km to 120 km underneath Scandinavia. A splitting of Scandinavian RSL data into a peripheral and a central part results in lithospheric thicknesses increasing from 100 km in the peripheral region to 160 km in the centre. It additionally improves the correlation of the thickening of the crust and lithosphere from the North Atlantic Mid-Ocean Ridge towards the Baltic Shield both from North to South and West to East. The used 3D viscosity structures in the FE modelling based on the shear-wave velocity perturbations from the S20A tomographical model [Ekström and Dziewonski, 1998] support these results.

The Belgian crust (London-Brabant massif) was fairly stable during and after the last ice age and is not influenced by GIA. The southern North Sea region including the Netherlands and NW Germany was more influenced by GIA in form of the collapsing peripheral forebulge than Belgium. Scandinavia, the Barents Sea and the British Isles clearly show an influence by the uplift of the crust.

7.3.2 Upper-mantle viscosity

The upper-mantle viscosity is determined to values around $(3 - 6) \times 10^{20}$ Pa s underneath Scandinavia, the Barents Sea and the British Isles by comparison with the RSL data. In the southern North Sea area, values around $(6.5 - 10) \times 10^{20}$ Pa s are found. The GPS data from BIFROST also support the value of 7×10^{20} Pa s, but for the Fennoscandian uplift region. This is a discrepancy between the results of the Scandinavian RSL data and the GPS data. In the FE modelling, the upper-mantle viscosity of $\eta_{um} = 4 \times 10^{20}$ Pa s is the background viscosity for the 1D and 3D viscosity structure of V1, which results fit best with the observations. Independent of the lithospheric thickness, the 3D upper-mantle structure of V1 underneath the investigated areas indicates higher viscosities of around 10^{21} Pa s in the first two upper-mantle layers. The transition zone is characterised by lower viscosities in the range of $(1 - 10) \times 10^{20}$ Pa s. Due to the less good fit of the observations, the 3D viscosity structures of V2 and V3 are not discussed.

A low-viscosity zone is found underneath the Barents Sea, with viscosities between 10^{19} - 10^{20} Pa s in a depth interval of 120 - 200 km. No such low-viscosity zone is found underneath Scandinavia, and no clear indication for such a zone underneath NW Europe. The viscosity structure in the FE modelling does not include the Barents Sea region. Here, only in the northwestern North Sea / Atlantic Ocean a low-viscosity zone is indicated, which is reasonable as the lithospheric thickness in this region is decreasing towards the North Atlantic Mid-Ocean Ridge to values less than the used one of 70 km.

7.3.3 Lower-mantle viscosity

All RSL data are insensitive to the lower-mantle viscosity underneath Northern and Central Europe, even in view of the Scandinavian RSL data, which provide a large time and depth range. From the results of chapter 2 only the BIFROST GPS data seem to provide enough information, as the 1σ-range is quite small compared to the RSL results. The FE modellings clearly show in a sensitivity analysis that the GPS data are nearly insensitive to the lower mantle, independent of its structure. This difference in the results of the methods can be explained with results from a sensitivity analysis recently published by Wu [2006]. He showed with an ice sheet with size of the Laurentide Ice Sheet that in the far field between 45° and 70° from the former ice-sheet centre, the present-day uplift velocity is most sensitive to viscosity variations in the upper lower-mantle (670 km to 1330 km depth). As the BIFROST GPS stations are located in this distance to the Laurentide Ice Sheet and this ice sheet is included in the inverse modelling of chapter 2, the best earth model fitting the GPS data indicates the value ($\eta_{lm} = 10^{22}$ Pa s) of the lower-mantle viscosity underneath North America! In the FE modelling the Laurentide Ice Sheet is not included and thus the GPS data are also insensitive to the lower mantle.

7.3.4 On the used ice model

The best fit with the present-day velocities from BIFROST is observed with the predictions of the 1D FE model. This is due to the ice model, which was constructed with the help of a 1D earth model to fit the sea level [see Lambeck et al., 1998a]. This earth model with a lithospheric thickness H_l of 75 ± 10 km, an upper-mantle viscosity η_{um} of 3.6×10^{20} Pa s and a lower-mantle viscosity η_{lm} of 0.8×10^{22} Pa s is comparable to the used one in chapter 4 ($H_l = 70$ km, $\eta_{um} = 4 \times 10^{20}$ Pa s, $\eta_{lm} = 2 \times 10^{22}$ Pa s). Nevertheless, the ice model has to be changed, especially in the central part, as the observed uplift maximum is located more in the East in the Gulf of Bothnia.

7.3.5 On the database

In this thesis, more than 1500 RSL data and the crustal velocities of 44 BIFROST stations have been used to determine the mantle viscosity beneath Northern and Central Europe. Nevertheless, more data, RSL data as well as GPS observations, are required in order to determine more exactly earth models with a smaller variation in the parameter range of lithospheric thickness and mantle viscosities for each region.

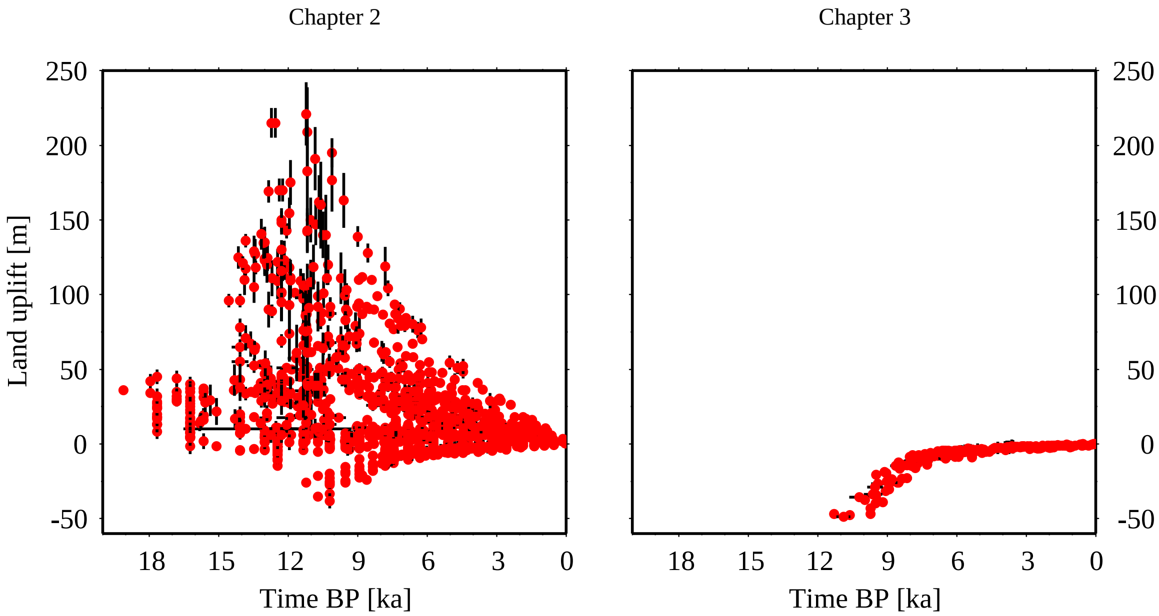

Figure 7.1: Comparison over time and depth range of the RSL data (red dots with black error bars) used in chapters 2 (1320 samples) and 3 (240 samples).

In chapter 2, 1320 North and Central European samples were used, covering 19,000 years and 300 m of uplift, eustatic and tectonic component. In chapter 3, a database with 240 samples is used for the investigation to the North Sea, covering 11,500 years and 50 m of subsidence and eustatic component (Fig. 7.1). This database includes much less rebound information than the Scandinavian database, resulting in the large white area from 0 to 250 m over the whole time on the right side in Fig. 7.1. Unfortunately, in the North Sea area no uplift data can be expected. The region is too far away from the former ice sheet, and thus the white area cannot be filled with sample dots. Nevertheless, more data can be obtained from 9000 years ago and before, and also deeper values of more than 50 m depth. With more older and deeper RSL data from the North Sea as well as data from the Danish sector one can better constrain the geographical extent and the temporal progression of the forebulge collapse, respectively. The question of the stable behaviour of the Belgian crust needs further investigation with new data, and also the difference in the upper-mantle viscosity between the North Sea region and the regions of Scandinavia, Barents Sea and the British Isles. In addition, the comparison between modelled and observational sea-level data can provide important information on local-scale processes such as sediment compaction, and/or tectonic subsidence, e. g. in the North Sea.

The best location of GPS stations in Fennoscandia is within the shape of the former ice sheet. Here, new stations could be installed to determine a more detailed picture of the lithospheric thickness and the upper-mantle viscosity, as the results show that the present-day uplift velocity is most sensitive to the depth interval from 246 - 550 km of the upper mantle. Also new stations far outside the former ice-sheet shape can contribute to future investigations in highlighting the lateral viscosity contrasts in the upper mantle beneath Fennoscandia. The sensitivity analysis in chapter 5 indicates with results depending on the block size, that the size of an area with constant viscosity in the upper mantle directly influences the signal at the GPS station.

7.3.6 Possible model improvements

The differences between the predicted and observed present-day velocities of the 3D FE models forces a revision of the 3D models in a future analysis, because it is quite unsatisfactory that a less sophisticated 1D model shows better results than a more sophisticated 3D model. This revision might include chemical variation due to fact that in the used models the lateral variations in seismic velocities seen in seismic tomography are caused by lateral temperature variation only. Using another tomography model, e. g. one of those introduced by Ritsema et al. [1999]; Zhao [2001] or Zhou et al. [2006], is another option, in addition in combination with a global crustal model [e. g. from Bassin et al., 2000].