Final discussions and conclusions

The large scale structure of the earth is governed and determined by geodynamic processes which cannot be fully understood by means of direct field observation alone. Quantities like temperatures, forces and velocities mostly cannot be directly observed due to their time and depth scales. Numerical models are useful tools to make predictions about those quantities. As a matter of fact, integration of various databases in models of different scales can significantly improve the understanding of the interaction of dynamic and geological processes. A mathematical formulation of these processes allows the development of numerical models which can provide tools to examine the interactions of active processes and parameters within constraints given by physical principles. Large-scale, basin-wide models can provide a framework for data acquisition and interpretation for sedimentary basins.

Sedimentary basins are explored for different scopes, e.g. hydrocarbon production and storage, deposition of waste materials, geothermal energy production. All these operations require specific information which cannot be derived from data acquisition of measurable geological observations alone, but have to be constrained in the context of the geologic processes which produced the results of some kind of measurements. Understanding that the evolution of sedimentary basins is governed by physical processes has initiated considerable efforts to quantify all these processes. Accordingly, various basin modelling techniques have been developed to describe complex geologic processes in terms of physical, chemical and physicochemical processes. Depending on the purpose of a study, basin modelling focuses on different aspects.

A short overview of all the known numerical approaches to continental deformation is described in Part 1 with several applications to the area of the Central European Basin System. This overview however elucidates the importance as well as the limits of the different modelling methodologies in the analysis of complex basins evolution. All the described modelling techniques aim to gain additional information concerning the temporal evolution and spatial distribution of parameters of the relevant tectonic processes. As an example, the kinematic lithospheric stretching models (i.e. McKenzie's uniform stretching with depth and its further implementations) incorporate thermal aspects of basin formation and evolution. They have successfully explained some first order features in long-term subsidence patterns of relative simple basins. Due to conceptual advances, more sophisticated numerical forward basin models were developed, introducing two dimensional aspects (i.e. lateral heat conduction or regional compensation of the applied loads on the lithospheric plate).

Furthermore, this class of more refined models allowed to incorporate various styles of lithospheric deformation in the conceptual formulation. Recently, numerical studies started to focus on more complex evolution-scenarios, incorporating multiple stretching phases and taking into account mechanical effects such as intraplate stresses. In the meanwhile, more detailed constraints from field observation and seismic images stimulated the development of more realistic numerical models. When applied to the CEBS, all these models have been able to reproduce some aspects of the complex evolution of the basin system. More specifically, it has been shown in Part 1 that the different models have been inadequate to address the full complexity of the structural developments of the sub-basins through time. Nevertheless, within the limits related to their theoretical background, all the described numerical approaches have provided insight into the tectonic development of this complex basin system.

Following these aspects, the second part of the present study (cf. Part 2) has attempted a 'rigorous' explanation of the major deformation pattern and development of the different (sub)basins of the Central European Basin System. To model these aspects, a large-scale suitable spherical thin-sheet model for different time slices has been adopted. Finite element temperature and strength models for the lithosphere have been developed in order to provide realistic input data for the integral model. The main goals of the model are:

(1) To obtain a better understanding of intraplate stresses;

(2) To quantify the role of depth-varying rheologies;

(3) To get a better understanding of the thermo-mechanical state of the lithosphere in the study area.

A number of models are presented to provide a description at a regional scale of the present-day dynamics of the Central European Basin System. The consistency of the results is constrained by direct comparisons of the model outcomes and two independent sets of data. The chosen reference parameters are the present-day regional stress field obtained from the "World stress Map Project" (e.g. Roth & Fleckenstein, 2001; Reinecker et al. 2005) and the strain rate eigenvectors derived from the last ten year GPS observations of the ITRF2000 database (Altamini et al. 2002).

The first set of models, Case I, mainly focuses on the effects on the predicted stress field and strain pattern as induced by thermal fluctuations due to crustal and sediments thickness variations. The response of these models resembles the observed features. However, this nearly-homogeneous model fails to reproduce the behaviour of the internally deforming lithospheric plate correctly, not being able to address small-scale variations in the recent tectonic setting of the basin system.

To study how deformation is distributed in response to heterogeneous lithosphere strength profiles, lateral structural and rheological variations have been included (cf. Case II and Case III). Homogeneous and heterogeneous models show differences in predictions. In general, heterogeneous models provide a significantly better fit of the data. The obtained results highlight the significance of rheology in driving deformations and controlling stress regimes even in tectonic scenarios which are dominated by boundary conditions. Inherited large-scale heterogeneities have a relevant influence on the modes of lithospheric deformation. Concerning the deformation style, lateral rheological heterogeneities induce variations in the azimuth of the strain-rate eigenvectors as well as in their magnitudes. In a similar way, the direction of the principal stress axes is not independent of the rheology of the lithosphere. The presence of different structural domains at crustal and shallow mantle level is responsible for the observed local variations in the direction of the regional stress field.

The obtained results (Case III) have demonstrated that strong strain localization as well as major bending in the principal stress orientation may be structurally related to weak crustal and/or shallow mantle domains within the continental lithosphere. From the obtained results, it follows that faults should not be considered as predefined structures within the lithosphere. Indeed, they may be regarded as the natural results of strain localization driven by structural heterogeneities at different depth-levels in the earth’s lithosphere. Of course, as soon as faults developed, they will determine the further evolution of the shallow structure of continental lithosphere. The main point is that faults may be regarded as the weakest zones thus prone to localize deformation. Nevertheless, the obtained results have demonstrated that the role of faults on large-scale continental deformation should not be overemphasized with respect to structural lithospheric heterogeneities. It is more likely that upper crustal processes including fault formation or reactivation might be driven by deeper lower crust and/or shallow mantle processes. Consequently, large scale fault-systems should be regarded as the shallower expression of deeper heterogeneities in the lithospheric structure.

After having elucidated how inherited crustal and lithospheric structures can control continental deformation, the remaining of the chapter deals with geodynamical models of the post Permian evolution of the Central European Basin System. The interactions between geodynamic tectonic forces and thermo-mechanical heterogeneities are carefully addressed. The main point is to understand how the evolution of subsidence centres and uplift areas through time can be controlled by regional variations in the lithospheric structure and minor changes in boundary conditions. In order to explain the observed deformation pattern, different mechanisms governing the development of intra-plate deformation are addressed.

Basin formation and evolution is related to deformation induced by the rheology of the sedimentary fill as well as of deep crustal/shallow mantle structures. Suitable boundary conditions are defined by plate tectonic studies. It is worth to mention that the thin sheet approach enables to investigate the interactions between far-field boundary stresses and/or strains and local variations in material parameters. The assumptions of the integral method, i.e. no shear stresses on horizontal planes and constant normal stresses at the surfaces of the plate, are usually given on the scale of entire lithospheric plates. However, the limits related to the theoretical background of the modelling technique prevent to account in details for the numerous complex processes behind the evolution of the sub-basins. More precisely, within the theoretical formulation of the thin sheet approach the plate may thicken or thin in the vertical direction as to maintain surface stresses constant but there are no vertical strain rate gradients. Consequently, this description can only account for homogenous thickening or thinning of the lithosphere. Nevertheless, the model explains the evolution of major subsidence centres and uplift areas through time. It suggests a correlation between the observed basin-differentiation characterizing the Mesozoic evolution of the CEBS and regional variations in lithosphere rheology as well as minor variations at the effective stress boundaries. On the one hand, the complex geological evolution of the Permian basins and Mesozoic Troughs reflects the mechanical response of these basins to far-field stresses which governed the megatectonic setting of whole Western and Central Europe. On the other hand, the results have also stressed the significance of pre-existing inherited structural discontinuities in driving continental deformation. The presence of lateral rheological contrasts controls the geometry and localization of intra-plate deformation.

Concerning the Late Carboniferous-Permian initial stage, the obtained results resemble the broad pattern of vertical deformation. In agreement with geological observations, subsidence occurs along the Southern and Northern Permian basins with the former showing higher amounts of vertical displacement. Moreover, also the location and geometry of domains of local accelerated subsidence under the North German Basin and in the Polish Trough are imaged. With reference to Triassic-Early Jurassic times, the overall scenario of uninterrupted subsidence in the area of the main Permian basins is imaged. A progressive overstepping of the basin margins established in the Late Permian is also reproduced as well as the persisting NW-SE-trending subsidence axis of the Polish Basin. Moreover, the velocity boundary conditions provide a dynamic setting in general agreement with palaeostress reconstructions with a regional E-W-oriented extensional stress regime. The occurrence of a thermal dome during Middle Jurassic times and the resulting uplift cannot be completely estimated since the model does not consider any additional thermal-induced stress and/or disturbances. In addition the centre of this thermal dome is outside the model area, preventing a detailed description of the dimension and geometry of the Middle Jurassic Central North Sea Dome. Nevertheless, the regional-scale extension of the Mid Jurassic dome is well imaged. The area characterized by uplift ranges from the Viking Graben in the north to the southern North Sea (offshore Netherlands) in a north-south direction and from the eastern part of England through Denmark and northern Germany to the easternmost Baltic Sea in an east-west direction. With regard to the inversion phase(s), the results account rather well for the observed differences in timing and magnitude of vertical displacement and structural style for the different sub-basins. The results demonstrate that slightly different sets of boundary conditions are able to determine the general kinematic of the complex basin. The long-wavelength intraplate compressional stresses released by the advancing Alpine front summed up with extensional tectonics across the Atlantic are sufficient to explain the observed regional style of inversion within the study area. Moreover, the same results elucidate how the localization of inversion zones may be related to differential shortening of the rheology of the lithosphere where zones of crustal weakness suffer from greater shortening relatively to the neighbouring stronger crust. Stress-sensitive and mechanically weak domains determine the development of continental deformation being able to induce differences in the kinematics also under uniform stress boundary conditions.