SUMMARY

The Upper Rhine Graben (URG) forms the central part of the European Cenozoic Rift System, an intra-plate rift located in the Alpine foreland. The development of the URG is linked to collisional deformation in the Alpine foreland accompanied by significant Moho uplift, with the maximum uplift being located in the southern part of the URG. The URG is currently reactivated as a sinistral shear zone driven by far-field loads (i.e. Alpine collisional and ridge push forces). This leads to relative slow tectonic deformation accompanied by low to medium seismicity but a significant amount of ongoing subsidence of several sub-basins (0.1 to 0.2 mm/a geological, 1 mm/a geodetical rate). The understanding of the present-day kinematics within the URG is still limited and only scattered data sets of stress indicators and in-situ stress measurements are available. The seismicity of the area is widespread and not restricted to the border faults of the graben. Few faults are known to be seismically active. However, for the majority of faults no information is available on their Quaternary activity or on their reactivation potential under present-day stress field conditions. The aim of this thesis is the simulation of the present-day crustal state of stress of the URG area using a multi-scale 3D finite element modelling approach and thus to provide data for a better understanding of the recent kinematic behaviour of the URG and the reactivation potential of the graben faults.

Three dimensional finite element analysis (3D FEA) is a tool that can provide detailed constraints on the kinematic behaviour and estimates of in-situ stress magnitudes and orientations of a geological system. The method of FE modelling is applicable to analyse the tectonic behaviour at various scales ranging from plate-wide models to local scale models. For this thesis, a multi-scale approach is chosen. This approach includes a regional scale model covering the entire URG and shoulder areas. Additionally, the kinematic behaviour of two sub-regions within the graben (central and northern graben segments) is investigated with two sub-models of higher spatial resolution including a large number of fault surfaces. In the framework of this thesis, a method and work process is developed for the construction of these complex model geometries using commercial software packages (gOcad®, HyperMesh®, ABAQUS™). The analysis and interpretation is performed using the in-house post processing package GeoMoVie©.

In order to construct and solve a 3D FE model many different data types such as the geometrical structure, material properties and boundary conditions have to be integrated. The first part of the regional modelling study includes a definition of the elements and geometric structure necessary to reproduce the tectonic behaviour and to quantify the contemporary crustal stress field of the present-day URG. The regional model contains three lithospheric layers representing the upper mantle, the lower crust and the upper crust consisting of shoulder and graben units. The varying thickness of these layers is implemented in order to analyse the effects of gravitational potential energy differences on the present state of stress in the URG area. Lateral depth dependent density variations are assigned to the lower crust and the shoulder and graben units in order to account for the complex Variscan structure of the model area. The lower crust and the lithospheric upper mantle are implemented in order to apply an unevenly distributed vertical load as a function of the Moho topography on the base of the upper crust. This vertical load is generated by gravitational unloading of the upper mantle. The graben is bounded by listric border faults, implemented as frictional contact surfaces.

In order to simulate the crustal state of stress for the URG region, appropriate boundary conditions have to be defined. In this study, displacement boundary conditions are defined at the sides and base of the model. Gravitational acceleration is acting on each element directed towards the Earth's centre. For the simulation of the kinematic behaviour of a tectonic system using a numerical model it is insufficient to consider only the boundary constraints active during the modelled time span. Rather, it is necessary to define an initial state of stress that mimics the natural conditions as closely as possible and then load this "pre-stressed" model with the appropriate kinematic and/or thermal loads. In this study, a spherical loading procedure and a pre-stressing approach is applied in order to account for the elastic compaction and to approximate the in-situ stress state, assuming hydrostatic pore pressure and the presence of residual stresses. The loading is conducted in several steps including elastic compaction of a generic spherical model, gravitational pre-stressing and tectonic pre-stressing of the regional model (global model). The stress state predicted by the regional model is calibrated using available in-situ stress estimations and stress indicator data. For the loading of the local scale (sub-models) the obtained basal and lateral displacements from the global model are applied as boundary conditions. For benchmarking of the results from the sub-models, the vertical surface displacements predicted are compared to the regional uplift pattern, local fault slip data and the distribution of areas indicating increased recent tectonic activity. Furthermore, predicted fault slip rates are compared to available geological and geodetical data. The results of the regional model study reveal a significant influence of the various topographies (surface, Conrad and Moho), as well as of the geometric structures implemented on the present-day stress state and the recent kinematic behaviour of the URG. The boundary condition analysis of the URG model shows that the amount of assumed Moho uplift is a critical loading condition on the regional kinematic model. The modelling results suggest that the URG is currently being reactivated as a sinistral strike-slip system with the central segment of the URG forming a restraining bend. The overall tectonic regime in the area is transtensional. Strain partitioning is predicted for segments of the border faults.

The results of *sub-model A*, addressing the central segment of the URG, indicate that within the present-day stress field, this segment is more compressional than the remainder of the graben. Highly variable faulting mechanisms including extension, strike-slip and inversion of pre-existing extensional faults are predicted for this area. The comparison of seismogenic faults in the area with the results of a slip tendency analysis suggests that damaging earthquakes in this region are possibly associated with not favourably oriented fault segments.

Sub-model B covers the northern URG segment and consists of several fault-blocks and sub-basins. The results for this model area indicate that within the present-day stress field, the northern URG segment forms a releasing bend. Here, the lateral compression on the graben is reduced kinematically due to a change in strike of the graben. The segment of the Eastern Border Fault, which is predicted to be most active, coincides with the location of the most pronounced Quaternary depocentre. Furthermore, high slip tendency and dilation tendency values for this fault segment indicate a locus of increased tectonic activity. For both sub-model areas the analyses of the slip tendency and dilation tendency cannot provide constraints on the seismicity of individual fault surfaces. It is however interesting to note that the few seismically active faults in the central and northern URG are characterised by significantly lower slip tendency and dilation tendency values than other faults that show evidence of large displacements over geological time spans.