Evolution and structure of the Upper Rhine Graben — quantitative insights from numerical modelling approaches

Vortrag

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Introduction

The Upper Rhine Graben forms the major segment of the Cenozoic Rift system of Western Europe. Although the rift was the target of many seismic and geological investigations, the style of lithospheric extension below the inferred faults, the depth to detachment, and the amounts of horizontal extension and lateral translation are still being debated. In this study, the data base to the Upper Rhine Graben was subjected to a finite element approach in order to include thermomechanical processes of the lithosphere as well as erosion and sedimentation. The study concentrated on the consequences of extension and lateral translational events on the structure and evolution in terms of basin geometry, sediment layer thicknesses, Moho elevation, and shoulder uplift on a lithospheric scale. The numerical approach was three dimensional in order to incorporate the lateral crustal heterogeneities in the Upper Rhine area and the varying ambient stress field.

The thermomechanical simulation of a real rift requires the knowledge of the parameters controlling its structure and evolution. Furthermore, field data are needed for assessing the modelling results. Both preconditions could be met by the production of comparative data sets as well as by a parameter study before the modelling of the rift evolution. The critical validation of the research level allowed the extraction of the parameters to be determined. The results of the parameter study already gave some cues on the points of controversy mentioned above.

In anticipation of the parameter study, a hypothesis on continental rifting processes was formulated. It describes the consequences of the potential factors controlling the vertical displacements of the graben, shoulder, and Moho under simplified conditions. Opposite to other concepts, the hypothesis also takes into account the mechanical behaviour of faults as a primary factor. The numerical results of the parameter study were compared with the forecasts of the hypothesis in order to identify additional processes acting in the more complex setting of the Upper Rhine Graben area. Moreover, the comparison allowed disclosing functional relationships between the vertical displacements and the controlling parameters. Apart from these insights in the continental rifting process the parameter variations rendered some important results specific to the Upper Rhine rift system. They are in detail:

1. The vertical displacements in the rift system are controlled primarily by the friction, depth, and geometry of the border faults in the brittle domain. The consequences of the temperature and rheology in the creep regime are of minor importance. The same holds for the effects of the erosion and sedimentation.

2. The boundary faults are sub-listric down to maximum depth of 15 to 16 km. The geometry of the faults

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remains the same during the rift-
ing. In the pre-rift setting, they
flatten from a dip angle of around
65° to some 40° at greater depth.
Beneath, the deformation is accom-
modated by ductile creep without a
need for discrete shear zones in the
lower crust and upper mantle.

3. The apparent frictional coefficients
mostly lie around 0.3 bis 0.4, but
at every point on the fault surfaces
lower than 0.5.

4. There are no crustal horizons where
a considerable restoration of the
isostatic equilibrium takes place.

5. High viscosities can be excluded at
any depth in the lower crust. The
variability of the lower crustal com-
positions is of no consequence for
the rift evolution.

6. The upper crustal creep behaviour
can be simulated only with much
higher viscosities as it is predicted
by the quarzite rheology. The re-
quirement can be followed by us-
ing the creep parameters of a felsic
granulite.

These results were put into the actual
modelling of the Rhine Graben evolu-
tion. Therein, the implementation of
the thermomechanical processes and the
balancing on a lithospheric scale allowed
reconstructing the vertical displacements
of the graben, Moho, and shoulder over
time. The comparative data sets are
matched with a rift evolution in two
phases. An extension being approxi-
mately orthogonal to the Rhine Graben
is replaced by lateral translation which
leads to a reactivation of the rift in a
sinistral sense. The horizontal exten-
sion of 7.5 to 8.5 km and a sinistral dis-
placement across the entire graben of
4.5 km at most are necessary in order
to accommodate the sedimentary thick-
nesses. Dextral and sinistral displace-
ments along the border faults take place
during the period of orthogonal exten-
sion as well. These displacements are
located at the fault segments where the
friction coefficients change laterally due
to a switch of the rift polarity. There,
the graben block is extended parallel to
the graben accompanied by a reduction
of the principal stress in the same direc-
tion which causes the lateral displace-
ments.

The conduction keeps pace with the
advection of heat at any time during
the rift evolution. There is no need
for a thermal input of subcrustal ori-
gin for initiation of the rift. No thermal
anomaly is created by the rifting in the
Upper Rhine Graben area. The mod-
elling results confirmed the ideas of the
graben as an example of a passive rift.
The numerical outcomes can serve as
decision guidance for solving conflic-
tive positions about the geodynamics of
the graben system. The fit between
model and reality gives preferences for
an evolution of the graben in two pe-
riods with different kinematics. The
lateral displacements calculated in the
study lie at the upper end of values
which are inferred from structural and
geophysical observations in the Rhine
Graben region. Other stretching di-
rections than orthogonal would result
to additional strike-slip displacements
above this threshold and, therefore,
have to be declined. In the period of lat-
eral translation during the Neogene, the
regional strike slip setting disintegrates
into different tectonic regimes along its
strike. The configuration resembles the
recent kinematics in the Rhine Graben
region. Thus, the study approves the
assumption of regional stress field being nearly constant since the beginning of the Miocene. The modelling results refer only to periods of sedimentary record. They contain no information about the tectonosedimentary evolution in times with hiatuses. The hiatuses are located predominantly in the period of rift-parallel translation. This is at conflict with the calculated displacements which are already at the top of the values inferred for the Upper Rhine Graben from other observations. However, the results show that the graben subsidence, especially in a strike slip regime, is highly sensitive to the mechanical properties of the border faults and their orientation to the local stress field. Slight modifications of these factors can result in a sticking behaviour of these faults over large distances which may account for the hiatuses.

Apart from continental rifting, southwestern Germany was affected by the migration of the Alpine peripheral forebulge into the Rhine Graben region. The modelling outcome permits separating the vertical displacements due to rifting from those related to the bulging processes. Future thermomechanical modelling studies require an implementation of these processes in order to achieve a holistic reconstruction of all geodynamic processes which were active in the Upper Rhine Graben area during the Cenozoic. Therefore, this study is regarded only as a first step to understand the interaction between extension, and lateral translation in a spatially and temporally varying stress field with a pre-existing structural inventory.