# Chapter 5. Summary and discussion

## Summary

This study originated in the assumption that thermally induced flow could lead to the saline springs observed in the NEGB. Data analysis performed by Christoph Jahnke (BTU, Cottbus) and Maja Tesmer (FU, Berlin) provided a regional picture of water chemistry in the NEGB. The basin is characterized by an inhomogeneous distribution of salt content within the pore water. Furthermore, there is strong evidence for density inversion at greater depth caused by increasing temperature. The density inversion occurs even when the fluids are saturated with salt. Chemical analyses, such as isotope contents and REY patterns emphasized the importance of head-driven flow in the shallow aquifer and the existence of upward inter-aquifer flow at depth below 1500 m. Therefore, mixed convection is likely the favoured fluid-dynamic of the NEGB.

For the first time in the NEGB, the mechanisms driving brine within the basin have been investigated by numerically modelling thermohaline flow. FEFLOW® 5 has been used for solving the transient thermohaline problem. The simulations results yielded important insights with regard to coupled hydraulic, thermal, and mass transport processes.

Owing to the complicated basin geometry and to the numerical instabilities characterizing density-driven flow, the first approach was two-dimensional. A model scenario has been built along a representative cross-section of the basin. By running preliminary simulations, the model allowed to define a robust finite element mesh and to evaluate an adequate grid resolution accounting for temperature effects. It turned out that 364 meter is the minimum grid resolution in the **x** direction required for preventing over-dissipative numerical approximation and for ensuring mesh convergence.

Based on this highly refined finite element grid, different kinds of simulations were run in order to study the various components possibly involved in brine transport within the NEGB.

Diffusive brine transport simulations, in which the flow is driven by concentration gradients, showed that the Buntsandstein unit is saturated with highly concentrated brine. Therein a steady-state concentration profile developed at early time stage. On the other hand, steep salt structures supplied a continuous halite replenishment. In the salt dome environment, halite continued diffusing and salty water fills the surrounding sediments in the lateral direction. Downward motion of dissolved halite, due to the gravity, is found to be dominant along salt flanks. The resulting drag forces generated localized convective cells in the overlying sediments providing the main recharge of fresh water. As heavier salt-laden water is produced, velocities decrease and the convective cells weaken or disappear. Brackish water with 1 g/L of dissolved salt occurs at depths between half and 1 km in the surrounding of shallow salt structures.

Subsequently, the regional flow has been taken into account in order to quantify the advective flow effects on the brine patterns. The mass profile is strongly influenced by head-driven flow even at low velocities. Upward or downward migration of dissolved halite is respectively found in relation to ascending or descending fluid circulation due to the regional flow. It was found that discharge areas occurring above shallow salt structures can lead to surface occurrences of salty water.

The effects of temperature anomalies have been evaluated by simulating free thermohaline convection. The calculated patterns showed features of a thermohaline and a static regime: narrow brine fingers penetrated in the sediments above the Buntsandstein unit and the thermal anomalies manifested as non-periodic waves which intensity decreases with depth. While in the diffusive regime the brine patterns are embedded within the stratigraphic units, thermal buoyant forces led to vertical plumes advecting salty water up to the surface. Flow velocities are increased of 1 order of magnitude in direct relation to the thermally induced convective cells. Furthermore, the increased temperature gradient in the vicinity of salt domes generated upward flow of brine even along the edge of steep salt diapirs. A general aspect of the thermohaline regime is the strong coupling of heat and mass transport which is manifested by salty and thermal plumes rising together.

The effects of regional flow have also been evaluated in combination with the free thermohaline regime. The major features of free convective flow are preserved. However, both salty and thermal fingers evolved into a smaller but larger number of plumes which are shaped by the regional flow. On the other hand, in the areas of the basin where the regional flow rates are smaller than the thermally induced velocities, brine and thermal fingers self-developed as in a free thermohaline regime.

In the mixed convection regime fluid viscosity effects have been quantified. Fluid viscosity increases the permeability of the layer in direct relation to increased temperature gradient. Therefore the thermally induced brine plumes formed faster and higher flow rates. As a result, mixing processes are enhanced leading to weakened convective cells and enlarged brine patterns. By contrast, the convective regime remains dominant in areas of the basin where pore water is close to fresh water conditions.

The experience gained with the 2D modeling approach has been applied to tackle the 3D thermohaline problem. A large scale regional model covering the whole study area (230x330 km) indicates that salt water occurs close to the surface within the discharge areas in the lowlands. However the coarse mesh resolution does not allow to quantify temperature effects on the mass distribution. Therefore a smaller scale model (10x10 km) has been constructed with a grid resolution accounting for possible thermally induced convective flow. It has been found that the convective regime described in the 2D models occurred even above flat salt structures.

## Discussion

The model simulated in this study represents simplified conditions of the NEGB. The model is not trying to reproduce reality in details but is meant to delineate the physical causes and forces that contribute to surface brine occurrence. However, to gain additional insights with regard to the long-term behaviour of this geothermal system, more complex models have to be set up. Accordingly, several items should be tested:

- Sensitivity analysis concerning initial conditions: the mass initial conditions used is layered: the initial concentration starts from freshwater condition above the Top Zechstein Salt while a saturation value has been set on the top of the salt. Furthermore, initial pressure and temperature conditions were obtained form steady-state simulations. Now that a robust model has been built up, it would be of great interest to test whether different sets of initial condition can be defined based on the available dataset.
- In addition, different model parameters should also be checked. The convection cells have wavelengths and flow patterns depending on permeabilities as well as on mass, thermal and hydraulic boundary conditions. Clausnitzer et al. (2001) investigated the impact of permeability on temperature oscillations. At the lowest permeability level, free convection vanishes and groundwater stratification is stable. The regional spotty occurrence of the vagabonding springs, therefore, could be due to minor changes in average permeability within a few stratigraphic horizons. However those simulations did not account for density variations due to the salt content and therefore should be re-evaluated with the present model.

Concerning the boundary conditions at the surface, the hydraulic head is assumed to be a subdued replica of the topography. This condition induces a steady state regional flow in which recharge and discharge areas do not evolve in time. However, on such a large time-scale, the role of changing climatic condition on water tables should be accounted for.

Heat and mass boundary conditions at the surface are of Cauchy type. The transfer coefficients which govern these natural boundary conditions were evaluated by rough approximations. Testing different values of these parameters is needed in order to obtain a better reproduction of the observed data. Due to the constant salt concentration at the Salt surface, brine is continuously replenishment supplied. However, in salt dome environment the boundary concentration is strongly dependent on the dynamic processes. Therefore, a Cauchy boundary condition should be as well considered and tested in further studies.

- Simulation time: the model is working with an artificial time scale set up to 200 ka. However the simulations show that a steady state is approached but not reached. Brine fronts are still unstable at the end of the simulation process and therefore fluid-dynamics is subjected to further temporal evolution. Long term simulations can provide more details on the development of these brine fronts.
- Interaction with faults: in the present study, faults were neglected. In reality, the NEGB system contains many faults which can strongly affect the shape and the spatial distribution of the convective cells. These interactions should be investigated in order to quantify their impact on the flow regime. Numerical models of thermal convection in faulted extensional sedimentary basins have been recently carried out by Simms and Garven (2004). Steeply dipping extensional faults can provide pathways for vertical fluid flow across large thick sediments and can modify the dynamics of thermal convection. The presence of faults perturbs the thermal convective flow pattern and can constrain the size and locations of convection cells. Depending on the spacing of the faults and the hydraulic properties of the faults and basin sediments, the convection cells can be spatially organized to align with adjacent faults.
- Paleo-history: it can be expected that the salinity distribution at shallow depth can reflect, to some extent, paleological and hydrodynamic conditions since Zechstein times. These paleo-conditions include: changes in the groundwater level and in the surface temperature as well as interrelationships between the aquifer and the seal-level of the North and Baltic sea during the younger geological history.

While all these effects need to be studied, the numerical results already correlate with the predictions from geochemical analysis, indicating that mixed convection is among the major factors currently affecting parts of the North German Basin, perhaps even causing salt brines to reach the surface in certain areas.