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Salty groundwater flow in the shallow and deep aquifer systems of the Schleswig-Holstein area (North German Basin).

Fabien Magri[*1], Ulf Bayer[1], Asaf Pekdeger[2], Roland Otto[3], Claudia Thomsen[3], Ulrike Maiwald[2]

(1) GeoForschungsZentrum Potsdam 4.3, Telegrafenberg, 14473 Potsdam, Germany
(2) Freie Universität Berlin Department of Earth Science Malteserstr. 74-100, 12249 Berlin, Germany
(3) Landesamt für Natur und Umwelt des Landes Schleswig-Holstein, Hamburger Chaussee 25, 24220 Flintbek

***Corresponding author**

Fabien Magri

Tel.: 0049 (0) 331 288 17 83

Fax: 0049 (0) 331 288 13 40

✉ fabienma@gfz-potsdam.de

Abstract

In the Schleswig-Holstein area, salty groundwaters are not always spatially related to the presence of shallow salt structures. Furthermore, hydrogeochemical data point to instable salinity profiles and to the occurrences of deep brines close to the surface. Therefore, complex interaction between shallow and deep solute migration must occur.

Numerical simulation of fluid flow, mass and heat transport have been carried out in order to understand the role of shallow salt dissolution and young geological features on groundwater flow as well as to investigate the interrelationships between shallow and deep aquifer-systems. For these purposes, a shallow (-500 m) and a deep profile model (- 5 km) have been constructed.

The results indicate that different flow regimes coexist within the study area. Shallow brine migration is strongly controlled by the geological features of the basin such as faults, Pleistocene channels and sand layers. Furthermore, shallow salt dissolution is the major cause for gravitational convection in the deeper aquifers. This source of salinization from above leads to the formation of instable salinity profiles at 2 km depth. Further interactions between shallow and deep fluid flow exist in the eastern part of the basin where brine upconing is due to both topography-driven flow and thermohaline convection. The simulations also showed that the hydraulic conductivity of the stratigraphic units influences the brine regime on a regional scale. Gravitational convection is likely to occur in permeable units located near shallow salt structures, while thermohaline convection persists within thick permeable units in which salt dissolution is not the dominant process.

The presented study provides new insights into fluid flow processes at basin scale. The described flows could develop in any geothermal basin hosting salt diapirs which pierce shallow aquifer systems.

Key words: Shallow salt diapir; brines; thermohaline convection; density-driven flow; numerical modeling; Schleswig-Holstein

1. Introduction

In different regions of the NE German Basin (NEGB), salty water reaches the shallow aquifer system. This long-term phenomenon is manifested by the occurrences of salty springs and by the growth of seashore salt grass in the inner part of the basin. Recent maps locating the observed salty springs and the brine patterns throughout the NEGB have been compiled by Müller (1993), Schirrmeister (1996) and Grube et al. (2000b). Around 25% of North Germany is affected by inland salinity (i.e., originating from upconing of deep-seated salt waters and dilution of salt diapirs) and about 5% by sea water intrusion. The chemistry of these brines indicates that most of the waters originate in the deeper part of the aquifers (Lehmann, 1974b, 1974a Voigt, 1972). In their studies, Hannemann and Schirrmeister (1998) concluded that the waters of the springs originated mainly in the deeper Pre-Tertiary subground. Numerical models of coupled fluid flow, mass and heat transport (i.e., thermohaline flow) supported this thesis. The results have shown that upward solute migration takes place within the NEGB. At 4 km depth, salty waters forming near deep-seated salt structures ascend up to the surface driven by thermal buoyant forces (Magri et al., 2005a, 2005b, in print).

On the other hand, it is still not clear how salt structures piercing the surface aquifers influence the complex dynamics of salty groundwater flow. Steep salt diapirs close to the basin surface provide a source of high salinity for shallow groundwater. Consequently, denser brines can sink into deeper aquifers. The resulting density-driven flow is often referred to as gravitational convection (Garven, 1995). In the NEGB, gravitational convection of brines has not been investigated yet and its effects on groundwater flow are unknown. Furthermore, the interaction between shallow and deep aquifers in relation to salty groundwater flow remains poorly understood. Not at least, other issues that need to be addressed are the role of young basin features such as faults, sand units and Pleistocene channels.

For investigating these aspects, the Eastern part of Schleswig-Holstein region (S-H) is a particularly suitable study area. This region (Fig. 1) is delimited by natural boundary conditions. An elongated salt wall reaching the basin surface stretches over more than 40 km along the Western part, while deeper salt pillows affect the Southern and Eastern area. The Trave River and the Baltic Sea bound the region in the North-East. Furthermore, wide areas of the basin are affected by faults and Pleistocene channels cutting into deeper strata (Fig. 1). Hydrogeologically the studied area consists of two Mesozoic-Tertiary basins, the Oldesloe Trough and the Hemmelsdorf basin.

Owing to the natural features of the S-H area, it will be possible to study the impact of shallow salt structures on salty groundwater flow, the interrelationships between shallow brine migration and young geological structures as well as the interaction between shallow and deep groundwater flow.

For these purposes, transient numerical simulations of groundwater flow are carried out along a selected profile of the basin (located in Fig.1) for two scenarios: a shallow and a deep aquifer system.

The paper is structured as follows. First an overview about the hydrogeochemical data and the two hydrogeological settings is given. Afterwards, the modeling approach is briefly recalled and the numerical results will be presented for both model scenarios. Summary and conclusions of the major outcomes of these investigations are given at the end of the paper.

Understanding the mentioned shallow-deep interactions and their interrelationships with inherited geological features will provide new insights into the origins and formation of shallow and deep brine patterns within sedimentary basins.

2. Hydrogeochemical data and hydrogeological settings

2.1 Hydrogeochemical data

Friedrich (1902, 1917) investigated groundwater salinization in Schleswig-Holstein first. Further research was performed by Heck (1931, 1932, 1944, 1948a, 1948b, 1949). Johannsen (1954) and Vinck (1955) contributed additional aspects of groundwater salinization. Small scale maps by Johannsen (1979, 1980) and Grube et al. (1996) localize groundwater salinization in Schleswig-Holstein. Local investigations concentrated on the area of Bad Oldesloe and Lübeck (Johannsen, 1960; Löhnert, 1968, 1969; Bach et al., 1974; Schenck, 1978; Agster 2000a, 2000b, 2001; Köhler et al., 2005). Saltwater intrusion in coastal aquifer systems was widely investigated e.g. by Dittmer (1953, 1956), Petersen (1956), Schneider (1979) and Johannsen (1980). A summarizing review is given by Grube et al. (1996) and Pekdeger at al. (2006). Groundwaters are generally characterized by Ca and HCO_3 (Fig. 2). Alkaline waters have a medium mineralization of few g/l of Total Dissolved Solids (TDS). The salinization is mainly due to Cl and Na ions. Other widespread ions are Mg and SO_4.

Groundwater salinization is related to structural elements such as shallow salt diapirs, fault zones or Pleistocene channels. Widespread higher groundwater mineralization (up to several g/ TDS) exists in aquifer systems located close to salinar structures, e.g. within the Oldesloe Trough. Nevertheless, most of the saline water occurrences in the Eastern part of the basin cannot be directly related to the presence of any shallow salt structures or faults neither to seawater intrusions. These waters are deep formation brines which reach the surface (Heck, 1932; Johannsen, 1980). In different areas of the Hemmelsdorf basin, the temperature field indicates anomalies which are characteristic of a convective regime (Pekdeger et al., 2006). Therein, thermally induced upward flows may play an important role. However, this hypothesis needs to be verified.

With regard to anthropogenic impact, highly saline groundwater mainly occurs in the neighbouring of the towns as well as along the coastline and the river systems where the aquifer is most exploited. In these areas, upconing of saltwater reaches the surface and forms saline springs. Examples are the saline springs in the discharge area of the river Trave (Löhnert, 1968; Cimiotti, 1983). Seawater intrusion is restricted to highly exploited costal aquifers.

Hydrogeochemical data also consist of shallow profiles provided by the Geological Survey LANU, as located in Fig. 2. These profiles were derived from wells drilled in the areas in which groundwaters are saline. They include the different lithologies and the types of groundwaters within the upper aquifers down to a depth of 500 m. More details concerning the stratigraphy will be given below. Hydrogeochemical data have been collected and compiled at the Freie Universität Berlin (Pekdeger et al., 2006). By example, in Fig. 3, the types of groundwaters and brine concentrations are shown for one of these profiles. Higher brine concentration is found in the Western part of the profile which is close to the Bad Segeberg salt diapir. Within the rest of the profile the TDS of the waters is rather low. As a result, instable fluid density profiles form locally. These brine lenses are characterized by an inverted salinity gradient in which salinity decrease with increasing depths (Fig. 3). This feature is reflected throughout the whole S-H and its origin is unclear.

2.2 Hydrogeological settings

Two structural settings are used for carrying out the numerical investigations. The first scenario is based on the shallow profile IX (Fig. 2). The second hydrogeological model is also based on the Profile IX and includes deep units (down to -5 km).

- The structural data of the shallow aquifer are based on geological profiles provided by the LANU (Agster, 2000a; 2001, 2005). The Profile IX is 30 km long West-East oriented and 500 m deep. The cross-section clearly shows different geological features which can influence transport processes (Fig. 4). All along the profile, the surface elevation varies. These topographical variations induce a regional flow (Tóth, 1999) from the highlands (recharge areas) to the lowlands (discharge areas). Regional flow enhances fluid circulation due to the viscous drag, promotes salt dissolution and drives salty plumes away from the salt domes (Evans et al., 1991). At the western ending of the profile the Zechstein salt is strongly uplifted. Besides being a source of salinity for groundwater, this salt structure provides a natural impervious boundary condition to fluid flow owing to its very low hydraulic conductivity. In that location, the vertical dipping fault points towards active salt-tectonics. Steep folds can be seen in the central part of the profiles together with two differently filled channels. The western channel is mainly composed of Quaternary sediments (till) while the central Pleistocene channel is filled with lacustrine sands. These units can act as preferential conduits for inflows of freshwaters as well as for uprising flow of deep-seated waters.

The Oldesloe Through is built up of lower Mica Clay. This syncline is mainly composed of sand strata down to a depth of 450 m below the sea level. The Hemmelsdorf basin displays a sequence of Tertiary sands uplifted at a depth of -150 m. The upper aquifer of the entire system is bounded at the bottom by a unit of marl which can be considered quasi-impervious (aquitard). A similar groundwater system for this area is thoroughly described by Grube and Lotz (2004).

This profile will serve as a structural model for numerically investigating shallow fluid flow and brine migration with regard to the described geological features of the basin.

- Concerning the deep structural data, this area has been the subject of many studies and industrial exploitations. In addition to wells and seismic data, structural maps were provided by the Federal Department of Geosciences and Mineral Resources (BGR; Baldschuhn et al., 1996) which cover the area under consideration. The digital version of depth maps from the Geotectonic Atlas of NW Germany (Baldschuhn et al., 2001) was integrated into a three-dimensional structural model by Maystrenko et al. (2005, 2006). This 3D model was finally adjusted by using the results from seismic interpretation. The reflection seismic profiles (located in Fig.2) were interpreted down to the Zechstein (Maystrenko et al., 2005, 2006). Therefore, the geologic identification of the different stratigraphic units along the studied profile is also well established (Fig. 5). Furthermore, the major geological features of the shallow aquifer systems described in Fig. 4 have been incorporated within the Post-Paleogene unit (Fig. 5). They include interbedded sand and clay strata as well as the Pleistocene channels. These units and the rims of the diapirs provide the contact zones between the deep and shallow aquifers.

In summary, the implemented deep model consists of eight units: from Post-Paleogene down to the Zechstein Salt which closes the model at 5.5 km of depth. The deep model has been extended to 33 km by incorporating a 4 km thick salt diapir. This will allow taking into account thermal effects resulting from the physical properties of the salt. At these scales, thick salt structures strongly disturb the temperature field owing to their high thermal conductivity. The resulting thermal anomalies can induce upward migration of dissolved halite which will interact with the shallow aquifer.

This profile will be used for investigating deep-fluid circulation. Owing to the mentioned structural characteristics, it will allow studying the interaction between deep brine plumes and the upper aquifer as well as the impact of the geothermal gradient on transport processes.

3. Modeling approach

For solving the equations governing fluid flow, mass and heat transport, the commercial finite element software FEFLOW® (WASY-GmbH, 2002) has been applied. The mathematical formulation of these equations is briefly recalled here and additional details can be found in Diersch and Kolditz (1998).

$$\mathrm{S}\frac{\partial \varphi}{\partial \mathrm{t}} + \mathrm{div}(\mathbf{q}) = 0 \tag{1}$$

$$\mathbf{q} = -\mathbf{K}\left(\mathbf{grad}(\varphi) + \frac{\rho_f - \rho_{0f}}{\rho_{0f}}\mathbf{u}\right) \tag{2}$$

$$\phi\frac{\partial C}{\partial t} + \mathrm{div}\left(\mathbf{q}C\right) - \mathrm{div}\left(\mathbf{D}\mathbf{grad}(C)\right) = 0 \tag{3}$$

$$\frac{\partial}{\partial t}\left(\left(\phi\rho_f c_f + (1-\phi)\rho_s c_s\right)T\right) + \mathrm{div}(\rho_f c_f T\mathbf{q}) - \mathrm{div}\left(\boldsymbol{\lambda}\mathbf{grad}(T)\right) = 0 \tag{4}$$

Equation (1) is the equation of fluid mass conservation. S is the medium storativity, φ is the hydarulic head. $\mathbf{q}$ is the Darcy (or volumetric flux density) velocity defining the specific discharge of the fluid.

The Darcy's law is expressed by Equation (2) where $\mathbf{K}$ is the hydraulic conductivity tensor, $\frac{\rho_f - \rho_{0f}}{\rho_{0f}}$ represents the buoyancy force induced by density variation, and ρ_f and ρ_{0f} denote the fluid density and its reference value, respectively.

Equation (3) is the equation of solute-mass conservation where ϕ is the porosity of the porous medium, C is the mass concentration, and $\mathbf{D}$ is the tensor of hydrodynamic dispersion.

Equation (4) is the energy balance equation for the fluid and the porous medium where c_f and c_s denote the heat capacity of the fluid and the solid, respectively, T is the temperature, and $\boldsymbol{\lambda}$ is the thermal conductivity of the saturated porous medium as a whole.

The finite-element mesh used for discretizing the shallow profile of Fig. 4 consists of approximately 101,000 triangular elements. The elements define a horizontal resolution of 20 m and have variable thickness in the vertical direction.

With regard to the deep profile of Fig. 5, a coarser mesh resolution of 120 m was used to discretize the units from the Paleogene to the Zechstein Salt. The grid of the Post-Paleogene unit, instead, is finer in order to accurately preserve the geometry of the smaller structures. Therein the resolution varies between 20 m and 40 m; the grid of the deep profile is made of 110,000 triangular elements.

The grids satisfy the regularity conditions and the resolution allows to model variations in fluid density.

Some simplifying assumptions have been made. According to hydrochemistry, major ions are Na and Cl. Therefore, brines are considered pure NaCl solutions. Fluid density data are numerically reproduced by use of polynomial expressions taking into account pressure, temperature and salinity dependencies (Magri, 2004; Magri, 2005). At this state of the research, viscosity variations have been neglected. However this issue will e addressed in the future investigations. Furthermore, the simulations results should not be considered as describing the reality as in nature groundwater flow occurs in three dimensions. Nevertheless the two-dimensional approach is supported by data and allows understanding the role of shallow and deep geological structures on brine migration.

3.1 Model parameters

Each stratigraphic unit is considered homogeneous and isotropic with regard to its physical properties (e.g. hydraulic conductivity, porosity). The values of these parameters for the shallow and the deep profile are given in Table 1 and Table 2, respectively. While it does not account for physical heterogeneity in the horizontal direction, this first rough hydrogeological model allows differentiating the major aquifers at depths.

For this study, the available data have been averaged to an appropriate spatial basin scale (i.e., km). Therefore, a certain degree of uncertainty exists due to the spatial variability of hydraulic properties. By observing Table. 2, it can be noticed that the whole Post-Paleogene unit has been considered homogeneous with respect to its thermal properties, while the structures within it are hydraulically different.

3.2 Boundary conditions

The following boundary conditions are applied:

- At the surface, head, temperature and solute boundaries are prescribed. The head is fixed to the local topographical elevation which induces a steady regional flow. Since springs of warmer saline waters are observed in the study area (Schirrmeister, 1996; Grube et al., 2000), heat and dissolved salt are allowed to flow through the surface by use of an open boundary condition (Cauchy). The reference values for the temperature and for the salt concentration at the surface are respectively 8 °C and 0 g/L (i.e. freshwater). Further details on the equations governing these boundary conditions can be found in Magri et al., (2005b) and Magri (2005).

- At the bottom, a constant-temperature boundary condition of 160 °C was defined. This value corresponds to a linear vertical gradient of approximately 30 K/km.

- At the top of the salt, the brine concentration was fixed at 345 g/L, representing an approximate value for halite saturation. By setting a constant concentration value at the Top salt, the basin undergoes a continuous salt replenishment. Nevertheless, the shape of the salt layer remained unchanged.

- The lateral boundaries are closed to fluid, heat, and mass flow.

3.3 Initial conditions

The initial pressure and temperature conditions are respectively derived from steady fluid flow and steady conductive heat transport models.

The initial salt concentration is set to saturation concentration (i.e., 345 g/l) within the salt while freshwater conditions (i.e. 0 g/L) are defined everywhere above the salt unit. However, the sediments of the NEGB were deposited during marine transgression (Scheck, 1997). Therefore, an initial salinity profile in which brine concentration increases linearly with depth has also been tested in order to account for paleo-salinity conditions.

4. Numerical simulations: results

Different types of numerical simulations have been carried out.

- Coupled fluid flow and mass transport simulations are run in the shallow and in the deep model scenarios (Par. 4.1 and 4.2 respectively).
- The impact of the geothermal gradient is then investigated in the deep model scenario (Par. 4.3).

4.1 Shallow profile scenario

Large-scale topography-driven flow (i.e. regional flow) and density-driven flow develop within the profile (Fig. 6a). Generally, in areas of variable topographic relief, the groundwater flows from recharge to discharge areas parallel to the land-surface topography. Here, the numerical simulations also indicate that the stratigraphic framework of the units strongly control brine migration within the shallow aquifer. Three units play a major role: the fault along the salt flank, the Pleistocene channels and the interbedded sand units.

Vigorous recharge inflow occurs from the uplifted cap rock along the fault system (Fig. 6a). In that area, close to the surface, flow rates can reach values up to 1 m/d. Brine plumes form in the upper part of the salt flank, just below the cap rock (Fig. 6b). These saline plumes protrude within the Kaolin Sand unit at few centimetres per day. Therein, streamlines are parallel to the Upper Micaclay unit, which bounds the flow due to its low hydraulic conductivity (Table 1). Within the Quaternary channel, brine with several g/l of dissolved salt discharges through the surface advected by the intense regional flow (Fig. 6b). Within this Pleistocene channel, the vertical stretched plumes define a narrow lens in which the salinity distribution is inverted. This is in good agreement with the hydrogeochemical observations (Fig.3). By contrast, the eastern neighbouring Pleistocene channel enhances inflow of freshwater as it is located in a recharge area. Within the Pleistocene channel the inflow is less intense (few centimetres per day) since the upper part of this unit is bounded by a marl cover which reduces the velocity field (Fig 6a). As a result, this unit favours freshwater and brine mixing. Therein, the TDS concentration is close to freshwater conditions (Fig. 6b: few mg/l, not displayed in the legend) and no brine lenses form.

Within the Cenozoic, downward groundwater flow along the salt flank is further enhanced by strong salt dissolution. Highly concentrated brines sink from the salt flank into the Cenozoic unit driven by density (Fig. 6b), generating a gravitational convective cell (Fig. 6 a).

As time progresses, the brine patterns within the Kaolin unit and the Quaternary channel do not vary (compare figures 6c and 6b) suggesting that therein a steady concentration gradient is reached. On the other hand, the dissolved halite saturating the Cenozoic migrates toward the steep sand units in the central part of the profile (Fig 6c). In this scenario, interbedded sand units provide a preferential channel for rising brine flow. Therein, salty waters ascend at few centimetres per day over more than 15 km below the upper part of the aquifer-system. This channelled groundwater flow exfiltrates in the lacustrine sediments of the Hemmelsdorf basin at 18 km from the Bad Segeberg salt diapir. Within the Lower Tertiary salt diffusion is dominant. This process is very slow and saturates the whole unit with brackish waters.

It turned out that the simulated flow and brine patterns were not drastically affected by changing the hydraulic conductivity of the different units, while the velocity field strongly depends on this parameter. In the presented scenarios, the flow velocity is rather heterogeneous ranging from half a meter per day in the upper part of the aquifer system to a few millimetres per day in the more impervious units. However, the velocity field allows a rough evaluation of brine residence times within the profile. By example, the brine plumes forming within the Kaolin unit need approximately 50 years to spread over the surface. On the other hand, the brine flow forming at the Bad Segeberg diapir takes more than 5,000 years to ascend over the central sand unit. This time scale is in good agreement with the results obtained by Grube and Lotz (2004). However, in their simulations, salt dissolution was not taken into account.

In summary, the results of these simulations indicate that the groundwater flow is affected by the presence of the fault, the Pleistocene channels and the sand units. The fault along the salt flank provides the major inflow conduit of groundwater. Descending waters dissolve the salt and form density-driven brine flow. These salty waters are then released through the Quaternary channel of the Oldesloe Trough, advected toward the surface by vigorous topographic-driven flow. As a result, bifurcated plumes rising to the surface provide the primary cause for the observed instable brine lenses within the shallow aquifer.

Ascending brine migration also takes place through the sand units which discharge the saline waters farther East within the Hemmelsdorf basin. On the other hand, the Pleistocene channel recharges the sediments with freshwater which prevents brines from reaching the surface. Heavy saline waters sink into the bottom aquifer and saturate the Cenozoic sediments. A salty front slowly diffuses throughout the Lower Tertiary. With regard to these deeper brine flows, the bottom boundary conditions are dominant. The prescribed no flow condition impedes saline waters to sink into the deeper units, forcing salt to diffuse eastward.

The deep profile scenario will allow investigating the interaction between shallow and deep transport processes.

4.2 Deep profile

The results of coupled fluid flow and mass transport simulations are illustrated for two time steps in Figures 7. At the beginning of the simulation process, brine patterns develop within the upper aquifer (Fig 7a). The dissolved salt stretches horizontally over 5 km from the salt diapir. A brine lens forms within the Quaternary channel and reaches the surface at its middle, advected by the regional flow. The process is analogous to the brine migration described in the previous shallow model scenario (compare Fig 7a and Fig. 6b). However, different fluid-dynamic processes are involved. Below the horizontal brine plume several brine fingers form and sink into the Paleogene unit (Fig. 7b). This source of salinity from above leads to an instable density stratification which in turn generates gravitational convective cells. In this scenario, the flow rate of the cells is on the order of millimetres per day. By increasing the hydraulic conductivity of the Palaeogene, the cells developed at higher flow rates (up to several centimetres per day). At the same time, highly saline patterns form along the steep salt flank and start sinking into the deeper units.

As time progresses, the sinking brine fingers merge within the Paelogene (Fig. 7c). Consequently, the convective regime evolves to a linear salinity gradient. On the other hand, within the Createcous and the Keuper, the dense brine plumes continue protruding eastward affected by gravitational convection. Density-driven cells of 1 km radius develop at the brine fronts. This can be explained as follows. Since the Cretaceous is more permeable than the Keuper (Table. 2), a brine front descends faster within the Creataceous than it migrates within the Keuper. As a result, a finger tip forms and sinks under gravitation into the underlying slower migrating brines. The downward movement of the brine lid pushes the deeper brines upwards generating the convective cells. Although the physical parameters assigned to the different units are a rough simplification of the reality (i.e. homogeneous sediments), the results indicate that kilometre-scale gravitational convection is likely to occur in permeable units adjacent to shallow salt structures.

At the final stage of the simulation, an extended brine plume stretches horizontally over 18 km. Since the plume forms at the salt diapir, the concentration gradient decreases in the eastward direction. Eventually, brines flowing at 2 km depth within the Cretaceous are advected toward the surface of the Hemmelsdorf basin, in relation to the discharge area. In the presented case, the brines reached the shallow aquifer 10,000 years after their formation at the Bad Segeberg salt diapir. At the Hemmelsdorf basin, an initially linear salinity profile (paleo-salinity conditions) also evolved to a brine upconing. This suggests that, at that location, surficial salty waters can be a mixture of formation waters (paleo-brines) and brines forming at the salt diapir.

Sensitivity analyses were used to study the effects of varying hydraulic conductivity of the Cretaceous and Keuper. By increasing this parameter by one order of magnitude, the general flow patterns did not change significantly. However, brines formed and migrated much faster. At given time steps, the calculated concentrations throughout the whole profile were also higher. The deep gravitational convection cells disappeared when the hydraulic conductivity of the Keuper was drastically decreased (set to almost impervious). In this case, a single brine tip developed migrating within the Cretaceous toward the Hemmelsdorf basin.

These simulations allowed studying the interrelationships between shallow salty water and deep brine flow. Dissolution of halite from above provides an instable source of salinization for the deep aquifer systems. Small convection cells driven by gravity form and brine lenses sink vertically toward the Paelogene unit. At the same time, highly saline plumes developing within the Mesozoic units are affected by gravitational convection at a regional scale. This fluid dynamic does not affect brine distribution within the shallow aquifer. However, gravitational convection within deep aquifers strongly perturbs the concentration field. The simulations indicate that, on a local scale (i.e., in a range of a few km), these cells can be responsible for salinity inversion. Furthermore, the described deep fluid dynamics are controlled by the hydraulic conductivity of the Mesozoic formations. After decreasing the value of this parameter, the gravitational convection did not develop, suggesting that this phenomenon is likely to occur in permeable units close to shallow salt structures.

The simulations also showed that in the Hemmelsdorf Basin the regional flow can form upconing of deep-formation waters and brine plumes. This is in good agreement with the hydrogeochemical data.

4.3 Deep profile: impact of the geothermal gradient.

At this state, the effect of the geothermal gradient on fluid transport processes has to be investigated. For this purpose, two different simulations have been carried out. In the first case, a coupled fluid-flow and heat-transport model is run (thermally induced flow). Subsequently, the effects of dissolved salt are also considered (thermohaline flow).

Thermally induced flow

The temperature field calculated from a coupled fluid flow and heat transport simulation is illustrated in Fig. 8. Different regimes developed within the profile.

Within the salt unit, the thermal regime is conductive. Owing to the strong contrast between the thermal conductivity of the salt and the neighbouring sediments (Table. 2), concave isotherms are found within the salt diapir while convex isotherms are adjacent to the salt flank. These anomalies are well known and found in geothermal basins hosting salt structures (e.g. O' Brien and Lerche, 1984).

Above the salt, advective, convective and conductive heat flow affect the whole profile. Within the Post-Paelogene units, the regional flow is dominant. Increased temperature gradients are found in direct association with discharge areas. For instance, the fluid temperature within the Quaternary channel increases by about 2 K. A similar temperature increase can be observed at the discharge area of the Hemmelsdorf basin. On the other hand, inflow of colder water decreases the temperature in the recharge areas.

According to Rayleigh theory in a porous medium, the onset of multicellular convection is favoured in thick and permeable units (Nield, 1968). This is the case for the Paleogene and the Cretaceous units where a thermally induced convective regime controls the flow. Thermal plumes of 1.5 km height rise vertically from the Cretaceous basis up to the surface, bounded by the regional flow. A zoom of an ascending thermal plume is shown in Fig 8b. The cell radius is 1 km and the flow rate in the central part of the plume is on the order of millimetres per day.

In the deeper units the isotherms are not perturbed and the regime is conductive.

Thermohaline flow

Here the simulations also account for salinity effects, providing a complete picture of the major transport processes within the profile. Temperature and salinity profiles are shown in Fig.9.

Highly saline brines protruding from the salt diapir into the Cretaceous overwhelm the less intense thermal convective regime. Heat plumes do no stretch vertically but develop almost horizontally in the brine flow direction (compare figures 9 and 8). Therefore, the temperature gradient increases horizontally from the salt flank toward the center of the profile. As a result, the temperature field can undergo several inversions with increasing depth in the western part of the profile.

In the Paleogene of the Hemmelsdorf basin, thermohaline convection persists. Above the horizontally stretched plume, the temperature oscillations generate small convective brine cells (half-kilometre radius). As a result, thermally driven saline waters ascend up to the shallow aquifer and spread locally at several points of the surface.

On the other hand, in the other units of the profile, the geothermal gradient do not significantly influence brine patterns. Within the Post-Paelogene, the regional flow drives heat and dissolved salt. Within the Bunstandstein and the Muschelkalk, the regimes are mass diffusion and heat conduction.

5. Summary and conclusions

Hydrogeochemical data indicate that in S-H salty groundwater occurrences are partly related to structural features of the basin such as shallow salt structures, faults and Pleistocene channels. The salinity profiles highlighted the presence of brine lenses and inverted salinity profiles throughout the basin. Furthermore, deep formation brines observed at the surface of the Hemmelsdorf basin point toward strong interaction between deep fluid flow and shallower aquifer systems.

Numerical simulations of fluid transport processes have been carried out on a shallow and deep profile scenario in order to study: (1) the role of shallow salt dissolution and young geological units on groundwater flow, (2) the interrelationships between shallow brine migration and deep fluid flow, and (3) the impact of the geothermal gradient on the whole groundwater system.

These investigations provided possible explanations for the unsolved issues and allowed to gain insights on transport processes within geothermal basin.

Brine flow within the upper shallow aquifer is strongly controlled by the different geological units. The fault system along the salt diapir is the major conduit for freshwater inflow. This groundwater recharge favours salt dissolution along the salt flank. The resulting brines flow easily within highly permeable aquifers. Quaternary channels located in discharge areas provide preferential conduits for brine outflow. Therein vertically stretched brine plumes define narrow brine lenses and inverted salinity profile. By contrast, this feature does not concern highly permeable channels located in recharge areas. The Oldesloer Trough sand units underlying the whole aquifer system promote ascending flow of brines. Brines can migrate within interbedded sand units over several km and discharge far from the salt diapirs where they formed.

The deep profile scenario allowed studying shallow and deep flow interactions and inferring the fluid-dynamics affecting brine flow within S-H.

Shallow salt dissolution provides an instable source of salinization for the deeper aquifers. Brine plumes sinking into permeable units can generate gravitational convection. This flow perturbs the salinity gradient leading to instable fluid-density stratification in which heavier fluids overlay lighter brines.

Deep formation waters can be advected toward the surface of the Hemmelsdorf basin by the regional flow. However, in this area, the geothermal gradient is also responsible for upward migration of deep brines. Therein thermohaline convection developed and salty waters reached the surface in different areas. By contrast, thermally induced flow is overwhelmed by vigorous downward flow of highly saline brines.

Beside topography-driven flow, the different convective regimes are a mechanism for extensive solute exchange between shallow and deep aquifers. The described flows could develop in any basin hosting salt diapirs piercing shallow aquifer systems.

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Figure captions

Fig.1: Study area and location of: the salt structures (salt pillows from Weber, 1977 - salt diapirs from Baldschuhn et al., 2001), Pleistocene dorrs (Hinsch, 1974) and the shallow geological profiles investigated by the “Geological Survey” LANU (Agster, 2005).

Fig.2: provides a map of the different types of groundwater in the Schleswig-Holstein aquifer at depth between 0 and -150 m. (modified after Tesmer, 2004) together with the location of: the salt structure (Baldschuhn et al., 2001), and the shallow geological profiles provided by the “Geological Survey” LANU (Agster, 2001).

Fig.3: Example of hydrogeochemical profile modified after Tesmer, 2004 (Number VII, in Fig.2). The chemistry of different brines is shown together with TDS concentration in mg/L. The shaded circles highlight instable stratification of brines (i.e. high salinity above more diluted brines). For clarity a 35:1 vertical exaggeration is used.

Fig.4: Interpreted geological profile (profile IX in Fig.2). This profile is used as structural setting for the numerical investigations of shallow fluid flow and brine migration. For clarity a 19:1 vertical exaggeration is used.

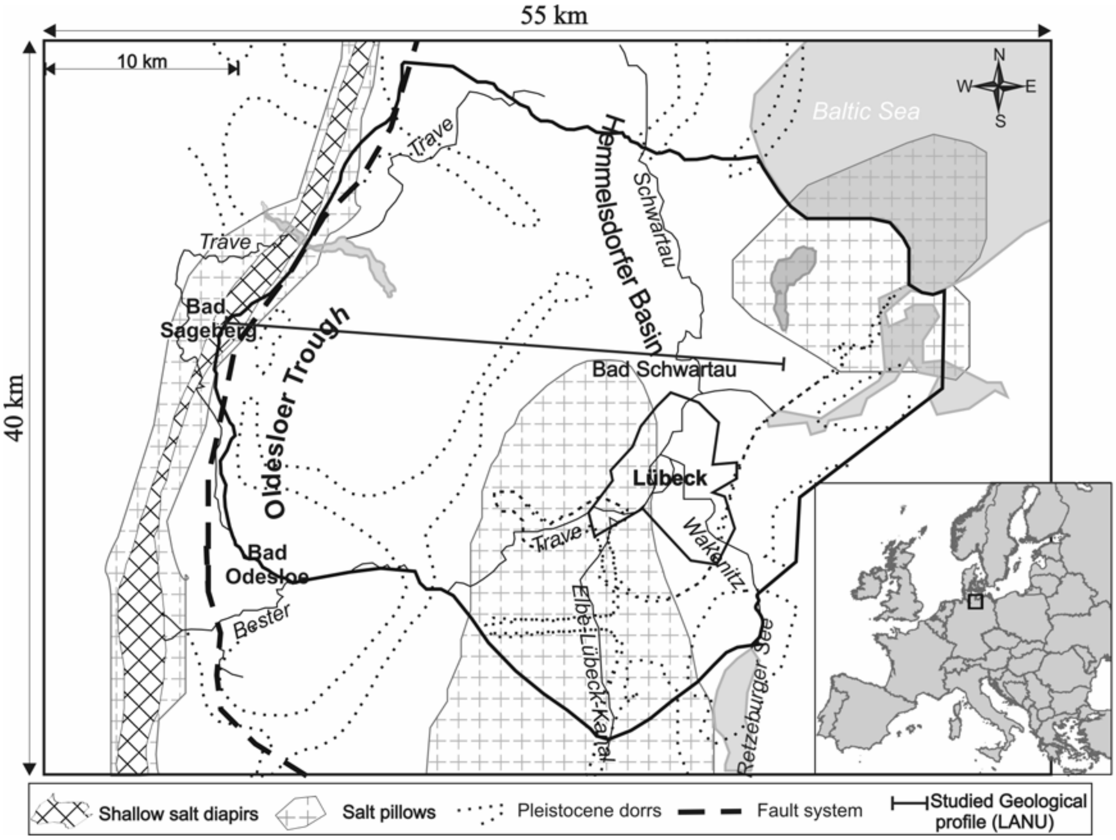
Fig.5: Deep profile structure along the studied profile (according to the data from Maystrenko et al., 2005). The Post-Paelogene unit includes the major features of the shallow profile illustrated in Fig.4. For clarity a 5:1 vertical exaggeration is used.

Fig.6: (a) Pore velocity field (m/d) calculated from a coupled fluid flow and mass transport problem. Dashed lines depict the groundwater flow pathways, arrows indicate the flow direction. (b) and (c) Calculated brine concentration (g/l) at (b) 50 y and (c) 52 ky. For clarity a 19:1 vertical exaggeration is used.

Fig. 7: Deep profile: coupled fluid flow and mass transport simulation. (a) and (b): Calculated salinity profiles in g/l at 290 y and (c) at 10 ky. The vectors depict the direction of the gravitational convective flow. For clarity a 2:1 vertical exaggeration is used.

Fig. 8: Deep profile: coupled fluid flow and heat transport simulation. (a) Calculated temperature profiles in °C at 15 ky. A zoom of the thermally induced plumes is given in Fig. 8b without vertical exaggeration.

Fig. 9: Deep profile: thermohaline simulation. Calculated mass (filled patterns, g/l) and temperature profiles (dashed lines, °C) at 15 ky.



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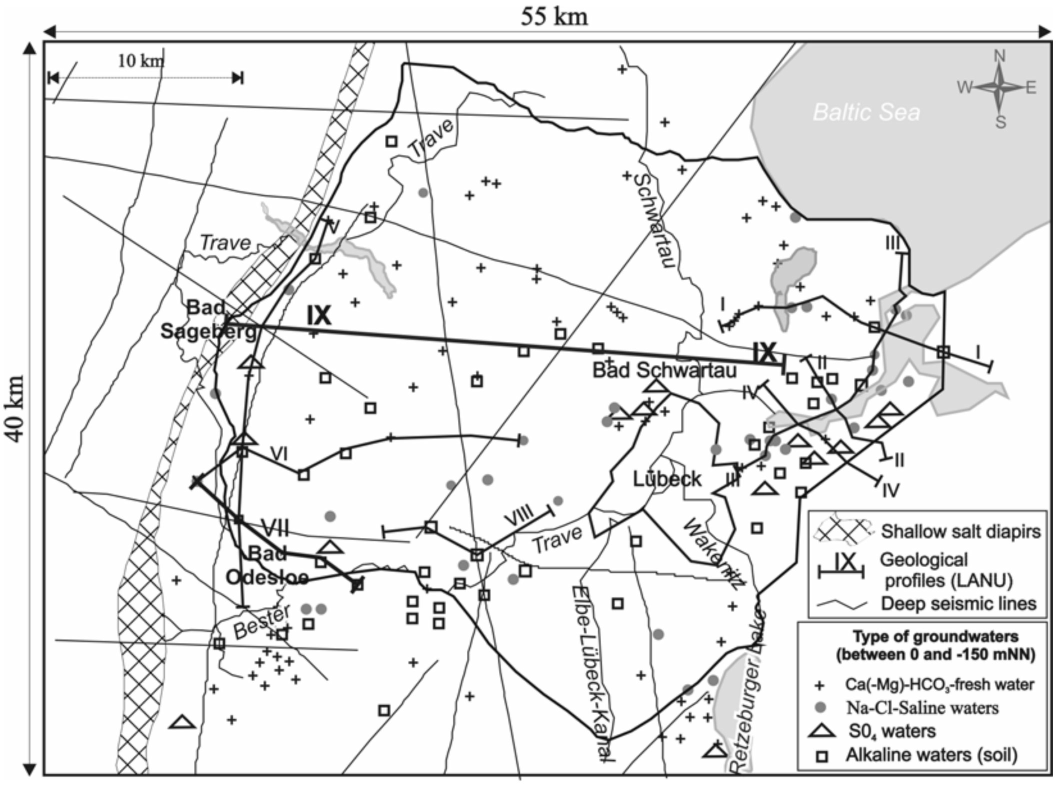

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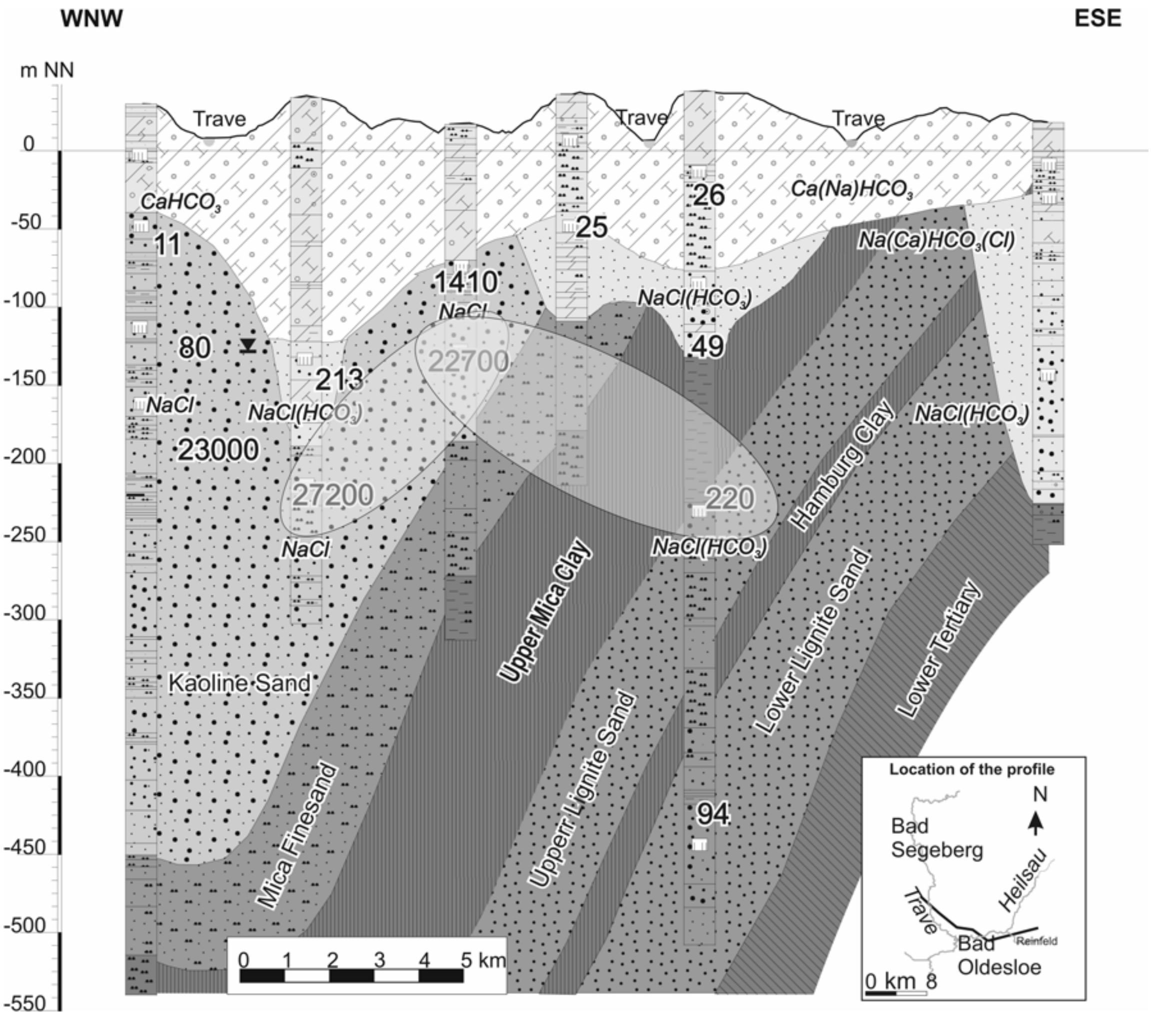

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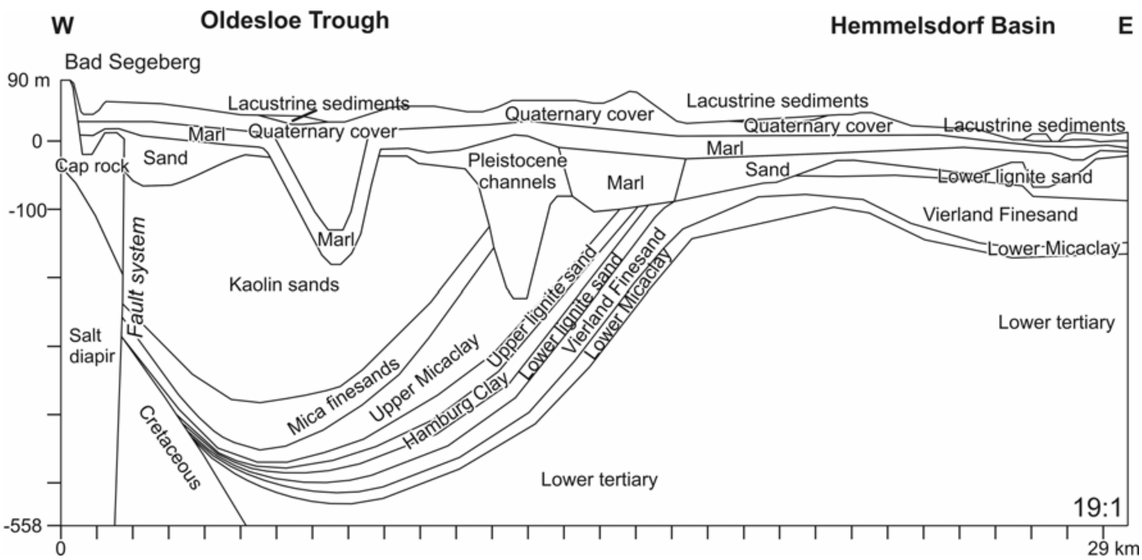

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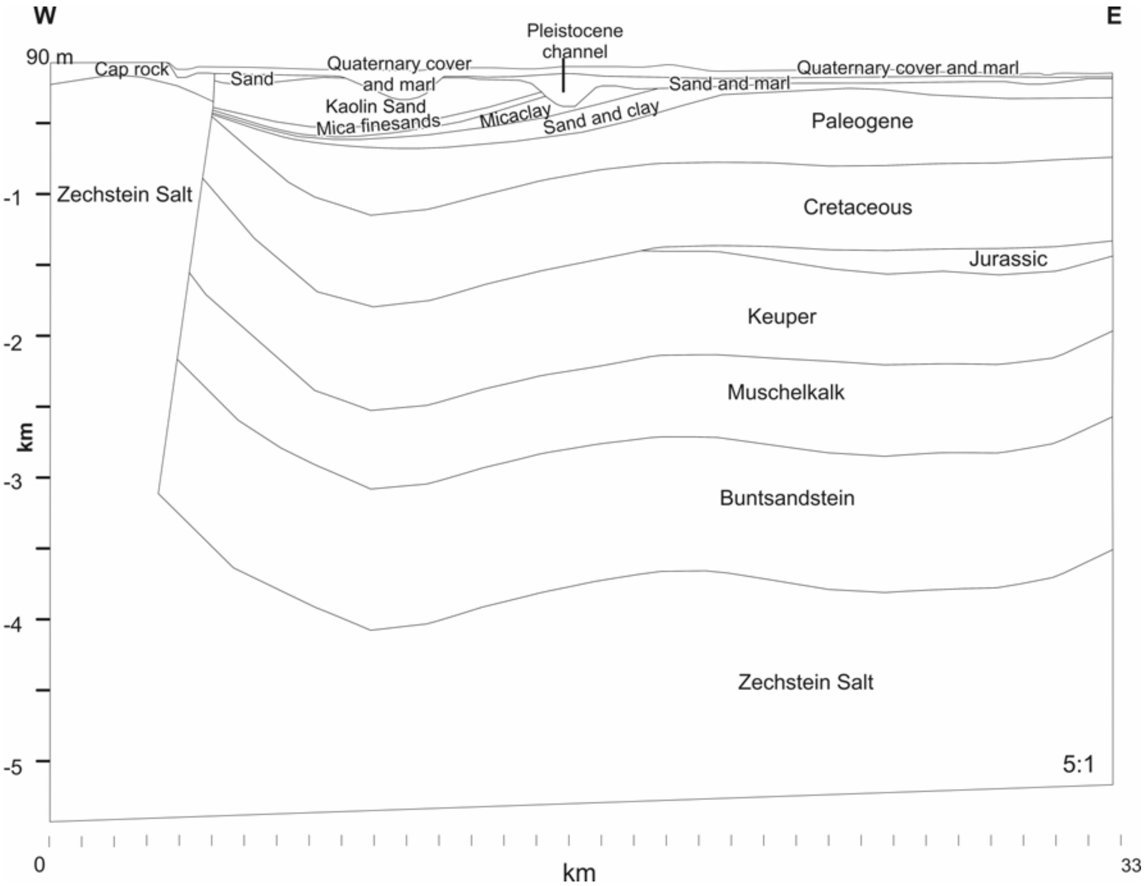

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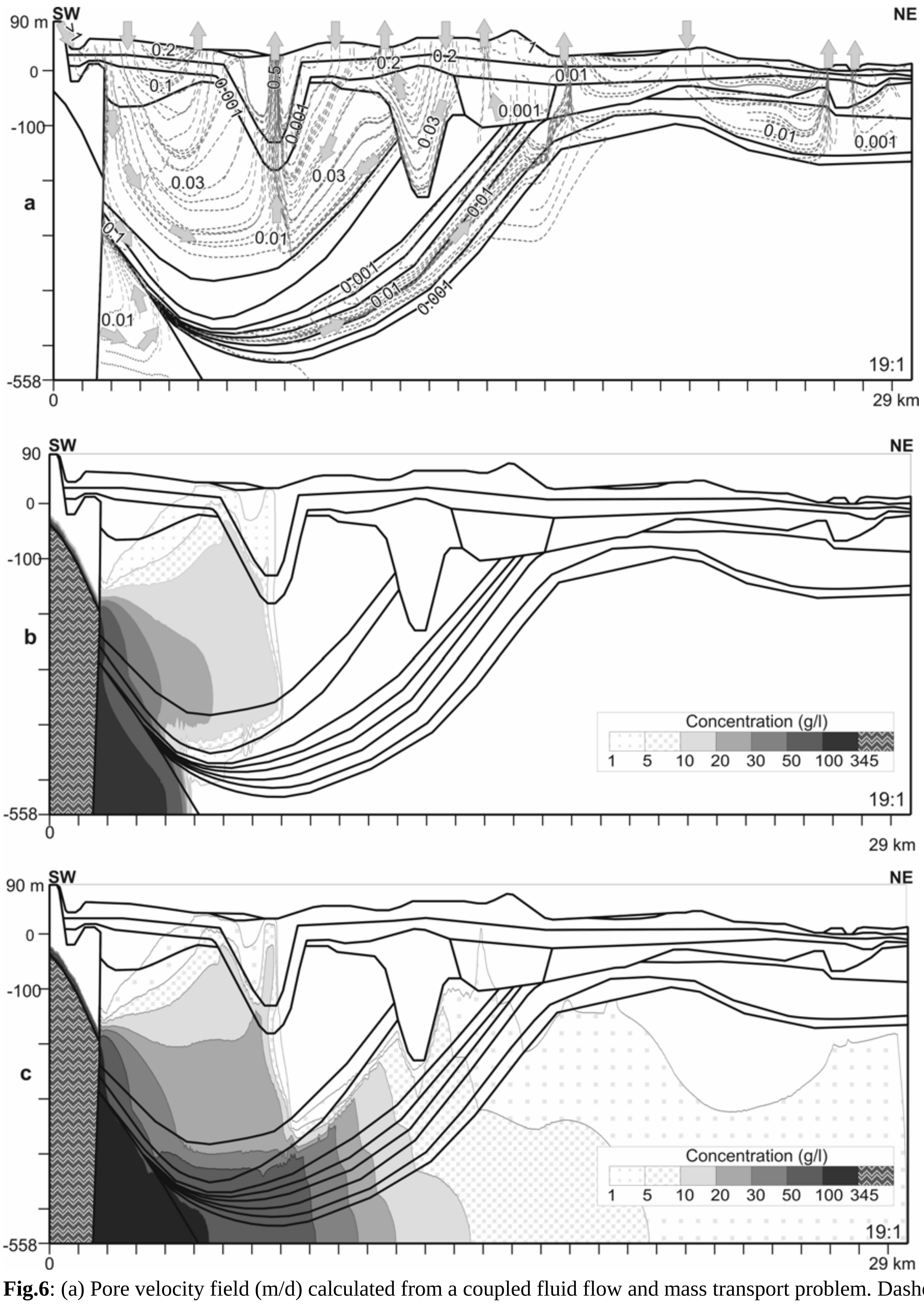

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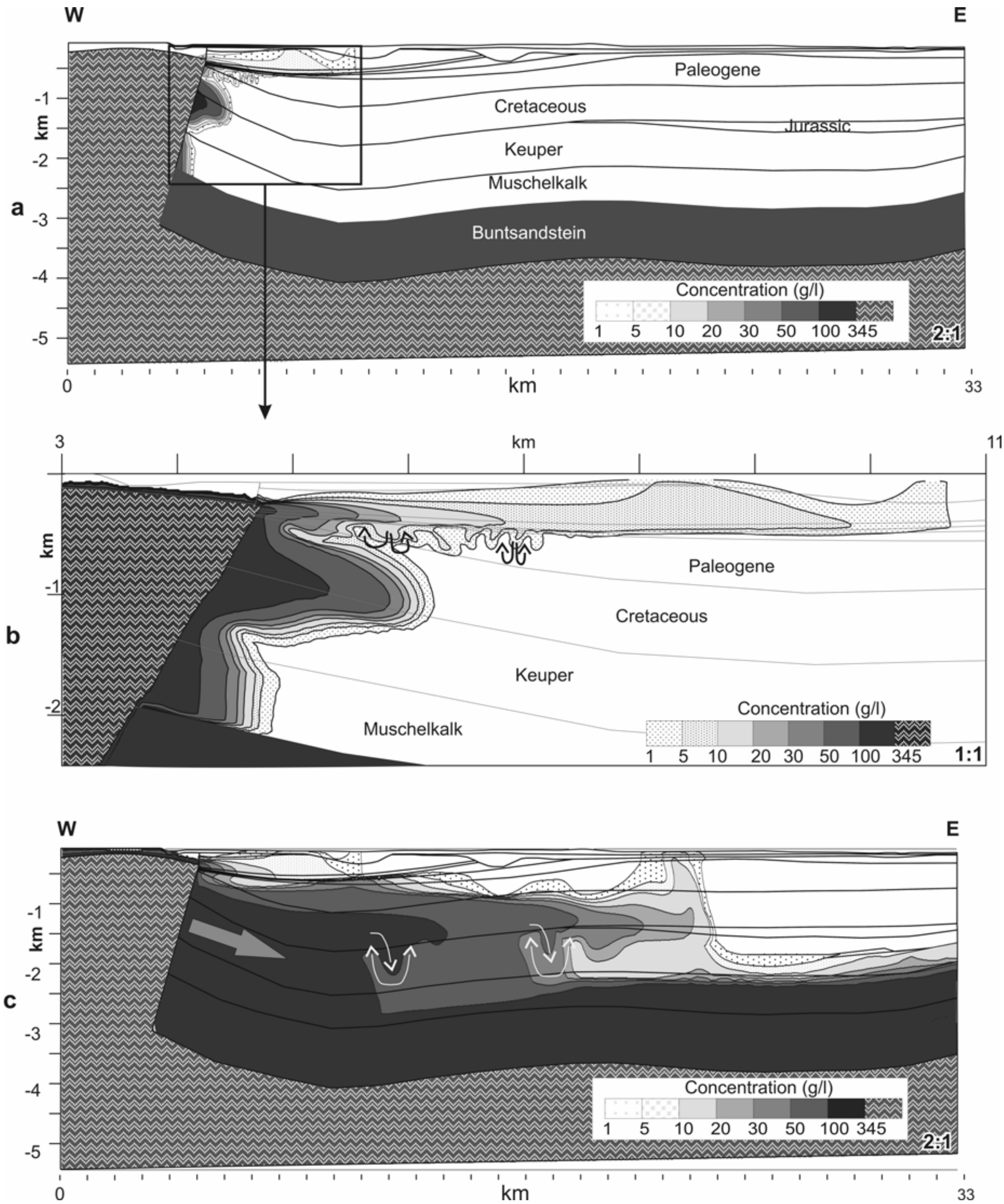

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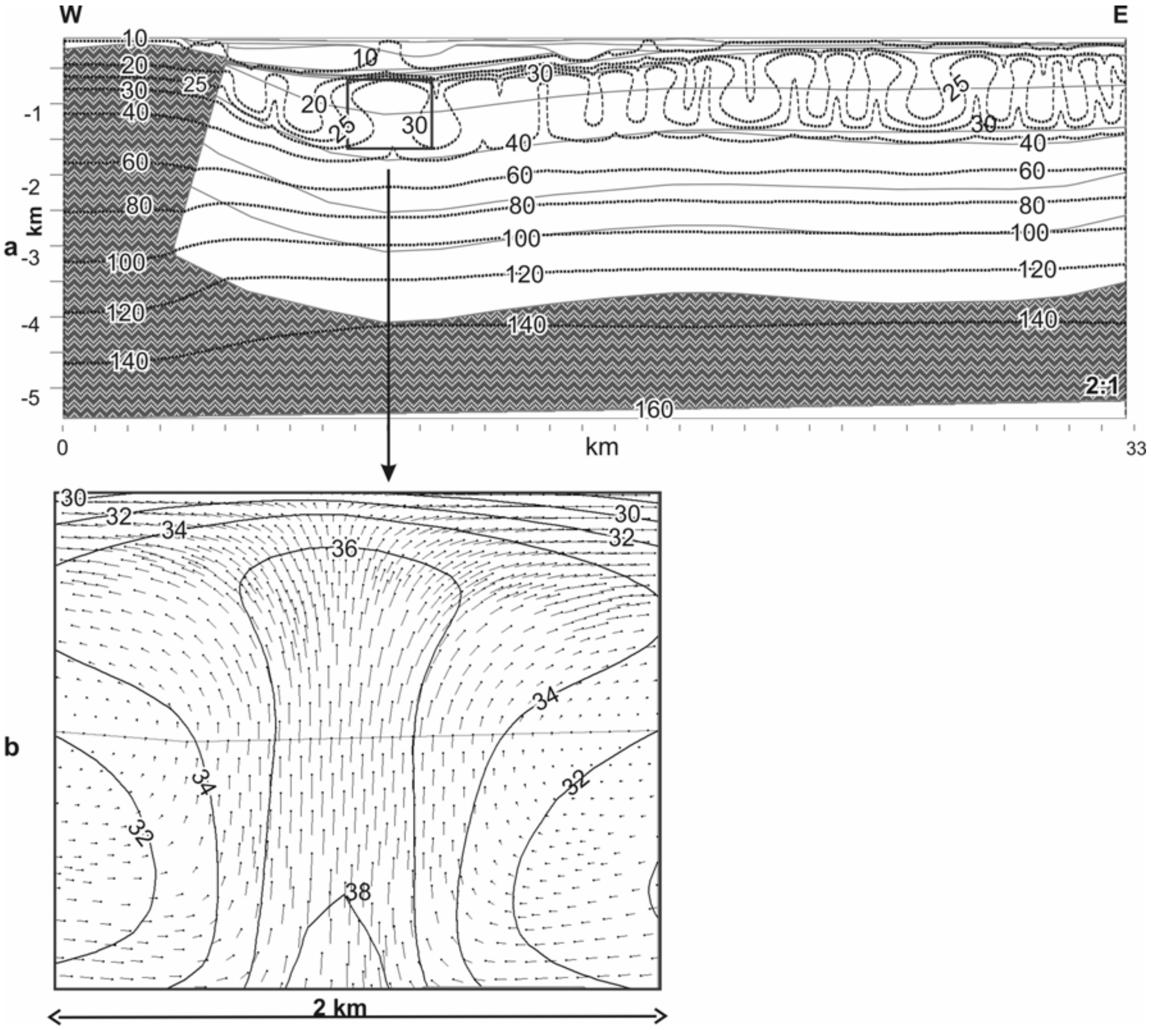

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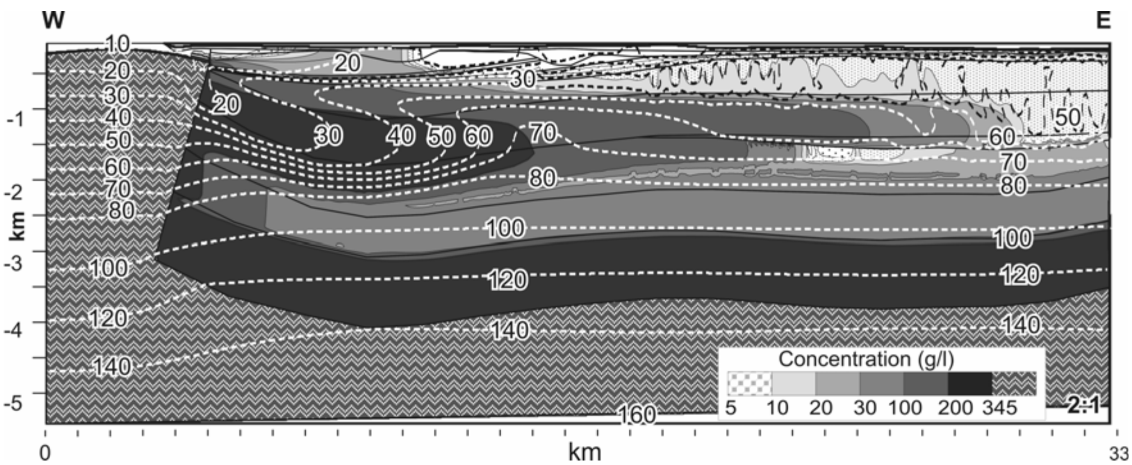

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