Interaction of Salt/Fresh-water Flow and Hydrochemical Zoning in an Aquifer of Pyrmont Area, SW Lower Saxony

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Abstract

The hydrodynamics and hydrochemistry of salt water and fresh water, including intermediate types, in solid rock aquifer systems in the area of Pyrmont are described on the basis of the latest research results (geoelectrics, isotop hydrology, soil air analysis). Theories on the source of the springs in this area are developed, which explain the different compositions of the springs and make it possible to protect them.

Bad Pyrmont is situated on a broad dome of Triassic rocks in the southern part of the Lower Saxony uplands. Inversion of the relief has caused the development of an erosion basin surrounded by a prominent ridge. Deep faults developed at the crest of the dome because this part of the structure was subjected to the strongest tectonic stress. Underground solution or subrosion of the Zechstein salts in the western part of the dome has caused the main salt bed to wedge out westwards along a N-S zone across the Pyrmont dome; this zone is reffered to as the "Salzhang" (salt slope). West of the "Salzhang", where subrosion has removed the salt bed that prevents gas rising from below, carbon dioxide of deep volcanic origin can now rise to the surface.

Extensive and deep-seated groundwater flow takes place within the entire Pyrmont dome and is illustrated by means of hydraulic sections. Groundwater flow is directed vertically downwards in the area of the surrounding ridge, centripetal horizontal flow predominates in the intermediate area, and the groundwater rises in the center of the basin to join the River Emmer, the main receiving stream.

The depth of the saltwater/freshwater interface is determined by the weight of the superimposed freshwater body. Hydrochemical sections show the shape and position of this interface and document a certain degree of hydrochemical zonation of the slightly mineralized fresh water. Genetic relationships between the two water types as well as within the hydrochemical zones of the freshwater body are described.

A knowledge of the hydrogeological relationships in the Bad Pyrmont aquifer systems permit wells withdrawing groundwater for different uses (medicinal, mineral, drinking and industrial water) to be sited relatively close together.

1. Introduction

Individual aspects of the geology and hydrogeology of the Bad Pyrmont area have been investigated over the past few decades, but during the last 20 years no comprehensive study has been carried out of the spring systems in the Pyrmont basin. A research project on the hydrogeology of the Bad Pyrmont area is being conducted by the University of Hannover using recently developed methods of investigation. The project is supported by the Lower Saxony Ministry for Science and Culture.

The aims of the project are to bring our knowledge of the geology of the Pyrmont anticline up to date, to investigate the hydrogeology of the Bad Pyrmont area with particular emphasis on the spring system, and to determine the source of the CO_2 in the spring water.

2. Methods used

Initially, an extensive search was carried out of the literature and unpublished records. This included all relevant data on springs, wells, gauges, and streams in the study area.

The update of the geology of the Pyrmont anticline was based on the results of recent drilling and the reinterpretation of older geophysical borehole logs. In the field, new exposures were examined and described. During the project, several boreholes were drilled and the data processed.

Geoelectric soundings were conducted in the study area together with the Joint Geoscientific Research Division of the State Geological Surveys of the FRG (part of the Lower Saxony Geological Survey). This was to obtain information about the shallow geology and the distribution of groundwater salinization of natural origin.
Soil air analyses were carried out to identify CO_2 anomalies, which possibly indicate the presence of fault zones.

A large number of hydrochemical analyses were carried out, which permitted several groundwater types to be recognised. In addition, an extensive hydrological survey based on isotope analyses carried out by the Lower Saxony Geological Survey provided valuable results.

The source and mode of formation of the groundwater were determined on the basis of interpretation and reconstruction of the hydrochemical regime and determination of the hydraulic relationships. These were derived in particular from measurements of the groundwater level and spring levels.

3. Results

The geological, hydrogeological and hydrochemical studies enabled a model of the origin of the Pyrmont springs to be developed. This in turn allowed the causes for the variable compositions of the springs to be postulated and provided data on which to base a scheme for protecting the springs. Before explaining the above model, it is necessary to give a short summary of the geology of the Pyrmont area.

3.1 Geology

Bad Pyrmont lies in the central part of a broad anticline of Triassic rocks about 35 km long and 12 km wide (Fig. 1).

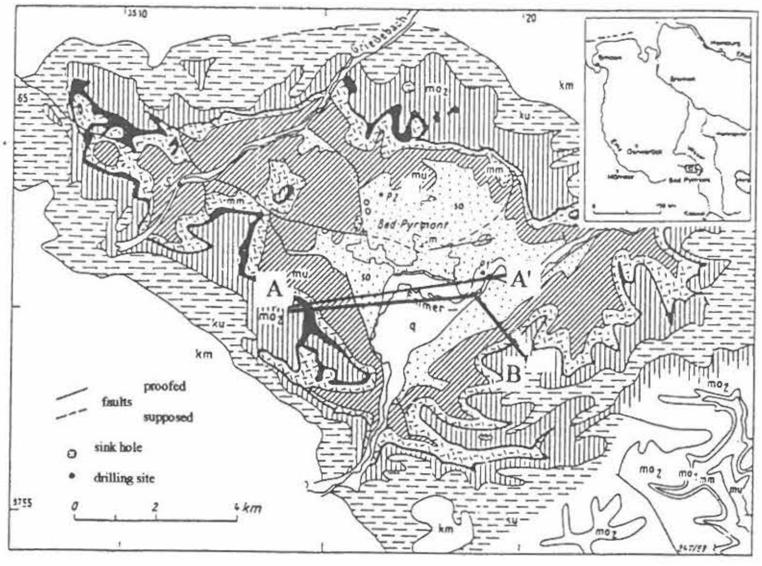

Fig. 1 Geological map of the Pyrmont anticline showing the location of sections A-B and A-A'

The Pyrmont basin, the broadened part of the Emmer valley in which Bad Pyrmont lies, is situated not quite at the centre of the crest of the Pyrmont anticline, which has an area of about 420 km^2. During formation of the anticline, the hinge region, which is the area of maximum strain, underwent deep fracturing. These fractures permitted groundwater to penetrate to considerable depths where the Zechstein salt was extensively dissolved. Underground solution or subrosion of the Zechstein salt in the western part of the Pyrmont anticline has caused the main salt bed to wedge out westwards from the so-called "Salzhang" (salt slope), a N—S zone running across the Pyrmont basin. . Since salt rock is impermeable to gas, its removal on the western side of the anticline permits CO_2 of volcanic derivation to rise towards the surface. Information on the nature of the, Rotliegendes, Zechstein and Buntsandstein in the core of the Pyrmont anticline has mostly been obtained from three boreholes, i.e. Pyrmont 1 (P1), Pyrmont 2 (P2), and Sonneborn (S). Figure 3 shows a geological section through the area.

The Pyrmont 2 borehole, which was drilled to tap thermal groundwater, penetrated the Zechstein and met a sequence of mostly strongly jointed, coarse sandstones, which probably belong to the Rotliegendes Cornberg Sandstone.

The Zechstein has a total thickness of about 600 m where it has not been affected by subrosion. It consists of several cycles, each comprising the sequence claystone, dolomite, anhydrite, and salt.

The lower part of the Buntsandstein consists of about 300 m of Lower Buntsandstein, alternating claystones and sandstones. The oldest rock outcropping in the built-up area of Pyrmont is the Middle Buntsandstein. It is 340—360 m thick and consists of an alternating sequence of sandstone and claystone. In the upper part there is a thick-bedded sandstone sequence (Bausandstein = building sandstone). The transitional beds to the Upper Buntsandstein (the Röt) comprise predominantly homogeneous, fine-grained, finely laminated shales with rare intercalations of thin, quartz-rich layers and sandstone beds. In the basal part of this sequence, there are intercalations of salt, anhydrite, limestone, and dolomite (Röt salt bed). The thickness of the Upper Buntsandstein where no underground solution (subrosion) of the evaporites has occurred is 170—200 m; the basal part mentioned above is about 50 m thick. About 140 m of Upper Buntsandstein was drilled in Pyrmont.

The higher and steeper parts of the hills surrounding Bad Pyrmont are made up of Muschelkalk, about 180—200 m thick and mostly limestones. Outside the hills, these rocks are overlain by the Keuper strata.. The bedrock in and around the Pyrmont area is overlain by superficial deposits of Quaternary age

In the spring of 1995, d.c. electric sounding was carried out by the Joint Geoscientific Research of the German Geological Surveys (GGA) around Bad Pyrmont in order to obtain more accurate information about the thickness and composition of the Quaternary deposits as well as the distribution and movement of geogenic salinization of the groundwater. The results are shown in the form of five vertical sections (BROST & ROGGE 1995) and are summarised shortly below. Fig. 3 shows section A—A′ as an example.

The Quaternary deposits consist predominantly of detritus, i.e. gravel and sand (100—130 Ωm), which is overlain by flood-plain loam (40—80 Ωm) in the valleys. The Quaternary deposits have a relatively uniform thickness of up to 30 m beneath the Emmer River lowlands. Two geoelectric stations where the base of the Quaternary is particularly deep represent exceptions, probably due to the presence of a concealed sinkhole above Röt or Zechstein salt. Alternatively, this could be due to a narrow Quaternary erosion channel.

The differences in specific resistivity and the different depths of various stratigraphic horizons on adjacent geoelectric sounding curves enable the locations and directions of several faults to be confirmed or corrected.

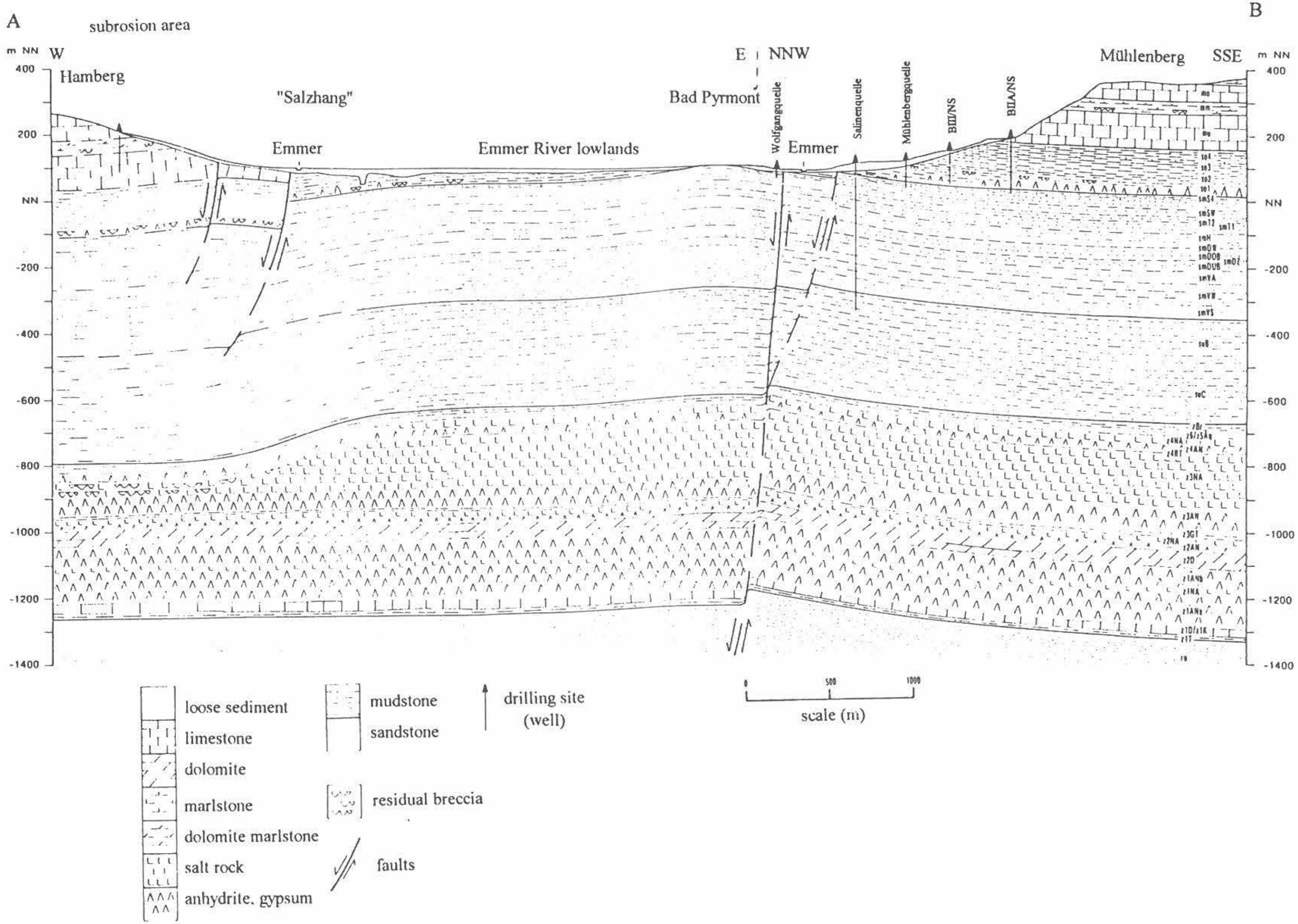

Fig.2 Geological cross section A—B

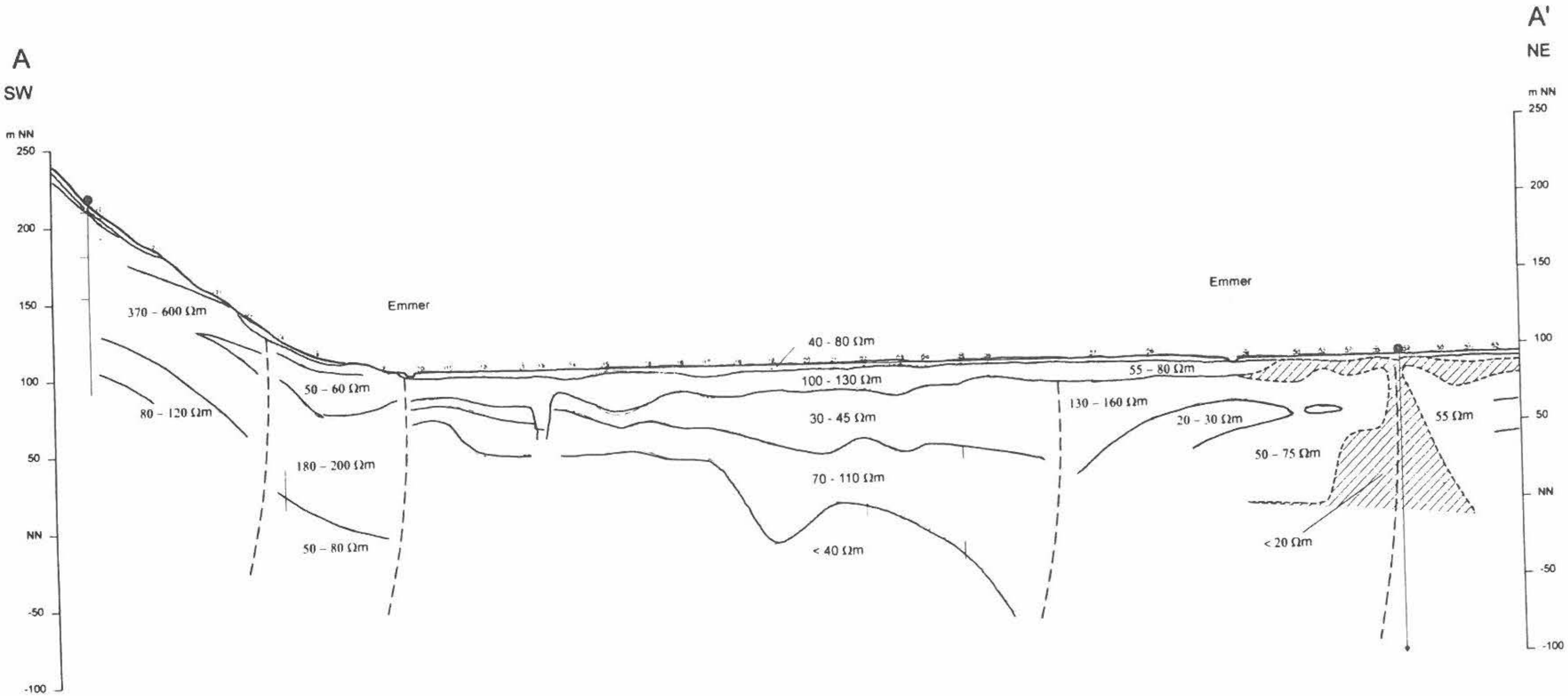

Fig.3. Geoelectric measurements at Bad Pyrmont, Section A—A′

The saline groundwater was demonstrated to be rising in the vicinity of a fault zone; moreover the distribution of salinized groundwater in the Quaternary deposits was plotted accurately. Evidence was found of salinized groundwater near the surface in the Emmer lowlands between Oesdorf and Löwensen within the urban area of Bad Pyrmont, as well as south of the swimming bath.

The geoelectric soundings show that clayey rocks belonging to the Buntsandstein are widely distributed below much of the Emmer lowlands. Below the Quaternary deposits, the low resistivities of 30—45 Ωm suggest claystone or siltstone of Röt age (Upper Buntsandstein) and clay transitional beds (Middle Buntsandstein). Below this the specific resistivity is 70—110 Ωm; this represents sandstones of the Middle Buntsandstein. This information is significant from the point of view of the protection these rocks afford to deeper groundwater (mineral-water aquifer).

The geoelectric soundings confirmed that the rocks above the Zechstein salt in the subrosion area NW of a line between Holzhausen and Lügde are considerably fractured, and also confirmed the position of the "Salzhang" described by HERMANN (1969b).

The positions and trends of several faults in the urban area (town park, "Dünsthöhle"), where it was not possible to carry out geoelectric soundings, were confirmed and corrected with the help of measurements of the CO_2 content of soil air.

The results of the geological studies are displayed in several geological sections. They form the basis of a model of the groundwater flow system supplying the Bad Pyrmont springs.

3.2 Hydrogeology

3.2.1 Hydrogeological structure

The hydrogeological structure is best explained using the semi-schematic cross section A—B (Fig. 4).

Over much of the area of the Pyrmont anticline, the Zechstein salt, which occurs at a depth of about 700 m below sea level, forms an almost impermeable lower boundary for the regional groundwater flow system. The area in which subrosion has taken place, i.e. west of the "Salzhang", represents an exception. In this area the salt bed, an effective barrier to rising water and gas, has been leached away, leaving a path free for rising CO_2 of volcanic origin. It is probable that the rise of CO_2 encourages the rise of groundwater, possibly confined groundwater, from the Rotliegendes into the overlying strata.

The lowest part of the aquifer system comprises the alternating claystones of the Lower Buntsandstein, which are present throughout the Pyrmont anticline. This part of the aquifer system contains slowly flowing or stationary groundwater.

The main aquifer of the mineral-water multiaquifer is made up of the sandstone-rich parts of the Middle Buntsandstein. They are separated by relatively impermeable clay-rich interbeds and alternating claystone-sandstone sequences. The Middle Buntsandstein is about 350 m thick and is also present throughout the study area. The uppermost beds, the Solling Buntsandstein crop out in parts of the Pyrmont basin.

On the limbs of the anticline the Upper Buntsandstein (Röt), a sequence about 100 m thick with a low to very low permeability, forms an aquiclude, which separates the mineral-water aquifer (Middle and Lower Buntsandstein) from the freshwater aquifer (Muschelkalk and Keuper). The permeability of the Röt is much enhanced in fault and fracture zones. The leached zones in the lower part of the Röt contain mineralised water and have a good permeability.

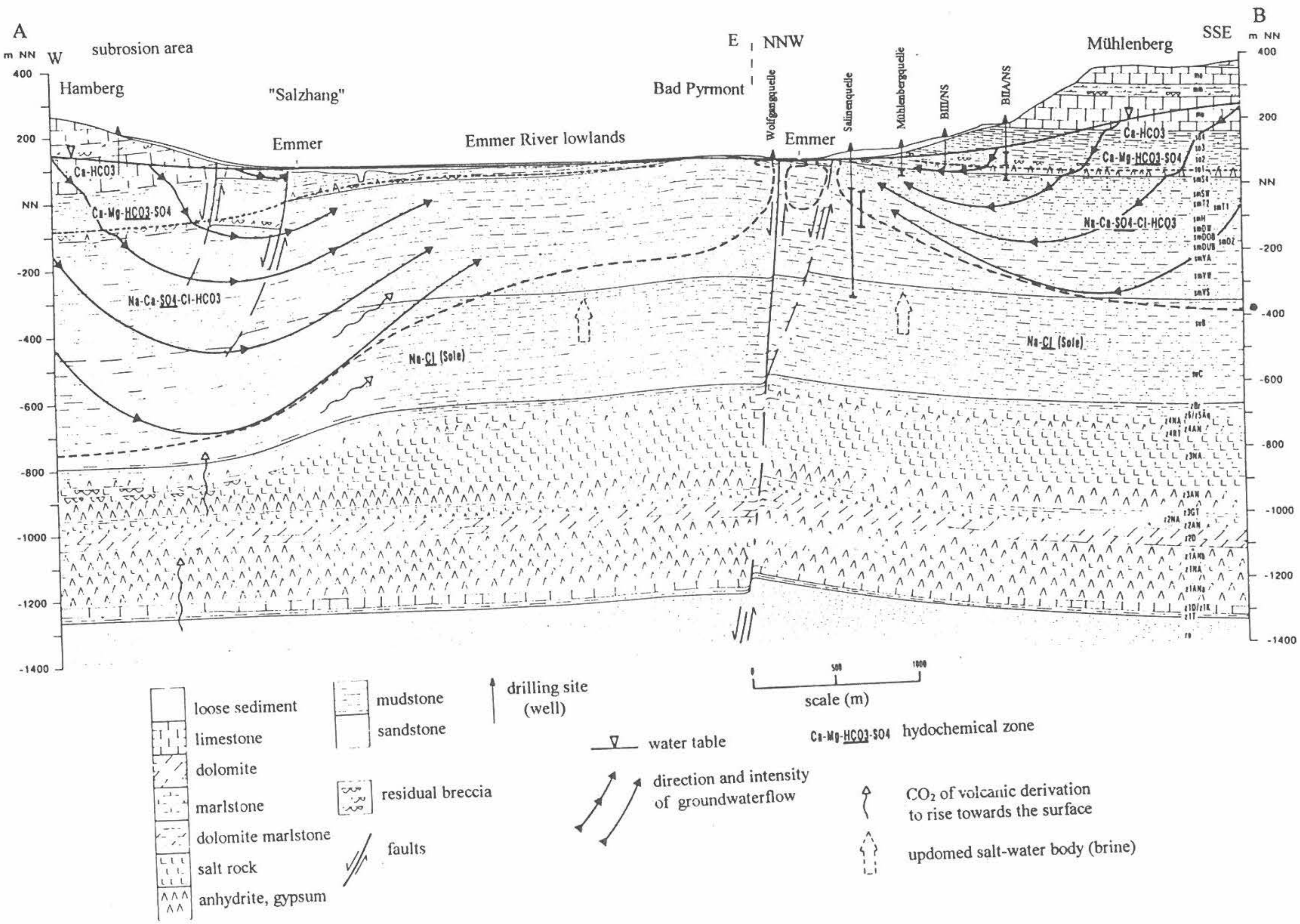

Fig. 4: Hydrogeological section A - B (semischematic)

The Lower and Middle Muschelkalk on the limbs of the anticline are important aquifers; they are separated by low permeability Middle Muschelkalk marls into two distinct aquifer levels.

The Keuper rocks have a predominantly low permeability. They are confined to the plateau in the SE part of the anticline core, and the outer parts of the limbs.

West of a line through Holzhausen and Lügde, subrosion has caused much deformation and fracturing of the strata. It must be assumed that the permeability is therefore considerably higher than in the other areas, in which the strata is almost undisturbed. The faults represent zones of particularly effective hydraulic conductivity.

3.2.2 Groundwater flow system

A model of the groundwater flow system in the Pyrmont pericline has been constructed on the basis of hydraulic data (groundwater levels and spring elevations) and the results of geological and hydrochemical studies. This provides considerably more insight into the hydrogeology of the area than previous descriptions (HERRMANN 1969a, SCHERLER & HAHN 1992). The hydrogeological situation of the Pyrmont springs must be assumed, in analogy to current hydraulic models, to have an extensive and deep-reaching groundwater flow system (Fig. 4) that extends over the whole Pyrmont pericline and can be subdivided into:

- elevated groundwater recharge areas (hills surrounding the area)
- connecting intermediate zones,
- low lying discharge areas (Pyrmont basin, Emmer lowlands)

This system can be divided on the basis of lithological, hydraulic and hydrochemical factors into 3 subsystems:

a) shallow near-surface groundwater flow system in the Quaternary deposits (pore groundwater, freshwater aquifer),
b) deeper groundwater flow system in bedrock (mostly fracture aquifer, freshwater and mineral-water levels),
c) more or less static, deep-groundwater flow system (saline water, brine).

In addition, the hydrogeological system of the Pyrmont anticline contains a large number of sometimes very local and often interconnected aquifers and aquitards, as well as fault zones.

In the hills surrounding the basin (groundwater recharge area), the downward vertical component of flow predominates, in the intermediate area the flow is horizontal and in the Emmer lowlands the groundwater rises (discharge area).

3.2.3 Interplay between rising saline water and near-surface groundwater

The flow velocity of groundwater decreases rapidly with increasing depth. This is partly due to the decrease in permeability of the rocks at depth and to the fact that the deeper groundwater is mineralized and has a higher density than fresh water.

The near-surface groundwater flow system in the Quaternary deposits together with the deeper groundwater flow system in bedrock form a major hydraulic unit. In contrast, the almost static flow system (saline water) plays a different hydraulic role. The fresh and mineralised groundwater is separated from the saline groundwater by a barrier. Diffusion and hydromechanical dispersion through this barrier, and vertical oscillations of the saline groundwater have led to the formation of a mixed zone, whose thickness is unknown, in which water and ion exchange between the two flow systems takes place. The regional flow system of the saline water is not yet known. One can postulate that it is towards the Weser River, being the nearest large receiving stream. The depth of the contact between the freshwater and mineral-water/ saline water depends on the weight of the overlying fresh and mineral-water body. This is highest beneath the peripheral hills. In the Emmer lowlands, where the pressure from the overlying groundwater is reduced by the groundwater discharging into the receiving stream (the Emmer River), the saline-water body is domed up.

As the results of the geoelectric soundings in the Emmer lowlands (BROST & ROGGE 1995) have shown, saline water migrates along hydraulically effective fault zones into the vicinity of the surface and spreads out laterally in the permeable Quaternary gravels. The rise of saline water is possibly facilitated by a gas-lift effect. This is caused by pressure due to the release of CO_2. The CO_2 of volcanic origin rises in the area in which the Zechstein has undergone subrosion into higher levels and there becomes mixed with saline groundwater and the circulating mineral water. This probably leads to mixing of the saline water and mineral water, but to an unknown extent.

The saline groundwater emerging in the Pyrmont medicinal springs is derived from the Zechstein salt, which is present about 800 - 1100 m deep beneath the springs. The main source is assumed to be the "Salzhang", which is still being leached. In the subrosion area west of the "Salzhang", mineralized groundwater descends to considerable depth as a result of the amount of fracturing which the rocks there have undergone. There, it dissolves the Zechstein salt, sometimes producing brine and sometimes mixed groundwater. It is possible that the leaching process is chemically facilitated by CO_2, which rises in this area from Paleozoic rocks beneath.

As the diagram of the groundwater flow system shows, all the Bad Pyrmont medicinal springs yield a mixture of slightly mineralized groundwater that flows down towards the valley and more mineralized groundwater rising from much deeper levels. Differences in the total dissolved solids (mineralization) are a result of differences in the hydraulic conductivity of the fault zones and different spring heights or abstraction depths. The proportion of rising deep groundwater tends to decrease with height of spring or abstraction level. In other words, the total mineralization decreases upwards.

3.3 Hydrochemistry

The Bad Pyrmont medicinal springs fall into three groups of different kinds of mineralization:

A. mineral-poor and mineral-rich hydrogen carbonate water

Ca-Mg- $\underline{HCO_3}^-$-$SO_4^{=}$ acidulous type

B. mineral-rich

Na-Ca-$SO_4^{=}$ Cl-HCO_3^- type

C. very highly mineralized chloride water

Na-$\underline{Cl-}$ $SO_4^{=}$ and Na-Cl (brine) acidulous types

In spite of the fact that the transition from strongly circulating, little mineralized groundwater to deeper, almost static, highly mineralized groundwater may be very variable and irregular (DVWK 1987, 1983), it is still possible to subdivide the Bad Pyrmont area into hydrochemical zones. This can be shown to be genetically related to the groundwater flow system. The composition of the water from the individual zones is dealt with shortly below (see above Fig. 5).

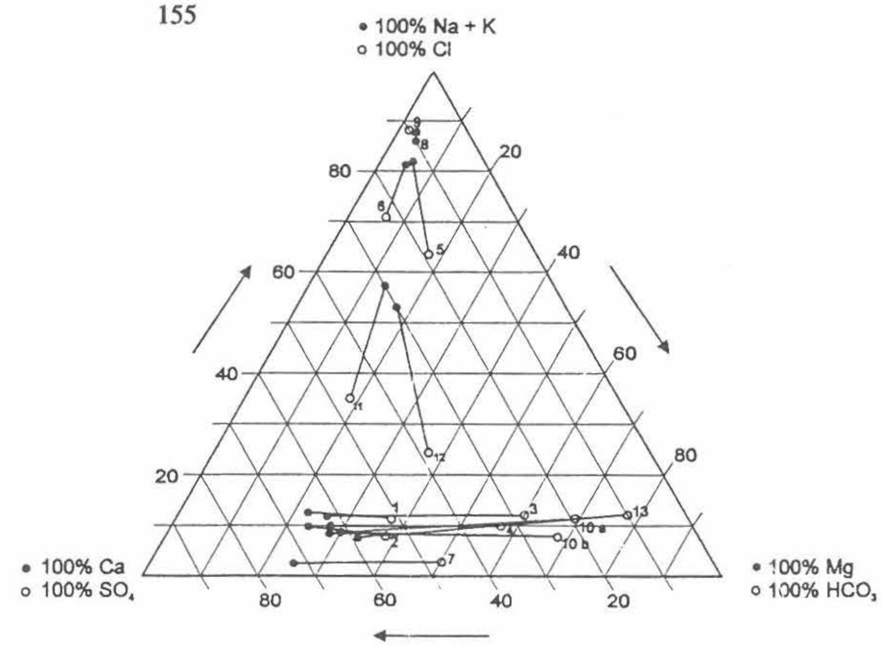

Fig. 5: Anion-cation diagram for the Bad Pyrmont medicinal springs.

Groundwater recharge takes place in the hills surrounding Bad Pyrmont. The groundwater then mostly flows over a long period of time down to a depth of about 1000 m. There is some interreaction between the aquifer and various kinds of groundwater. The composition of the water is the result of various physicochemical processes such as:

- solution and precipitation,
- adsorption, desorption and ion exchange,
- diffusion,
- oxidation and reduction,
- mixing.

Below the hills surrounding Bad Pyrmont, a hydrochemical zonation can be demonstrated on the basis of the different types of groundwater in the springs and wells of that area (BII/NS, Mühlenberg spring, and saline spring). Hydrogen carbonate water is underlain by sulphate water and this in turn by chloride water.

Infiltrating water from precipitation (groundwater recharge) takes up CO_2 while it passes through the soil. The action of the CO_2 on the carbonate in the Muschelkalk (mu) causes Ca and HCO_3^- ions to go into solution in the near-surface groundwater. This slightly mineralized hydrogen carbonate water circulates fairly rapidly and is usually oxygen-bearing. Solution of gypsum and anhydrite in the Middle Muschelkalk (mm) and Upper lower Röt (so4 to so2) gives the groundwater an elevated $SO_4^=$ content.

During its downward passage into deeper parts of the aquifer system, the groundwater dissolves considerable amounts of gypsum and anhydrite from the relict salt beds in the Röt. $SO_4^=$ now assumes a dominant role in the composition of the groundwater. Free oxygen disappears as a result of the oxidation of sulphide and decomposition of organic matter. The HCO_3^- is considerably reduced on account of the strong increase in total mineralisation.

The high NaCl concentration in more or less static groundwater at deep levels is probably due to solution (subrosion) of Zechstein salt, particularly at the Zechstein "Salzhang".

Diffusion and hydrochemical dispersion at the interface between the almost static, highly mineralized, chloride water (brine) and the clearly circulating sulphate water causes mixing in these two types of groundwater. The resulting mixed water flows towards the discharge area, the Bad Pyrmont basin, and as it rises, it mixes with slightly mineralized water of various compositions.

The Pyrmont basin is discharge area not only for rising shallow fresh groundwater and relatively mineralized groundwater, but also for rising saline groundwater.

The hydraulic conditions at depth beneath the Pyrmont basin suggest that the saline groundwater body is dome shaped. The saline groundwater migrates along fault zones right up into the rocks near the surface and spreads out laterally in the highly permeable Quaternary gravels. The pathways along which the saline groundwater rises towards the surface are closely bound to the fault zones (BROST & ROGGE 1995): The chloride water (Na-Cl-$SO_4^{=}$ acidulous type) flowing from the Wolfgang spring originates from these zones of rising saline water.

During the rise of saline groundwater and relatively highly concentrated mineral water, they become mixed with various different types of slightly mineralized water which flow valleywards. This causes a general dilution of the saline groundwater and a modification of the composition in the direction of that of the shallower groundwater.

The CO_2-bearing saline water of the Salinen springs I and II originates from the updomed saline groundwater body; it has also undergone mixing - in fact it is the first result of a series of mixings.

In the higher parts of the aquifer system, the rising saline groundwater mixes with intermediate sulphate water and downward-flowing, slightly mineralized hydrogen carbonate water. At the abstraction depth of the Mühlenberg spring, mixing (in this case dilution) has produced a mineral water belonging to the Na-Ca-$SO_4^{=}$-Cl-HCO_3^{-} type.

As it rises further, the proportion of chloride water decreases in favour of the hydrogen carbonate water with which it is mixed. This produces a mineral water belonging to the Ca-Mg-HCO_3^{-}-$SO_4^{=}$ acidulous type, which is characteristic of many of the springsand wells in the town area of Bad Pyrmont.

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