

Hydrogeology of Deep Groundwaters in Austria

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9 Figures and 4 Tables

Abstract

Deep groundwaters, which are defined as groundwaters having underground residence times greater than 50 years as indicated by the absence of anthropogenic tritium can preferentially be found in major sedimentary basins. Exploration for thermal waters mainly takes place in the Upper Austrian Molasse Basin and in the Styrian Basin. In the Upper Austrian Molasse Basin the main thermal aquifer is situated in Upper Jurassic carbonate rocks. There, waters are low-mineralized (1-1.5 g/kg TDS) and are of meteoric origin, as proved by isotope investigations, and differ greatly in their hydrochemical characteristics from those in the juxtaposed Upper Cretaceous and Tertiary sediments. In the Malm aquifer a regionally developed flow system has been established. Recharge mainly takes place at the northeastern basin edges, whereas the area of discharge was identified west of Linz. The deep groundwaters exfiltrate to the Danube. In the central and southern parts of the Molasse Basin formation waters with no exchange with the surface occur (mainly in the Hall and Puchkirchen Formation). They are often linked with oil and gas deposits.

In the Styrian Basin deep groundwater chemistry is governed by the occurrence of post-volcanic carbon dioxide. Only in regions where this influence is absent are deep groundwaters having mineralizations comparable to those of the mobile Malm waters in the Upper Austrian Molasse Basin. Highly mineralized Na-HCO₃-Cl-waters with high carbon dioxide partial pressures were tapped preferentially in the deeper parts of the Fürstenfeld sub-basin. Degassing of carbon dioxide at the well head and in the upper part of the casing leads to carbonate precipitation and is a certain limit for the utilization of these waters. The waters are of non-meteoric origin and lie on a mixing line, which is similar to that in the Upper Austrian Molasse Basin. In contrast to the Upper Austrian Molasse Basin, the isotope enriched end points of the mixing line have not yet been identified. In the upper parts of the Tertiary basin filling generally less mineralized waters can be found. Single tests in the Blumau well 3 have shown that in a vertical section of more than 300 m in sediments of Sarmatian age deep groundwaters are nearly identical with respect to their hydrochemical and isotopical characteristics.

Introduction

Austria is subdivided into different geological units, which differ greatly in their hydrogeological properties (ZÖTL and GOLDBRUNNER, 1993). Approximately two thirds of the Republic's area are covered by the Eastern Alps which reach a maximum altitude of nearly 4,000 m (Großglockner mountain). The northern part of Austria at the border to the Czech Republic is occupied by the southern Bohemian massif. This non-Alpine unit exposes a deeply eroded remnant of the Central-European branch of the Variscan orogenic system. It is built up essentially by medium- to high- grade metamorphic rocks of Precambrian to Paleozoic age and extensive granite plutons of Variscan age. The Bohemian Massif dips southwards and eastwards below the Molasse Basin (Molasse Zone of Upper and Lower Austria) and extends farther beneath the Alps. Drinking water supplies rely mostly on wells in alluvial sediments of valley floors. Some wells produce from weathered basement rocks, mostly granites. The production rate of wells is generally low (<5 l/s).

The Molasse Zone comprises a sequence of detrital sediments of Late Eocene to Middle Miocene age unconformably overlying the foreland basement. The marine to brack-

ish-water deposits obtain a thickness of up to 4,000 m near the tectonic border of the Alps. The pre-Tertiary basin floor consists of Upper Cretaceous and Upper Jurassic sediments. The latter comprise an up to 750 m succession of carbonate rocks which have undergone karstification during the Lower Cretaceous when the carbonate rocks were formed the land surface. Thermal waters of temperatures of more than 100 °C can be found at depths of locally more than 2,000 meters.

In the Helvetic and the Flysch Zones, which build up the hilly northern foreland of the Alps, springs with low discharge (<5 l/s) prevail due to the geological conditions (mostly low permeable sandstones and marls).

The Penninic Zone appears in Austria in a number of tectonic windows below the higher Austro-Alpine units. The whole complex comprises a crystalline basement of mostly Variscan granites and migmatites and Paleozoic and Mesozoic metasedimentary series. Because of the predominance of crystalline rocks and the altitude, the springs are mostly of low discharge and therefore are not of interest for thermal use.

The Northern Calcareous Alps occupy the highest tectonic position in the Austro-Alpine nappe complex. Due to

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Tertiary and Quaternary karstification, flow systems of high yield and low residence time (some weeks to months) have been established. The low residence time and systems of lacking protection against pollution causes problems for the use of these waters for drinking purposes. Due to the elevation in the Alps, the temperature of the emerging springs does not exceed 10 °C, and in systems with low storage capacities fluctuations of the output temperature occur with low temperatures in the cold season. The water supplies of Vienna (pipeline systems from the Alps some 100 km), Salzburg and Innsbruck rely on karstic water from the Northern Calcareous Alps. Karst systems can also be found in the limestone rocks of the South Alpine unit.

Within the Alps, shallow groundwater from Quaternary sediments in the valley floors of the main rivers is used for drinking water purposes and industrial use. The sediments consist of high permeable sands and gravels of fluvio-glacial and glacial origin. The thickness of these sediments can reach more than 100 metres and the permeabilities are in the order of 10^{-2} to 10^{-3} m/s. Groundwater in these sediments is unconfined and lies shallow. The temperatures of the shallow groundwater are influenced by the air temperature; therefore, they generally do not exceed 10 °C. Yield of single wells is as high as 100 l/s and more.

In the Central Zone of the Eastern Alps igneous and metamorphic rocks prevail. Therefore, springs with generally low yield (<5 l/s) are the basis for the drinking water supply.

The lowlands of the eastern and southeastern part of Austria are occupied by Neogene sediments. In the Styrian Basin (federal countries of Styria and Burgenland), which is part of the Pannonian Basin, sediments of Karpatian to Upper Miocene age with a maximum thickness of 2,900 m have been deposited. Beside the Molasse Basin of Upper Austria, the Styrian Basin is the second important geothermal region in Austria. Thermal aquifers can be found in the pre-Neogene basement, where carbonate rocks of the Graz Paleozoic exhibit favourable permeabilities. Thermal waters with a temperature of up to 140 °C can be expected. The main use of the waters is for spas, which are of great economic importance. Drinking water supplies are from wells in the Neogene sediments at a depth of up to 300 metres. More than 1,500 private wells have been encountered, but there are also public water supplies. Due to the enhanced heat flow at the border of the Pannonian Basin (up to 100 mW/m²), the drinking water supplies are also of some interest for thermal use by heat pumps.

The Vienna Basin is a fault-bounded graben or a pull-apart basin respectively, which is situated in the transition area between the Alps and the Carpathians. The longitudinal axis is some 200 km, the maximum width reaches 60 km. The pre-Neogene basement is formed by four Alpine tectonic units (Rhenodanubian Flysch Zone, Northern Calcareous Alps, Greywacke Zone and Central-Alpine Zone). The Neogene basin filling comprises sediments of Karpatian to Dacian age. The main subsidence of the basin started during the Lower Badenian. The maximum thickness of the Neogene is considered to be 5,500 m in the Schwechat depression. Aquifers for geothermal use lie in the pre-Tertiary basin floor, whereas in the unit of the Calcareous Alps thermal waters with temperatures > 100 °C can be expected (see: drilling Aspern 1; RONNER, 1974). In the Neogene

basin filling aquifer systems for exploiting geothermal energy do exist (for example Aderklaa Conglomerate), but conflicts with the interests of the hydrocarbon industry have to be taken into account.

Deep groundwaters, which are defined as groundwaters with underground residence time greater than 50 years, as indicated by the absence of anthropogenic tritium can predominantly be found in the major sedimentary basins. Frequently deep groundwaters show mineralizations > 1g/l (as TDS) and can therefore be designated as healing waters according to Austrian legal regulations.

Exploration and exploitation of aquifers bearing thermal waters takes place mainly in the Upper Austrian Molasse Basin and in the Styrian Basin. From 1976 to 1999, a total of 28 wells for thermal water with a cumulative length of some 50 km was drilled in these areas.

Upper Austrian Molasse Basin

Figure 1 shows a map of the Upper Austrian Molasse Basin with locations of wells and flow direction in the Malm aquifer in the pre-Tertiary basin floor; this is the most important aquifer for thermal waters in the basin. Flow in the regional system in the Malm aquifer can be seen in the hydrogeological profile in Fig. 2. The Late Jurassic carbonate series originate from platform sediments. In the northern and northwestern part of the basin they directly overlie the crystalline basement of the Bohemian Massif. They are frequently dolomitized and show secondary porosities. The maximum thickness is stated to be 750 m (NACHTMANN & WAGNER, 1986). Aquifer properties are given by fracturing linked with fault zones. These faults belong to two generations. Pre-Tertiary faults, cutting the Jurassic and Cretaceous sediments, are generally NNW-SSE striking, whereas the Oligocene faults show more or less a E-W trend. The vertical throws attain 1,000 m for the pre-Tertiary and 300 m for the Tertiary faults. The Tertiary faults were created by extension and got their present shape by a north-directed compression, which started in the Early Miocene (NACHTMANN, 1995). The difference in permeabilities between the fault zones and those parts not or minimally affected by tectonic movements is more than two orders of magnitude according to pumping tests and model calculations. In some drillings, indications of karstification predominantly at the top of the sediments exist. The vertical section of favourable permeabilities in drillings generally does not exceed 150 m. Karstification processes took place during regressional phases in the Lower Cretaceous and prior to the transgression of the Upper Eocene. Hydrochemical conditions do not allow recent karstification in the deep parts of the aquifer.

Transmissivity values based on long term aquifer tests show a range between $2.8 \cdot 10^{-4}$ and $3 \cdot 10^{-2}$ m²/s, storage coefficients have been determined in the order of $2 \cdot 10^{-4}$ to $6 \cdot 10^{-5}$. Taking an average transmissivity of $3 \cdot 10^{-3}$ m²/s, the total flow for the some 40 km broad aquifer in the Upper Austrian Molasse Basin can be calculated to be 240 l/s for a gradient of $2 \cdot 10^{-3}$. In the southwest of the basin, the border of the aquifer is formed by the Central Ridge Zone where Upper Jurassic carbonates are not present due to pre-Eocene erosive processes. Hydrogeological research in the last two decades concentrated on the task to explain the

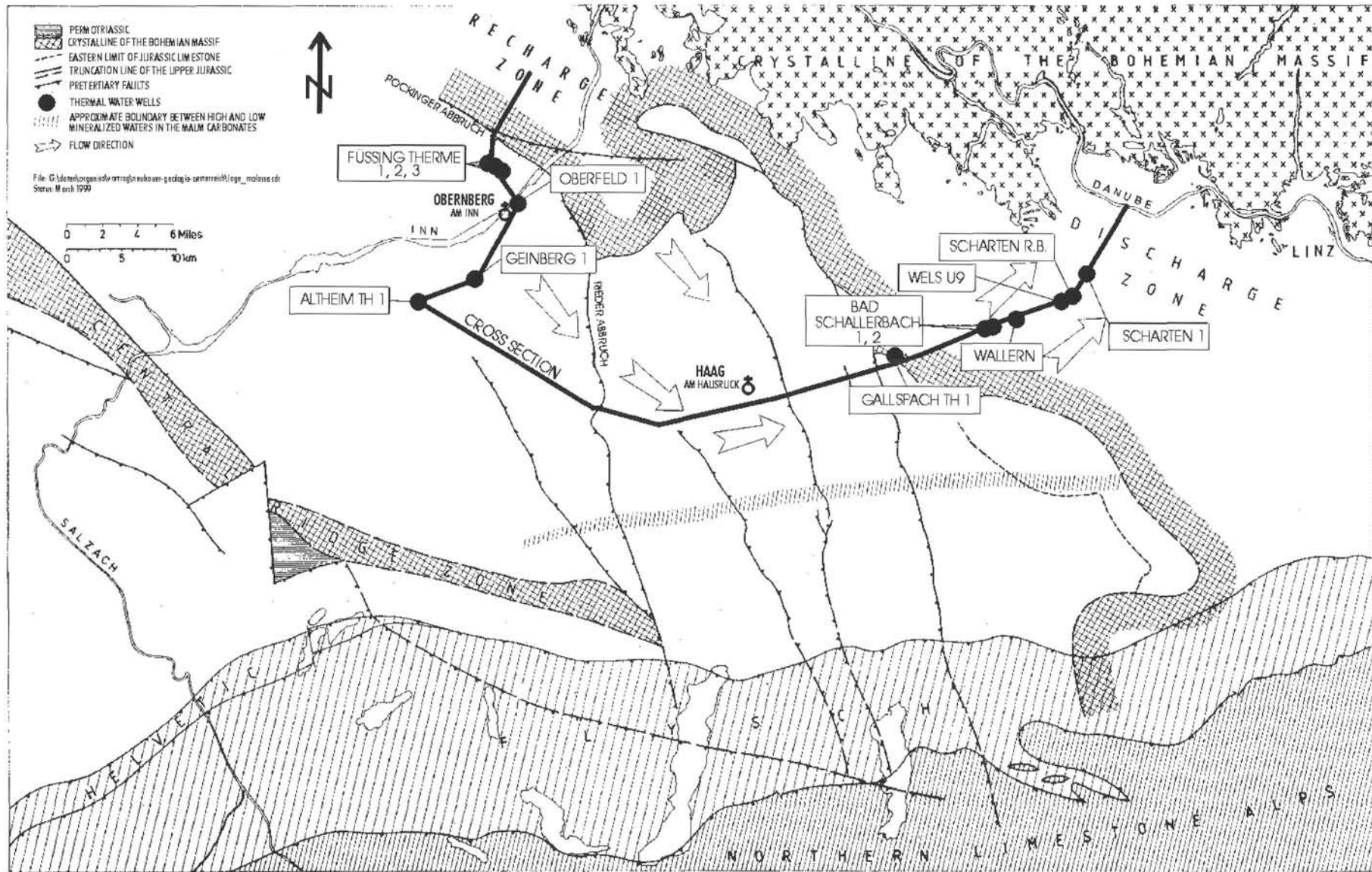


Fig. 1
Map of Upper Austrian Molasse Basin showing locations of wells and flow direction in the Malm aquifer.

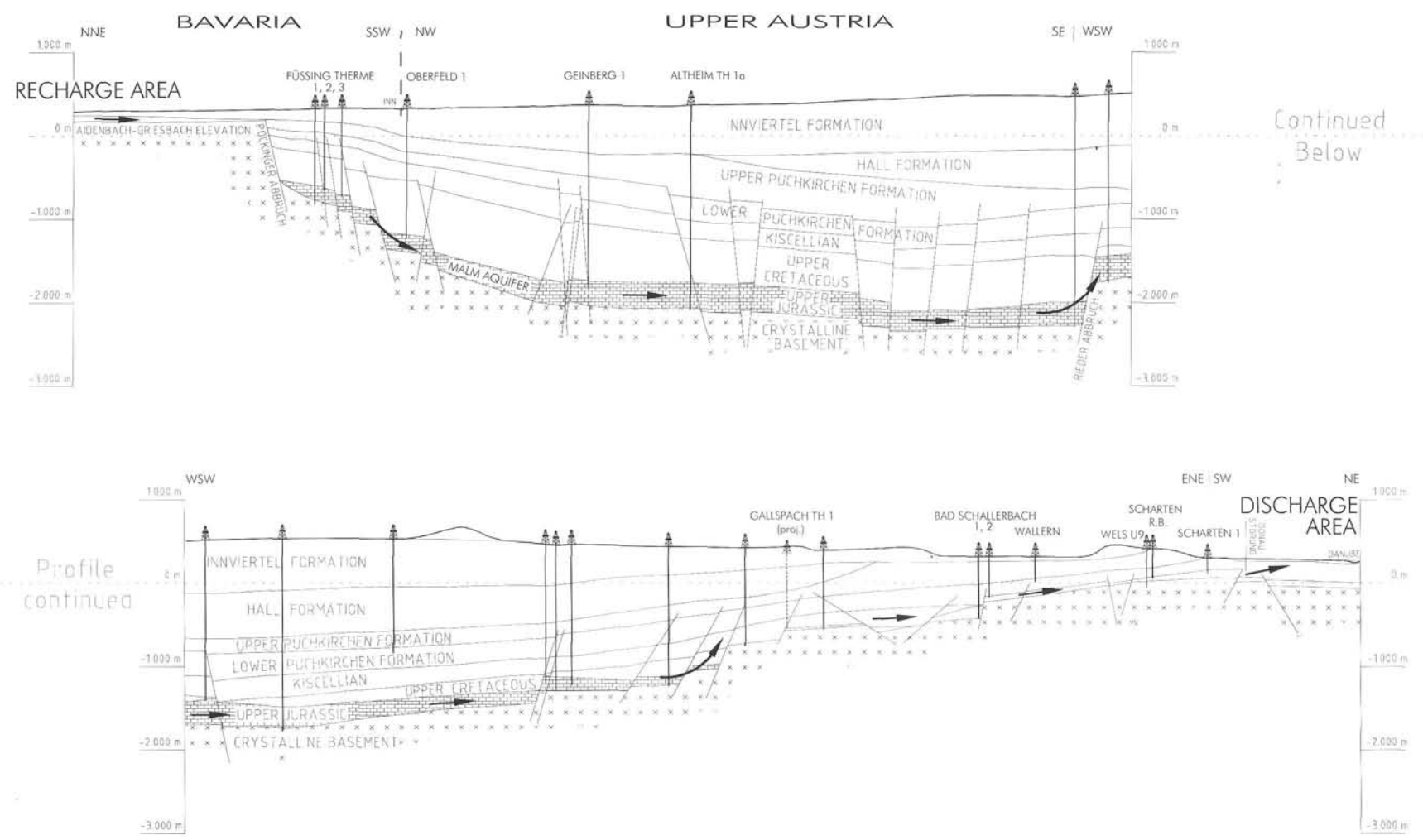


Fig. 2
 Cross-section from the recharge area in Lower Bavaria to the discharge area west of Linz (Upper Austria).

→ Flow Direction
 Only Thermal Water Wells are named

origin of the deep groundwaters in the Malm aquifer. They differ greatly in their hydrochemical characteristics from the waters in the Upper Cretaceous and Tertiary sediments as their total mineralization is only 2.2 g/l in average, compared to 15-17 g/l in the Tertiary formations (Fig. 3). The latter are of the Na-Cl-type, whereas the Malm waters are generally of the Na-HCO₃-Cl-type.

Figure 4 shows a plot of the isotopes deuterium and oxygen-18 for deep groundwaters from the Upper Austrian Molasse Basin. Some of the samples were taken from producing oil and gas wells and have been separated from the hydrocarbons (ANDREWS et al., 1987, GOLDBRUNNER, 1988). Deep groundwaters in the Innviertel Formation, which originate from aquifers with a maximum depth of 500 m are low in mineralization (TDS <0.5 g/l in general) and are used for drinking water purposes. They are of meteoric origin, as indicated by their position in relation to the meteoric water line (MWL). Recharge of regionally developed flow systems having an extent of some 50 km took place during the young Pleistocene, as indicated by the depletion in deuterium and oxygen-18; low recharge temperatures were determined by their noble gas contents (ANDREWS et al., 1985). In contrast to the waters from the Innviertel Formation, those from the Hall Formation, which are frequently connected with natural gas deposits of biogenic origin, are formation waters without exchange with meteoric waters. The highest enrichment especially related to oxygen-18 is typical for the waters from the Upper and Lower Puchkirchen Formation. This enrichment versus SMOW (Standard Mean Ocean Wa-

ter) is due to exchange processes of the fluid phase with rocks silicates. Samples from the Upper and Lower Puchkirchen Formation mainly originate from gas wells in the south of the Molasse Basin. The gas-bearing sequence is formed by conglomerates, sandstones and shales originating from mud streams and turbidity currents (MALZER, 1981). This facies is restricted to a relatively narrow strip running parallel to the northern edge of the Alps. In the Bad Hall imbrication structure for isotopically enriched formation waters can be found close to the surface. Waters from deeper stratigraphic horizons (Eocene and Upper Cretaceous) bearing oil and gas generally show less enriched waters, which is especially remarkable for the oil-bearing horizons in the Upper Eocene, the main target for oil exploration in the Upper Austrian Molasse Basin. Deep groundwaters from the Malm aquifer show the slightest deviation from the meteoric water line. Their position is on the lower end of a mixing line between non- or restricted mobile formation waters as represented by the waters in the Puchkirchen Formation and meteoric waters. The Malm waters are mobile and belong to a regional flow system according to the classification of TOTTH (1963). It has a rather long extension of some 150 km and stretches from the edge of the Franconian Alb (Lower Bavaria) to the area west of the Upper Austrian capital Linz. The lateral bounds of the systems are given in the north and northeast by the outcropping crystalline rocks of the Bavarian Forest in Bavaria and the Sauwald region in Upper Austria, respectively, and the Central Ridge Zone in the southwest. In hydrocarbon

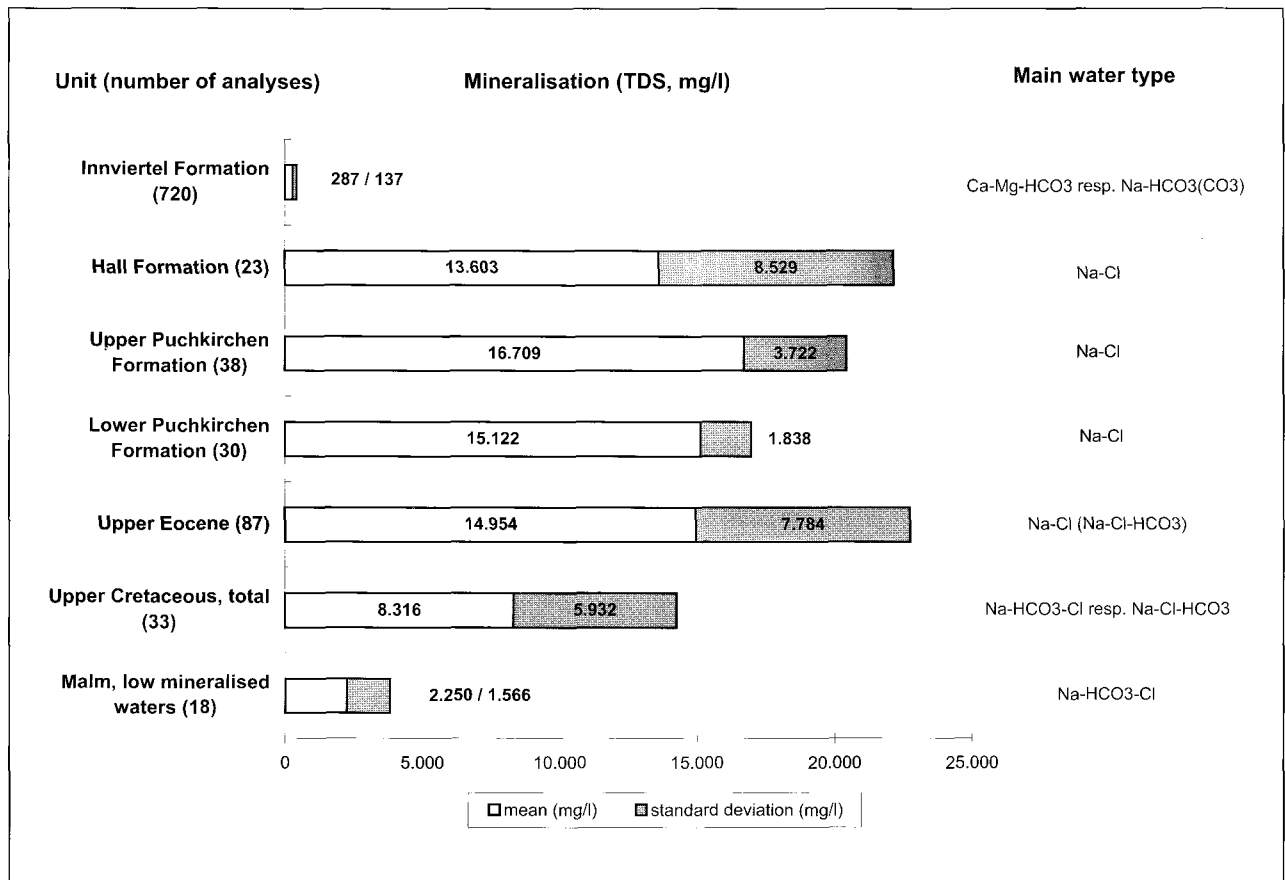


Fig. 3
Tertiary basin filling and pre-Tertiary basin floor: hydrochemical characterisation.

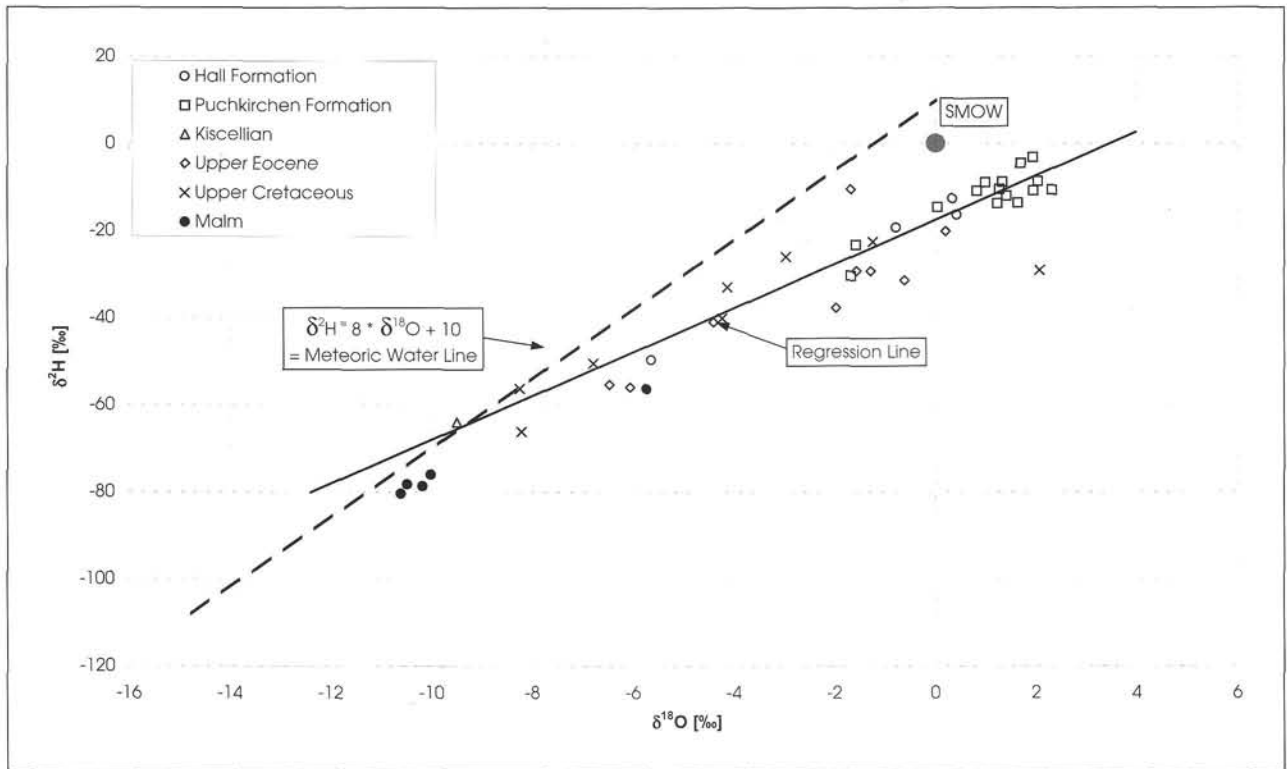


Fig. 4
Isotope plot (deuterium and oxygen-18) of deep groundwaters and formation waters of the Upper Austrian Molasse Basin.

wells reaching the Malm carbonates in the southern Molasse basin close to the overthrust of the Alps only high-mineralized waters have been found showing stagnant conditions in this area. Thus, the southern limit of the Malm aquifer, which is locally not well defined, is controlled by hydrodynamic processes.

The distribution of water types in the Tertiary and Mesozoic sediments and the results of the isotope investigations give clear evidence that the regeneration of the Malm aquifer cannot take place over the hydraulic roof according to the leaky aquifer principle, as claimed by German authors (e.g. ANDRES and FRISCH, 1981). Recharge of the regional system of the Malm was proven to take place mainly at the basin edges, where recharge areas can be located in the Bavarian Forest (HUBER, 1998) and the Sauwald region in Upper Austria (GOLDBRUNNER, 1984, 1988). The profile in Fig. 2, which represents a flow line from the recharge zone to the area of discharge, shows that recharge in the northeast takes place in crystalline rocks, as Malm carbonates are not present, due to erosive processes and truncation. Tertiary transgressional sands of Oligocene age, directly overlying the crystalline basement form the aquifer for the deep groundwaters in those areas. The Malm carbonates generally dip towards the south and are intersected by fault zones of various throws. According to the depth of the Malm carbonates temperatures in the aquifer range from 50 °C, such as the Füssing wells in Lower Bavaria, top of Malm at 1,000 m) to 106 °C in Upper Austria (Altheim and Geinberg wells, top of Malm at 2,100 m).

Towards the east the profile intersects a pre-Tertiary fault called the "Rieder Abbruch" with a throw of some 600 m. At this fault the carbonates lose their lateral contact, so that deep groundwater flow takes place mainly in the weathered

zone of the crystalline rocks. East of the fault zone the thickness of the Malm carbonates is reduced to 150 m and thins towards the east, where the erosive edge of the carbonates is reached. In some parts in this area, e.g. the Trattnach oil field, a hydraulic contact between the mobile waters in the Malm carbonates and oil bearing horizons in the overlying Cenomanian sands have been proved by pressure observations, hydrochemistry and isotope measurements.

In the area east of the limit of the Malm carbonates flow of the regional deep groundwaters takes place in Tertiary sandstones, which belong to transgressional series and become progressively younger in the northeastern and eastern directions (Upper Eocene, Kiscellian and Egerian). The main aquifer in this area is formed by the Linz Sand (Egerian, part of the Puchkirchen Formation), a light quartz sand with high permeabilities and porosities. Due to the structural situation the deep groundwaters ascend from deeper parts of the basin to shallower depths, causing a pronounced thermal and hydrochemical anomaly. Geothermal gradients caused by convection have been observed to be as high as 6.5 °C/100 m, compared to 4-5 °C/100 m in the deeper parts of the Molasse Basin in the Innviertel region. The deep groundwaters exfiltrate to the main receiving stream of the area, the Danube. In the shallow parts of the discharge zone mixing of regional and local flow systems occurs (SCHUBERT, 1996). The hydraulic function of the Danube is augmented by the fact that it cuts into the permeable Oligocene sediments. The discharge zone of the deep groundwaters is located at the intersection of two large strike-slip faults (SCHUBERT, 1996).

With regard to the possibility of exploiting geothermal energy, the Malm carbonates exhibit the best prerequisites

because of their depth, especially in the Innviertel region, where temperatures of 100 °C can be expected, and their demonstrably good local permeability.

Geothermal projects have been established in the villages of Altheim, Geinberg, Haag am Hausruck and Obernberg (for locations see Fig. 1). The biggest installation is in Altheim, where thermal water from the Malm aquifer is used for district heating, covering the heating demand of more than 500 households.

The intensive abstraction of thermal waters (artesian production in Altheim during winter season: 35 l/s) and the close neighbourhood of production wells has led to pressure drops and has caused bilateral problems between Bavaria and Austria. To stabilise the formation pressures reinjection wells have been launched in Austria. These projects were partly supported by the European Union in the THERMIE program.

One of these projects is in Geinberg (for location see Fig. 1). The small village is situated some 5 km from the Bavarian border. Geinberg was one of the first geothermal projects in Austria. Based on an abandoned hydrocarbon exploration well ("Geinberg 1"), hot water from the Malm aquifer has been used since early 1980 for geothermal purposes. In 1998, a spa and hotel resort was built, thus increasing the need for energy on the one hand and thermal water for bathing, cures and recreation on the other hand. The initial production rate of the well Geinberg 1 was reported as high as 22 l/s. In the early 1990's, the rate of free overflow started to diminish because of the regional pressure decrease leading to a flow rate of only 9-11 l/s.

In 1998, a second well (Geinberg Thermal 2) was drilled to complete a geothermal doublet. It was designed as a deviated well situated 24 m away from the existing well Geinberg 1. To prevent a hydraulic shortcut between abstraction and reinjection, the underground distance of the wells in the aquifer is some 1,600 m. Drilling of deviated wells, including horizontal and extended reach drilling, is a technology widely used in oil and gas exploration for years, but it has not been performed in water well business at that scale before this time. As a result, this technology was regarded as highly innovative for geothermal exploration and therefore, was supported by the European Union.

Drilling was performed using a rig with a hook load of 225 t. Use of top drive technology for the deviated section ensured fast and secure handling during drilling, piping and cementing. By using this modern oilfield technology, drilling operation (including piping and cementing) could be finished within 52 days. The bore reached a measured depth (MD) of 3,155 m, corresponding to a true vertical depth (TVD) of 2,225 m.

The first drilling section in the Quaternary (gravel in silty matrix) and the Innviertel Formation (shale, marl, sand and sandstone) and the top layer of the Upper Puchkirchen Formation (brown shales) was drilled with a bit diameter of 17½" (445 mm) to a depth of 600 m to set the conductor casing, which was cemented to the surface to protect the drinking water bearing horizons in the Innviertel Formation (Fig. 5).

In this section a deviation of only 1° of the drilling was proved by single shot measurements and wireline logging. Restricting the deviation was essential to avoid collision with the existing well Geinberg 1. The kick-off point for directional drilling was situated just below the casing shoe. For this operation a down-hole motor with a steerable sys-

tem was used. Deviation was directed north (azimuth 394.95°-4.4°), the inclination reached a maximum of 64° and the build-up rate was 2°/30 m at maximum. The drilling 12¼" (311 mm) penetrated the Upper Puchkirchen, Lower Puchkirchen and the Kiscellian sedimentary rocks. All these formations are pelitic in composition. The shale interval of the Kiscellian (thin alternating shales and fine sands) was regarded as critical with respect to the stability of the deviated borehole, so fast drilling operation and an instant setting of the 9½" intermediate casing at 1,755.4 m was essential for the success of the drilling operation. At a measured depth of 1,577 m a synthetic fault was passed in marls of Campanian age (Upper Cretaceous), which was indicated by slow penetration rates, by the occurrence of polished fault surfaces on cuttings and by the appearance of CO₂ in the mud gas survey. The same synthetic fault was passed by the Geinberg 1 drilling at a depth of 2,083 m in Lower Turonian calcareous marls. The development of fractures in this section led to total mud loss during drilling operation. This is indicative of hydraulic communication between the fractured parts in the Lower Turonian and the aquifer in the Malm, which had a vertical distance of 43 m in the well Geinberg 1.

The section to the top of the productive formation was drilled with a bit diameter of 8½" (216 mm) within 13 days to a measured depth of 2,880 m (1,124 drilled meters). It penetrated mainly pelitic Upper Cretaceous sediments. The casing was set in Cenomanian sandstones some 20 m (vertical depth) above the top of the Malm aquifer, thus avoiding possible mud losses, which could endanger the more than 1,100 m long and unstable open section in the Upper Cretaceous sediments.

The thermal reservoir was drilled with a bit diameter of 6½" (156 mm) to the total depth of 3,155 m MD (2,225 TVD). The top of the Malm was reached at 2,910 m MD (2,117 m TVD). The vertical depth of top Malm in Geinberg 2 differs insignificantly from Geinberg 1 (2,126 m). This is caused by an antithetic fault, which was passed by the deviated drilling at a MD of 2,658 m and which induced a greater thickness of the Coniac sediments. By keeping the mud weight smaller than 1.1 kg/dm³, heavy mud losses have been avoided in the carbonate aquifer, which has a slight underhydrostatic pressure. The geological profile of well Geinberg 2 is presented in Table 1.

In the 12¼", 8½" and 6½" sections mainly PDC (polycrystalline diamond compact) bits were used, which ensured high penetration rates (maximum 250 m/d). During deviated drilling azimuth and inclination were continuously recorded by MWD (Measuring While Drilling). Therefore, it was possible to correct the drilling if required. The landing point at top of the Malm carbonates was reached at the exact position that was essential, as the Austrian water law regulations restrict the allowance of use of groundwater to the land property at the surface. Geophysical borehole measurements in the deviated sections were performed during drilling operations (LWD = Logging While Drilling) as natural gamma ray. The measurements enabled lithostratigraphic correlation with the existing well Geinberg 1.

After cleaning the hole, a first hydraulic test was started, which showed a maximum production rate of some 18 l/s with air lift pumping. To increase the production, stimulation using a total volume of 60 m³ of hydrochloric acid (15% with 6% acetic acid and 1% citric acid) was carried out. The acid

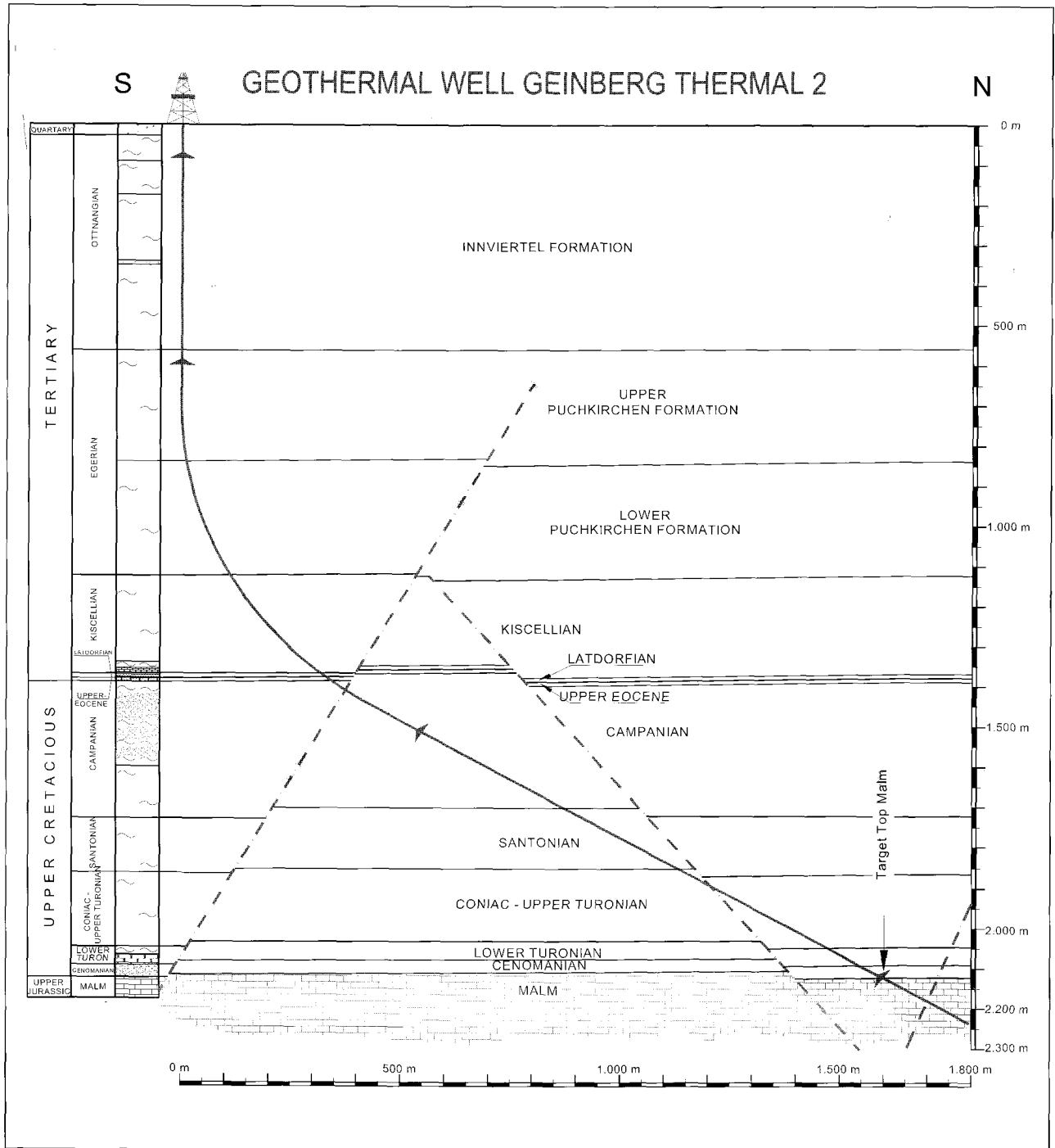


Fig. 5
Deviated well Geinberg Thermal 2, geological cross-section.

was pumped through a coiled tubing string, which allowed the movement of the string from end depth to the top of the open hole section in the Malm carbonates during stimulation. After stimulation the production rate with air lift pumping reached a maximum of some 50 l/s at an outflow temperature $>100^{\circ}\text{C}$. The production index (PI) was calculated to be 10 l/s per bar, which is in the same order of magnitude as for well Geinberg 1.

Reinjection tests were undertaken using well Geinberg Thermal 2 as production and Geinberg 1 as reinjection well. At a flow rate of 30 l/s, a maximum flowing pressure of 1.9

bar was encountered at well Geinberg 1, thus proving the suitability of the well for reinjection. At the same time, this result showed that the decrease in production rate of well Geinberg 1 since the early 1990's was due to the regional pressure decrease in the aquifer and was not caused by a well problem.

The same water type was found at well Geinberg Thermal 2 as at well 1 (sodium-bicarbonate-chloride water with a TDS of 1.2 g/l). This mineralization is indicative of the mobile deep groundwater type in the fractured and karstified Malm aquifer.

Table 1
Stratigraphy of well Geinberg Thermal 2.

| MD (Measured Depth) | TVD (True Vertical Depth) | Lithostratigraphy | Thickness MD |
|---------------------------|------------------------------------|---|-----------------|
| 34 m | 34 m | Terrace Gravels (Quaternary) – | 34 m |
| 558 m | 558 m | Innviertel Formation (Miocene) | 524 m |
| 835 m | 835 m | Upper Puchkirchen Formation (Oligocene) | 277 m |
| 1,113 m | 1,108 m | Lower Puchkirchen Formation (Oligocene) | 278 m |
| 1,485 m | 1,361 m | Kiscellian (Oligocene) | 372 m |
| 1,411 m | 1,321 m | Shale interval | 298 m |
| 1,454 m | 1,345 m | Banded marl | 43 m |
| 1,469 m | 1,353 m | Light marly limestone | 15 m |
| 1,485 m | 1,361 m | Latdorfian | 16 m |
| 1,502 m | 1,371 m | Upper Eocene | 17 m |
| 1,497 m | 1,369 m | Nullipora Limestone | 12 m |
| 1,502 m | 1,371 m | Sandstone | 5 m |
| 2,910 m | 2,117 m | Upper Cretaceous | 1,408 m |
| 2,100 m | 1,704 m | Eary Campanian | 598 m |
| 2,353 m | 1,845 m | Santonian | 253 m |
| 2,748 m | 2,048 m | Coniac – Upper Turonian | 395 m |
| 2,835 m | 2,087 m | Lower Turonian | 87 m |
| 2,910 m | 2,120 m | Cenomanian | 75 m |
| ET* 3,155 m | 2,225 m | Upper Jurassic – Malmian (dolomite) | 245 m |

* end depth

Free overflow of the well was enhanced by modifying the well head design and lowering the position of the outflow to some 20 l/s and the outflow temperature in the order of 100 °C. Regular thermal water production for exploiting geothermal energy started on the 22nd of December 1998. The geothermal cascade involves several steps: industrial processes in a dairy, district heating in the village of Geinberg, the thermal resort and spa, direct use of water in the spa and heating of a greenhouse as a last step. This results in a temperature interval of 70 °C, which corresponds to a thermal output of approximately 5.8 MW. The reinjection temperature reaches a minimum of 30 °C thus allowing reinjection without additional pumping because of the higher density of the fluid at that temperature. On the other hand, the low density of the thermal water at 100 °C enables free overflow of the thermal water in well Thermal 2.

Styrian Basin

The Styrian Basin is the second important area for exploration and exploitation of thermal energy in Austria (for location see Fig. 6). In this region thermal waters are mainly used for spas and recreation centres, which are of great economic importance. Figure 7 shows a geological profile, which crosses the Fürstenfeld sub-basin from north to south. The surroundings of the basin, which outcrop some 15 km north of the well Waltersdorf 1 are represented by Austro-Alpine basement rocks. In some parts of the basin rocks of the Paleozoic of Graz, which belong to a higher nappe, overlie the crystalline basement. The upper part of the Paleozoic is formed by dolomites of Devonian age. These dolomites were found in the hydrocarbon well of Waltersdorf 1 at a depth ca. 1,100 m, having a thickness of 150 m. Due to intense tectonic deformation, the dolomites are highly fractured and therefore, exhibit good aquifer properties. Pumping tests produced low mineralized thermal water of 60 °C, which related to water type and mineralization (TDS 1.3 g/l; Na-HCO₃-Cl-type) can be compared to the mobile deep groundwaters in the Malm aquifer of Upper

Austria. According to the stable isotopes deuterium and oxygen-18, the origin of the deep groundwater of Waltersdorf is entirely meteoric. Evaluation of borehole measurements (electric logs and measurement of spontaneous potential) showed that the entire section of the Tertiary basin filling, comprising clastic sediments of Badenian to Pannonian age, and the Paleozoic basin floor have been flushed by meteoric waters, making the area unsuitable for the discovery of hydrocarbons. This hydrogeological situation is explained by regeneration of the different aquifers from the northern basin border. After the erection of a spa, a second well (Waltersdorf 2) was drilled some 1,600 m from well 1 in early 1990, which generally showed the same geological and hydrogeological results.

The geological profile is further based on the drilling Blumau 1/1a, which is 4.6 km away from Waltersdorf 1. This hydrocarbon well encountered Tertiary sediments with the same stratigraphic extent, but a greater thickness than in Waltersdorf 1. It came directly into Paleozoic phyllites at a depth of 1,600 m, which form the lower unit of the Paleozoic of Graz in the Styrian Basin. After cementing the borehole up to 1,000 m, the drilling was deviated towards SE to reach the deeper part of the Fürstenfeld sub-basin (Blumau 1a). The borehole runs approximately parallel to a WSW-ENE trending growth fault. This is indicated by the high thickness (approximately 1,000 m) of breccias and conglomerates of Karpatian age consisting of Paleozoic carbonates and crystalline rocks which were eroded in the hinterland and de-

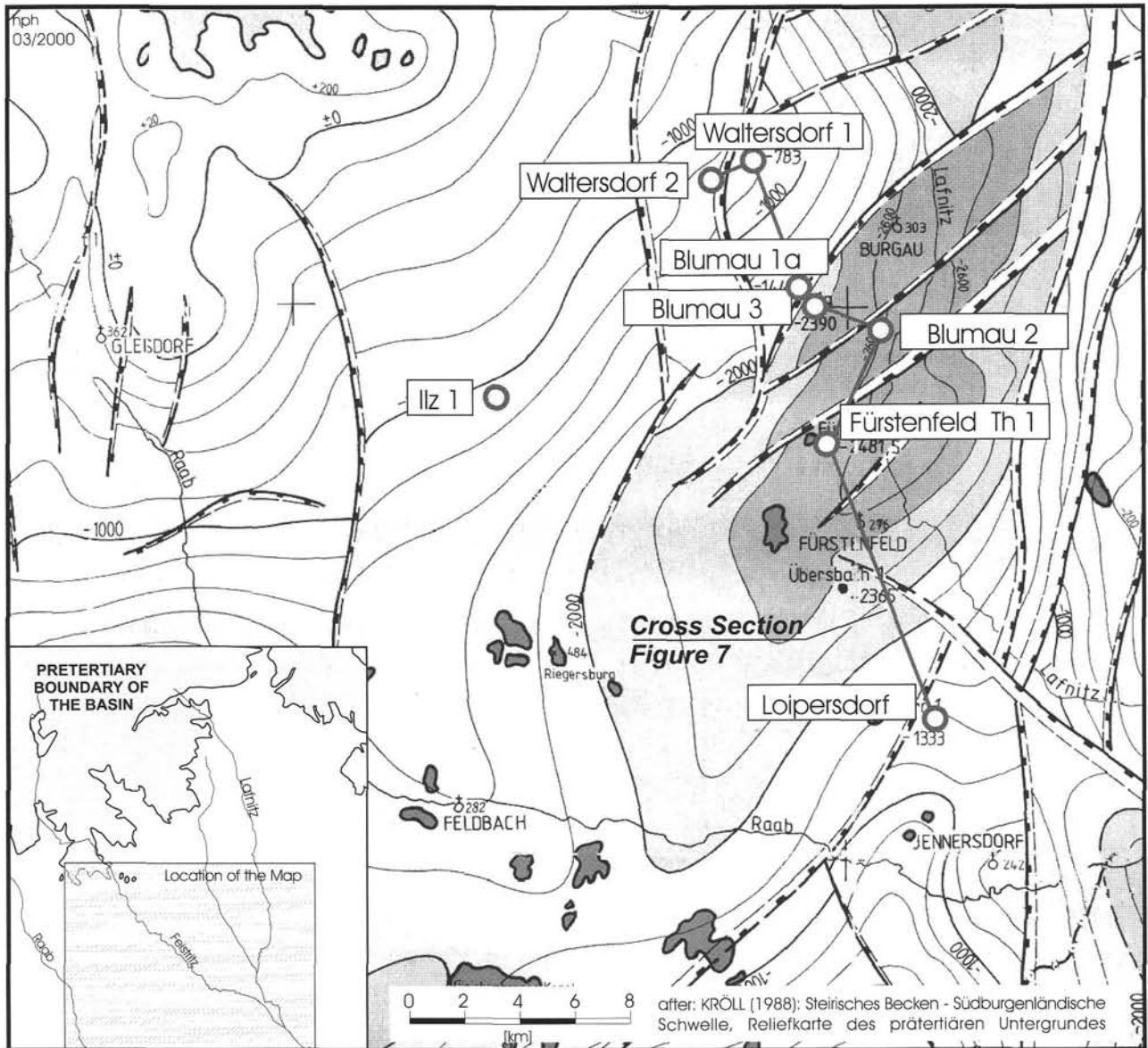


Fig. 6
Map of Styrian Basin showing locations of wells.

posited by rivers. The top of the Paleozoic dolomites was found at a depth of 2,600 m. The dolomites were intensely fractured. This led to total mud loss, which forced the drilling operations to end at a measured depth of 3,100 m without reaching the Austro-Alpine crystalline basement.

The deep groundwater of Blumau 1a differs greatly from Waltersdorf 1, as it is of the Na-Cl-HCO₃-type with a total mineralization of 17.5 g/l. The outflow temperature is 100 °C. Presence of CO₂ gas (gas/water ratio 20:1 at well head) results in high contents of bicarbonate (more than 4.5 g/l). The high chloride content (ca. 5 g/l), compared to 180 mg/l in Waltersdorf 1, and the isotopic results (see Fig. 8) show that different aquifer systems have been tapped by the two wells. This was also proved by pressure observations in the two wells showing the absence of a hydraulic connection. Therefore, the Karpatian breccias and conglomerates which are mud supported can be regarded as tight.

In 1995, a second well (Blumau 2) was drilled for the installation of a geothermal doublet for the geothermal energy supply of a newly built thermal resort and spa. Using structural maps based on seismic surveys, the borehole was situated at a SW-NE trending antithetic fault. Due to the structural position of the drilling, the top of the dolomites was reached at a depth of 2,363 m, the fault zone was met at 2,368 m. This was indicated by total mud loss during drilling and evidence of widening of the borehole diameter in this section. The borehole has a total depth of 2,843 m and did not reach Paleozoic phyllites and/or rocks of the Austro-Alpine crystalline basement, thus showing the great thickness of the carbonate sequence. The production rate (free overflow) reached 60 l/s at an outflow temperature of 102 °C. After acid stimulation the free overflow increased to 80 l/s and more.

Figure 9 shows the results of production measurements, which were performed at a rate of free overflow of approx.

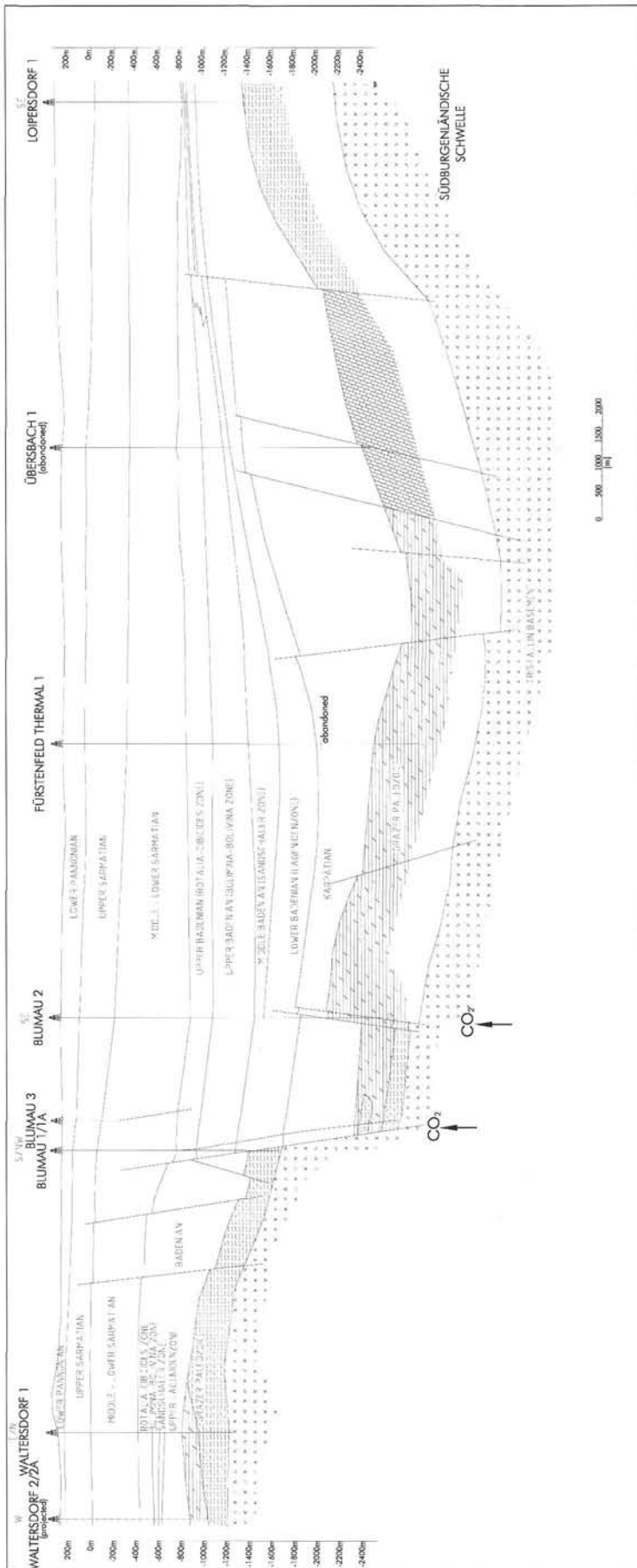


Fig. 7 Geological profile of the Fürstenfeld sub-basin within the Styrian Basin, from wells Waltersdorf 1 to Loipersdorf 1 (based on Kröll et al., 1988).

60 l/s. The density of the fluid was in the order of 1,01 g/cm³ in the 7" liner, where flow velocities were in the order of 3 m/s at the flow rate of 60 l/s. Entering the 9 5/8" casing degassing processes took place leading to a decrease in density to 0.98 g/cm³, while flow velocity reduced to 1.5 m/s. At 560 m a massive degassing processes led to a consequent decrease in a final density of 0.63 g/cm³ at 25 m. The degassing processes resulted in precipitation of carbonates from the surface down to 300 m.

On the other hand, the degassing led to a consequent increase of the flowing pressure, which is expressed in Fig. 9 as the differential pressure to the hydrostatic pressure at the definite level. The values in the 7" casing corresponded to the pressure drawdown in dependence on the flow rate and the transmissivity of the formation. In the 9 5/8" section the difference to the hydrostatic pressure diminished and rose to values greater than the hydrostatic at 250 m caused by intensive degassing of CO₂. This effect, known as the gas lift effect, was responsible for the free outflow at wellhead, where the flowing pressure reached 5 to 6 bars. Due to the equilibration with the atmospheric CO₂, precipitation of carbonates at surface took place to a great extent. This was due to the small solubility for CaCO₃, in particular at a temperature of 100 °C. The values for dissolved calcium in the water sampled under *in-situ* conditions at a depth of 1,520 m compare well to those at surface after equilibration with atmospheric CO₂, which shows a deficit in the order of 100 mg/l. The amount of precipitated CaCO₃ can be calculated for a flow rate of 60 l/s to be as high as 1,300 kg/d. The carbonate precipitation led to a complete block of the 10" outflow pipe during outflow tests. Samples of the precipitate were analysed (Tab. 2).

The low values for MgCO₃ are due to the slow kinetics of formation of dolomite. The high quantity of strontianite is remarkable. The values can be compared to the hydrochemical analysis of the water (Tab. 3).

The difference in total dissolved solids between Blumau 1a and Blumau 2, which is in the order of 6 g/l, cannot be explained at the moment. This is also true for the isotope results (D, ¹⁸O), which are nearly identical (Fig. 8). The geochemical differences are in contrast to the fact that a pressure connection between the two wells has been proved by hydraulic tests.

Pumping tests with submersible pump showed that a flowing pressure of 25 bars is required to prevent precipitation of car-

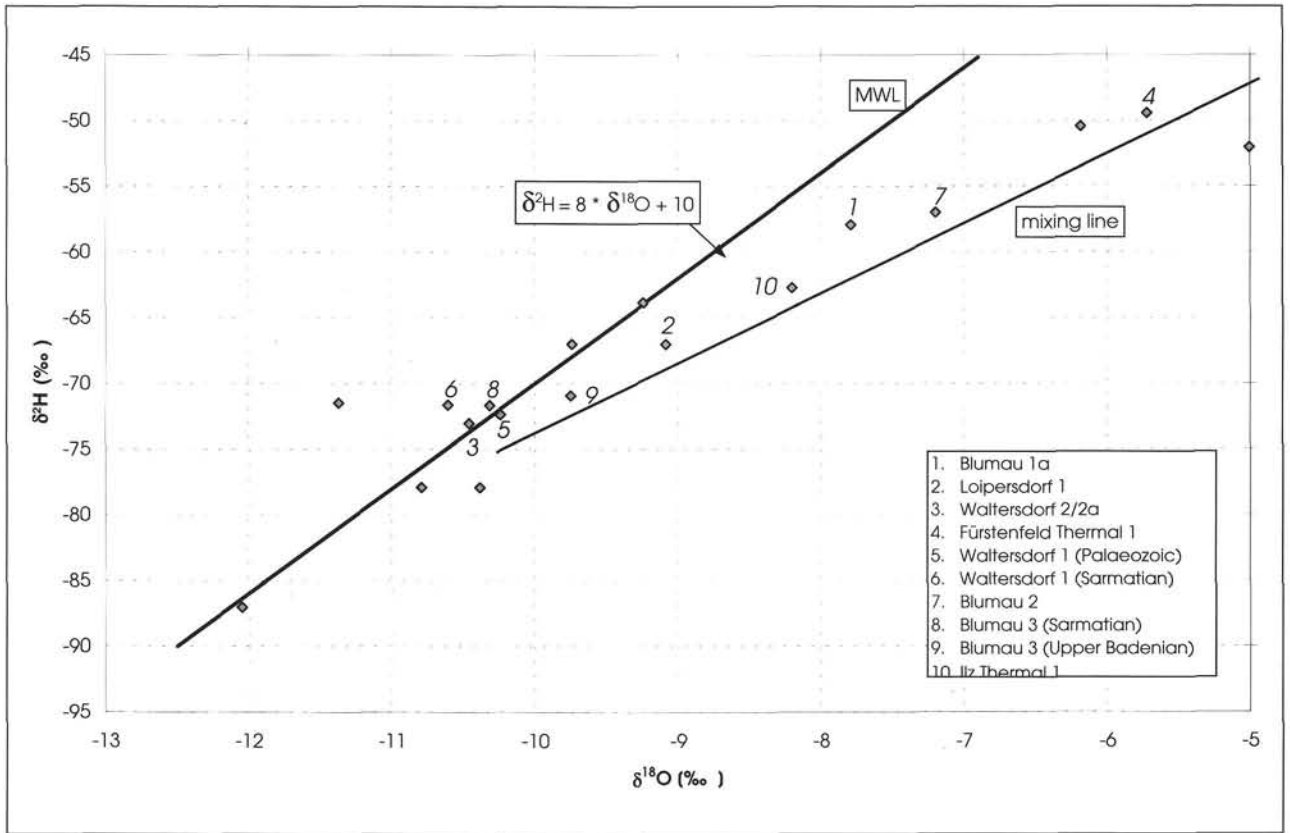


Fig. 8 Isotope plot (deuterium and oxygen-18) of the deep groundwaters and formation waters of the Styrian Basin (MWL = Meteoric Water Line).

Table 2 Results of geochemical investigations of the carbonate precipitation of well Blumau 2 (in g/kg).

| | |
|-------------------|------|
| CaCO ₃ | 868 |
| CaSO ₄ | 3.7 |
| MgCO ₃ | 2.7 |
| NaCl | 18.7 |
| KCl | 0.2 |
| SrCO ₃ | 106 |

Table 3 Hydrochemistry of well Blumau 2 (average of several samples taken at outflow in mg/kg).

| | |
|--|---------------|
| Sodium (Na ⁺) | 8.000 |
| Potassium (K ⁺) | 230 |
| Magnesium (Mg ²⁺) | 25 |
| Calcium (Ca ²⁺) | 11 |
| Strontium (Sr ²⁺) | 22 |
| Sulfate (SO ₄ ²⁻) | 650 |
| Chloride (Cl ⁻) | 7,600 |
| Bicarbonate (HCO ₃ ⁻) | 7.050 |
| Sum | 23,566 |

bonates in well 2. This gives clear evidence that production of the thermal water at Blumau is not possible at free overflow conditions, because of the low flowing pressure. Hydraulic evaluation of the pumping tests using the well Blumau 1a as piezometer resulted in transmissivity values

for the aquifer of $2.6 \cdot 10^{-4}$ m²/s for the near well area and $5.1 \cdot 10^{-5}$ m²/s for the distant sector. The latter value expresses the influence of the aquifer boundary in the north formed by the growth fault at well Blumau 1a.

The CO₂ is regarded as a postvolcanic product linked to the Neogene volcanism of the Styrian Basin. It ascends from mantle regions along fault zones, as indicated by ³He/⁴He measurements. The precipitation problems, which are caused by degassing at decreasing pressure are a large obstacle to geothermal use of the deep-seated thermal waters.

Similar conditions to those in the Blumau boreholes were encountered in the well Ilz 1, some 15 km west of Blumau. Based on reflection seismic measurements, the drilling was located nearby the Ilz shield volcano, which is of Karpatian to Badenian age and is completely covered by Neogene sediments. The target of the drilling was a synthetic fault structure in the Paleozoic basin floor. The top of the Paleozoic carbonates was reached at a depth of 1,465 m and carbonate rocks persisted to the end depth of the well at 1,906 m. They are developed as a sequence of dolomites of different lithotypes. Between 1,666 and 1,702 m the fault zone was penetrated, indicated by cataclastic rocks and polished fault surfaces. The section is also characterised by high values of natural gamma ray and a decrease in rock density. Pumping tests showed a flow of 15 l/s; the temperature at the wellhead is as high as 80 °C. The hydrochemistry of the water is similar to Blumau, in particular Blumau 1a, representing a Na-HCO₃-Cl-water type, TDS 17.6 g/l; Na = 5.4 g/l, HCO₃ = 8.8 g/l. Carbonate scaling is also a great problem in this well.

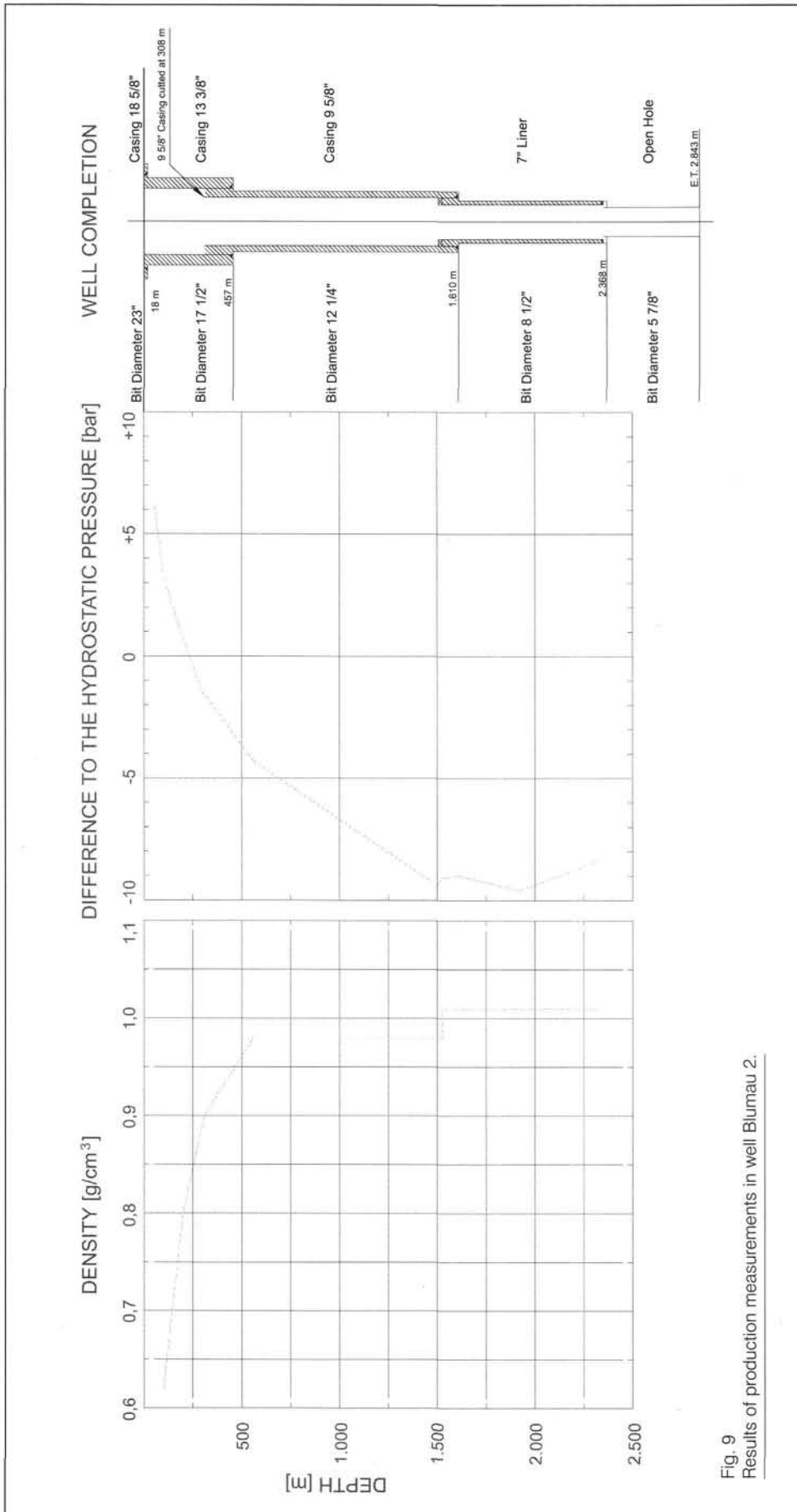


Fig. 9 Results of production measurements in well Blumau 2.

The isotope plot in Figure 8 (deuterium and oxygen-18) shows that the waters of Blumau and Ilz are not meteoric as indicated in the isotopic plot and lie on a mixing line, which is similar to that in the Upper Austrian Molasse Basin. The isotope enriched end points of the mixing line have not yet been identified for the Styrian Basin.

A third shallow well was already planned for the Blumau spa in the design phase of the project to avoid scaling problems in the pipes and the pools of the spa. The well Blumau 3 was drilled to a depth of 1,200 m for the exploration of permeable horizons in the Sarmatian and Upper Badenian. To obtain the most suitable water type for spa use single tests in the well were performed. These tests are predominantly used in the hydrocarbon industry. Permeable horizons, identified by geophysical borehole measurements, were developed by perforating the cemented casing at a definite interval. After perforation, a short term pumping test using airlift was undertaken to obtain information about productivity of the horizon, temperature and the chemical composition of the water. After finishing the pumping test, a packer was set in the casing, thus preventing mixing after the next interval was perforated. In this way it was possible to study the hydrogeological status of permeable horizons in the Middle and Lower Sarmatian and the Upper Badenian of the well.

The deep groundwaters in Sarmatian of well Blumau 3 between 647 m (more than 300 m vertical section) can be regarded identical in respect to their hydrochemical

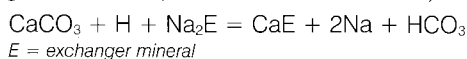
Table 4
Results of single tests in well Blumau 3.

| Test* | Number of Horizons | Intervall | T (°C) | TDS (mg/l) | Na (mg/l) | HCO ₃ (mg/l) | Cl (mg/l) | D (δ ‰) | ¹⁸ O (δ ‰) |
|-------|--------------------|-------------------|--------|------------|-----------|-------------------------|-----------|---------|-----------------------|
| I | 2 | 910.0-956.3 m | 42 | 1,602 | 482 | 1,043 | 40 | | |
| II | 4 | 783.5-956.3 m | 42 | 1,643 | 449 | 1,135 | 40 | | |
| III | 3 | 706.8-744.8 m | 40 | 1,576 | 431 | 1,087 | 48 | -72 | -10.2 |
| IV | 2 | 647.4-672.0 m | 38 | 1,614 | 444 | 1,117 | 45 | -72 | -10.3 |
| V | 4 | 1,084.0-1,118.0 m | | 3,121 | 849 | 2,216 | 22 | -71 | -9.8 |

* Tests I-IV are in Sarmatian, test V is in Upper Badenian horizons.

(and isotopic) status (Tab. 4). This indicates a uniform flow system. The waters are low mineralized (TDS 1.6 g/l) and are low in chloride; sodium is in the order of 450 mg/l, showing that ion exchange processes (calcium exchanged for sodium) are important for the hydrogeochemical evolution of these waters. The values of the stable isotopes deuterium and oxygen-18 indicate a recharge under non-Pleistocene conditions. Free CO₂ or a CO₂ gas phase are not present, proving a separation from the deep-seated aquifer in Blumau.

The waters from the perforated horizons in the Upper Badenian have nearly double the mineralization (TDS 3.1 g/l), which is due to a doubling of the sodium and bicarbonate content, whereas the chloride content is only half of the Sarmatian waters. This proves that flushing of meteoric waters took place in the horizons of marine origin. Also in this horizon free CO₂ or CO₂ gas is not present. The high bicarbonate values can be explained by ion exchange following the scheme (THORSTENSON et al., 1979)



After evaluation of the tests, the horizons of test V was not included in the completion of the well and was sealed off by cementation.

Farther south, profile Fig. 7 shows the deeper parts of the Fürstenfeld sub-basin, where the borehole of Fürstenfeld has tapped formation waters in the Middle Badenian (Sand-schaler Zone) with a total mineralization of 45 g/l (Na-Cl-type). The well of Loipersdorf 1 is located on the Südburgenländische Schwelle, a swell zone which forms a hydraulic boundary between the Styrian Basin and the Pannonian Basin.

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