

## Hydrogeological Exploration of an Alpine Marble Karst for Geothermal Utilization

Ingo Sass, Claus-Dieter Heldmann, Clemens Lehr and Rafael Schaeffer

Technische Universitaet Darmstadt, Geothermal Science and Technology, Schnittspahnstr. 9, 64287 Darmstadt, Germany  
sass@geo.tu-darmstadt.de

**Keywords:** Alpine karst aquifer, middle deep borehole heat exchanger storage, Hochstegen formation

### ABSTRACT

Karst aquifers are very vulnerable hydrogeological units. Geothermal use via drillings therefore is handled very restrictively by the authorities of many nations. The hydrogeological properties of karst aquifers can affect the efficiency of geothermal systems strongly. However, karst aquifer properties require special exploration and exploitation. The marble karst aquifer of the Hochstegen Formation was investigated to construct a medium depth borehole heat exchanger storage at Finkenberg, Austria. Investigations of streams and springs all over the Tux Valley led to an attribution of characteristic hydrochemical signatures to each tectonic unit in accordance to its lithology. By determining the hydrochemical properties of waters in the area of Finkenberg it became evident that the geological catchment of the Hochstegen Formation reaches there from 840 to 2650 m above sea level.

Results of geological surveying and exploratory drilling demonstrated that the tectonic situation is much more complex than described in the official geological map. The Hochstegen Formation can locally reach significant higher thicknesses than estimated before. In addition, the layer sequence is more unconformable as supposed. Karstified zones up to 400 m depth were detected within the boreholes. Groundwater flow velocities up to  $14 \text{ m}\cdot\text{d}^{-1}$  were determined by applying Optical Frequency Domain Reflectometry (OFDR) in Borehole Heat Exchangers (BHE). The drilling operations were accompanied by a perpetuating testimony for neighboring springs. Therefore, collected data allowed calculation of the groundwater velocities. A total number of nine 400 m-deep boreholes were drilled. The borehole heat exchange storage system has a heat extraction capability of about  $1 \text{ GWh}\cdot\text{a}^{-1}$  and  $400 \text{ MWh}\cdot\text{a}^{-1}$  storage capacities. The successful conclusion of this project and gathered knowledge up to now led to the idea to explore the Hochstegen Formation for extensive geothermal use. Exploration of a 1200 m-deep well for hydrothermal use is currently in process.

### INTRODUCTION

#### Karst Exploration for Geothermal Utilization

The investigation of karst aquifer systems in comparison to porous and fissured aquifers requires a modified strategy. Karst systems are typically more anisotropic and have larger and longer inhomogeneity. The storage coefficient and preferential flow paths may strongly vary on any scale in the rock formation. A systematical exploration of a karst system as used for vulnerability assessment and hydraulic analysis can be expensive and requires a long term observation. Still this cannot eliminate the high possibility of missing the karst conduits on the drilling site (Bakalowicz 2005, Goldscheider and Drew 2007).

No morphological karst phenomena like caverns or dolines can be observed around the Finkenberg area, but the possibility of a deeper karstification at the project site was supposed in this study because a large cave system is located in the same rock member about 15 km SW upstream in the area of Hintertux.

### SCOPE

A geothermal energy supply was designed for heating and cooling of a hotel and spa resort complex. The geothermal system was supposed to have some heat storage capability for higher efficiency. The aim was to build a medium depth borehole heat exchanger array at Finkenberg (Tyrol, Austria). The marble karst aquifer of the Hochstegen Formation in the Tux Valley (Fig. 1, Zillertal region) had to be prospected for geothermal utilization for the first time.

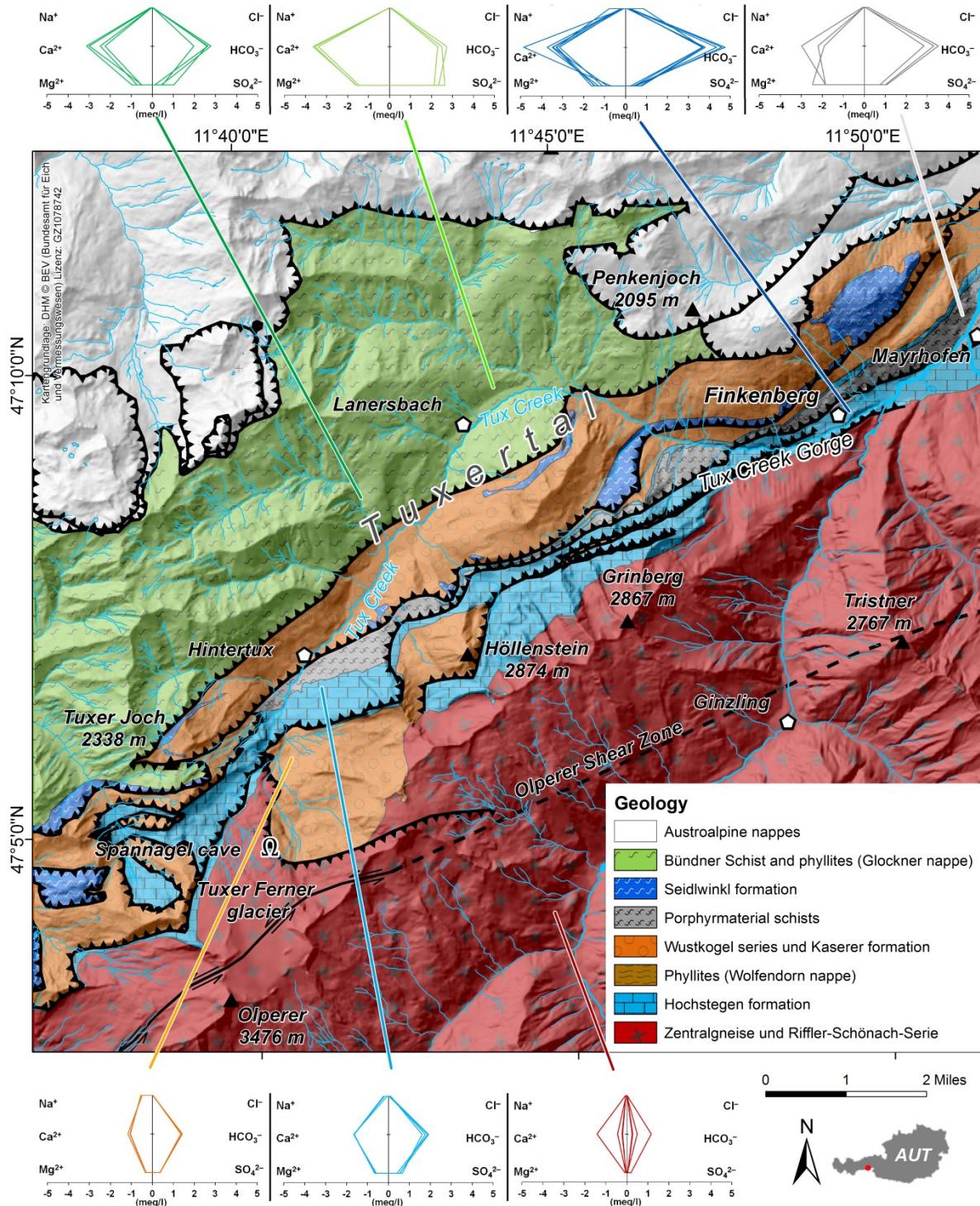
Drilling and grouting in a karst aquifer bears serious risks for groundwater quality and technical success. Detailed information about the hydrogeology and geology was demanded in advance. At the layout of the project, neither geothermal and geotechnical characteristics were known, nor studies of the local karst hydrology were present. Therefore, a scientific research program was designed and implemented in project preparations and accompanying investigations.

A hydrochemical investigation program was carried out with the intention to develop a groundwater classification procedure with routine hydrochemical parameters. The aim was to identify possible changes in groundwater flow paths triggered by the drillings, because there are some karst springs very close to the drill site (within 100 to 800 m distance).

The hydrochemical conditions in the catchment area of the Tux Valley were not well known. It was also the goal of a hydrogeological evidence routine, to observe springs closely related to the drill site during and after implementation of the construction of the BHEs to document possible effects of drilling on the spring water quality and quantity in Finkenberg.

No deep drilling or borehole heat exchanger was present in Tuxertal. We developed a preservation of evidence scheme to document and quantify the impact of the drilling operations on karst water quantity and quality, jointly with the mining authority and water authorities. Due to this there were serious requirements regarding the technological aspects, supervision, and hydrological perpetuating testimonies by the regulatory authorities. Additionally, the thermophysical and geotechnical properties of the rocks, had to be explored, which also depend on the karst hydrogeology. The entire BHE plant was designed on the basis of optical

frequency domain data which allowed reducing of the number of heat exchangers from a preliminary 12 to 9 BHEs in the final layout (Sass and Lehr, 2013).



**Fig. 1: Simplified geological map of Tux Valley and chemical compositions of analyzed water samples grouped by lithological origin in Stiff diagrams**

In addition, a very short construction time was permitted by the government because Finkenberg is a touristic region. A fast drilling technique had to be preferred. The pneumatic down-the-hole hammer drilling was chosen according to the expected hard carbonate rocks. Although used in hard crystalline or consolidated rocks for shallow drillings, the limit is given by the compressor air pressure (typically 2–2.4 MPa) and usually ends with a 240 m water column (Misstear et al. 2006). In this case the drilling target depth of 400 m was reached with a higher pressure, marking the recent limit of reachable depth. The field investigation had to verify the absence of plastic rocks. Although all rocks below superficial covering are metamorphic rocks of greenschist or higher grade facies, there is a possibility of hydrothermal alteration in fault zones.

The research project was started in 2011 with geoscientific field investigations. The results were incorporated into the following technical planning including:

- Geological and structural mapping
- Definition of structural units
- Hydrogeological mapping of the structural units
- Hydrochemical characterization of springs and streams in the Tuxbach catchment and assignment to the structural units
- Hydro-chemical monitoring of the springs in Finkenberg monitoring all springs before, during, and after the drillings

#### **Approach of an iterative data mining and BHE dimensioning during dual step site development**

During construction of larger buildings the geothermal site can usually be built in separate phases. Normally construction of the building takes much longer than the drilling, grouting, and connection of the BHE field. For this reason, it is possible to continue data acquisition during the realization phase instead of conducting it separately. The expenditures for splitting the drilling in separate phases, costs regarding transportation, installation, and deinstallation of the drilling equipment have to be minor to the risk of a miscalculation. In particular, the separate admission procedures take additional time.

Using the exploration drilling for initial BHE reduces the effective costs and provides direct local geological information. Equipping the initial BHE for Enhanced Geothermal Response hybrid fiber-glass-copper-cable test (Lehr and Sass 2014) leads to important geothermal data acquisition for further dimensioning processes. An EGRT (enhanced geothermal response test) is cheaper than the study of the karst system and provides exclusive information about the concerning area. The resulting temperature profile will show local geothermal gradient, which is the first important hard fact about the underground geothermal model.

In combination with the geological profile and the laboratory-measured heat conductivity of the units, the EGRT also provides a method for calculating the share of convectional heat transport. In this valuation, the effective thermal conductivity leads to groundwater velocities, an important information about the karst environment of the BHE.

#### **GEOLOGY**

Finkenberg is located at about 840 m a.s.l. at the mouth of the Tux Valley in the Ziller Valley and 3 km east of Mayrhofen, which is about 630 m a.s.l. (Fig. 1). In Finkenberg the valley is glacially formed as a wide U-shaped valley lying between the Grinberg peak (2,867 m a.s.l.) of the Tux mountain ridge in the south and the Penkenjoch (2,095 m a.s.l.) in the north. Up to 60 m-deep canyon of the the Tux Creek is topographically significant. The gorge direction is tectonically preset by the course of the thrust faults of the Alpine nappes. The prominent cutting of the creek is explained by the solubility of the dolomite marble member.

The area belongs to the Tux Alps in the NW edge of the Tauern Window surrounded by the Tertiary nappes and thrust folded mountains of the eastern Alps (Schmid et al. 2013). The Tauern Window strikes in E-W direction over a length of 160 km with a width of about 30 km (Kurz et al. 1998). Its rocks originate from intrusion, rifting, and subduction processes around the Triassic Paleo-Tethys Ocean. These rock have undergone metamorphism during the collision of the adjacent European and African plates. In Zillertal, the main ridge has been exposed as a part of the uncovered Tauern Window gneiss (Central Gneiss) of the Variscan basement. The indenter tectonics after the main subduction of the oceanic crust resulted in deformation and nappe stacking. The overlying nappes originated in part from the metamorphic rocks underneath the sedimentary basins of the Tethys and they are called Schieferhuelle (Vesela and Lammerer 2008). The Central Gneiss in the Tauern Window area was uplifted and has covered the denudated nappes since Tertiary times. In the Tauern Window, the Penninic nappe stack is surrounded by stacks of Austroalpine nappes in the central area which have been uplifted 25–35 km and eroded since Tertiary (Selverstone 1985). The Venediger nappe, the lowest Penninic nappe, consists of the Central Gneiss core, which is an antiformed ortho- and paragneiss (Kurz et al. 1998).

The geothermally significant dolomitic marbles of the Hochstegen Member represent the tectonically lowermost member of the tectonic structure of the Schieferhuelle. They have been metamorphosed under greenschist facies conditions and they are also strongly deformed. The Hochstegen marble is a parautochthon covering the northern part of the Ahorn Kern antiform of the Central Gneiss and is thrusted by the Hochstegen marble of the lower Wolfendorn nappe (Frisch 1968, Frisch 1979).

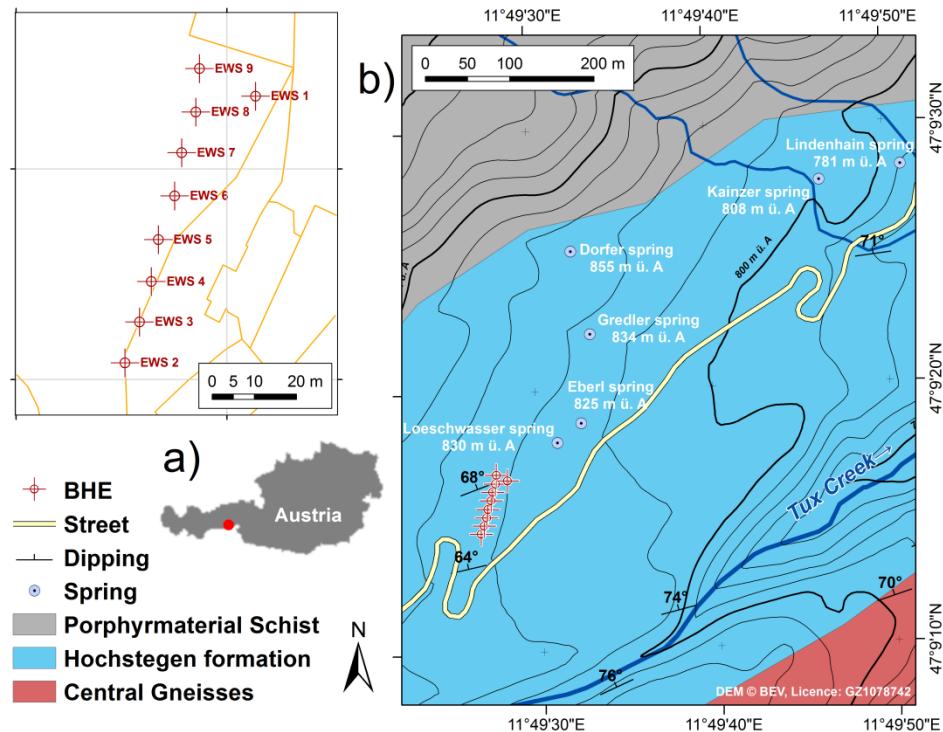
The higher nappes of the Schieferhuelle were mainly pushed onto each other and stacked in northern movement on the basement rocks of the Tauern Window later. The lower nappes, as well as the Wolfendorn thrust fold complex, and the Central Gneiss are both characterized by long, subvertical, E-W-striking, sinistral fault systems. According to these deformation zones the dolomitic marbles have been strongly sheared. The Tux Stream Gorge is an expression of mechanical weakening due to the shearing and movement along the faults and reasonably geologically mapped and investigated for hints of deep karstification. Especially the transposition by the 50 km long Ahorn Shear Zone (Fig. 1) is taken into account. This major mylonitic shear zone has an extension to the 300 km Salzach–Enns–Mariazell–Puchberg transregional fault system (Rosenberg and Schneider 2008, Toeplitz et al. 2011). During the Tertiary period, exposure of the Tauern Window the SEMP was a compressive shear element but in the late Tertiary the shear zone was reactivated as an antithetic normal fault.

#### **Hochstegen Formation**

The lowermost layers of the Hochstegen Formation consist of quartzites, quartzite schists, and kyanite and graphite-bearing phyllite. This is followed by brown colored, sandy calcite marble. The middle and upper part of the Hochstegen Formation is several hundred meters thick at Finkenberg and is built by limestone and dolomitic marble which are gray to anthracite in color. Varying graphite contents are responsible for the color variations. These rocks are the specific target reservoir formation of the geothermal project. The deposition begun in the Upper Jurassic in the Glockner Ocean in a shallow marine environment (Kurz et al. 1998). The sequence is interpreted by Veselá and Lammerer (2008) as a development from the proximal to distal facies. During the Alpine orogeny, the Hochstegen Formation underwent a metamorphic overprinting and was stapled by multiple thrust phases. Today the Hochstegen Member in Finkenberg is dipping 65 to 80° to the NNW (330° to 350°) and is situated on a flank of the

anticlinal structure of the Tauern Window (Fig. 2). The thrust faulting and layering of the formation caused an estimated minimum vertical thickness of about 600 m at Finkenberg, while the average thickness in the Tux Valley is about 350 m.

The Hochstegen Formation is overthrust on to the gneisses of the Ahorn gneiss core and the Tux gneiss core. The deformation of the fault over the Ahorn gneiss core is characterized by a mylonitic zone which is exposed about 400 meters south of the drilling site at the hotel restaurant "Schoene Aussicht" and the cemetery of Finkenberg. Gray to black marbles were encountered in the drillings, both with preserved foliation and with disrupted and recrystallized caciritic structures. In some parts of the profile pyrite-rich sequences with increased graphite contents can be observed. However, the phyllites folded in between the two nappes of the Hochstegen Formation, like shown in the geological maps (GBA 2005a, GBA 2005b), could not be detected during this study.



**Fig. 2: Location of Finkenberg in Austria (a) and geological map for the project site (right) with the BHEs and local springs (as listed in the preservation of evidence program)**

The intensity of fracturing and karstification varies strongly in the Hochstegen Formation, due to its lithological composition and the inhomogeneous tectonic stress directions. Rock layers with increased graphite content have been strongly deformed by shearing than the low-graphite layers. At local shear zones, subparallel and subordinated to the regional shear zones, the rock is brecciated and often cemented with calcite. The stratification of the Hochstegen Formation was determined at the immediate proximity of the drilling site in Finkenberg by Kiessling and Zeiss (1992). The vertical distance of fractures is close, varying from 6–15 m.

## HYDROGEOLOGY

Due to its position along the valley and its karstic cavities, the Hochstegen Formation has an important impact on the groundwater flux along the Tux Valley (Fig. 1). It is supposed to be the main groundwater drainage of the entire catchment. Due to the subvertical position of the layers combined with the relatively low total thicknesses, the drainage effect can be understood as a simplified line-like directed system extending from Hintertux to Finkenberg. An estimated and very simplified average hydraulic gradient of about 5 % results from the difference in height between the thermal springs in Hintertux at the Badhotel Kirchler (1,490 m a.s.l.) passing the Grazerau spring at the eastern entrance of Finkenberg (about 800 m a.s.l.) and reaching Mayrhofen at 630 m a.s.l.. The flow path length is approximately 15 km.

In addition to direct infiltration, the aquifer recharges the largest amounts of water from the side valleys. The northern side valleys are located in the Wolfendorn Nappe and in the southern side valleys Central Gneisses of the Tauern Window are exposed. The waters from the south are subjected to surface run-off. In some cases, ponors and swallow holes recharging the Hochstegen aquifer were observed in the Grinberg Alm area. The same applies to the melting water from some of the surrounding glaciers especially below the Tuxer Ferner, where water enters into the Spannagl cave system. Minor amounts of waters in the crystalline (mostly gneisses) Tauern Window catchment may infiltrate at fault zones. The groundwater is typically poorly-mineralized and undersaturated in carbonate (Stiff diagrams in Figure 1). Karst grooves, limestone pavements, swallow holes, and other karst features are distributed locally in the marbles of the Hochstegen Formation.

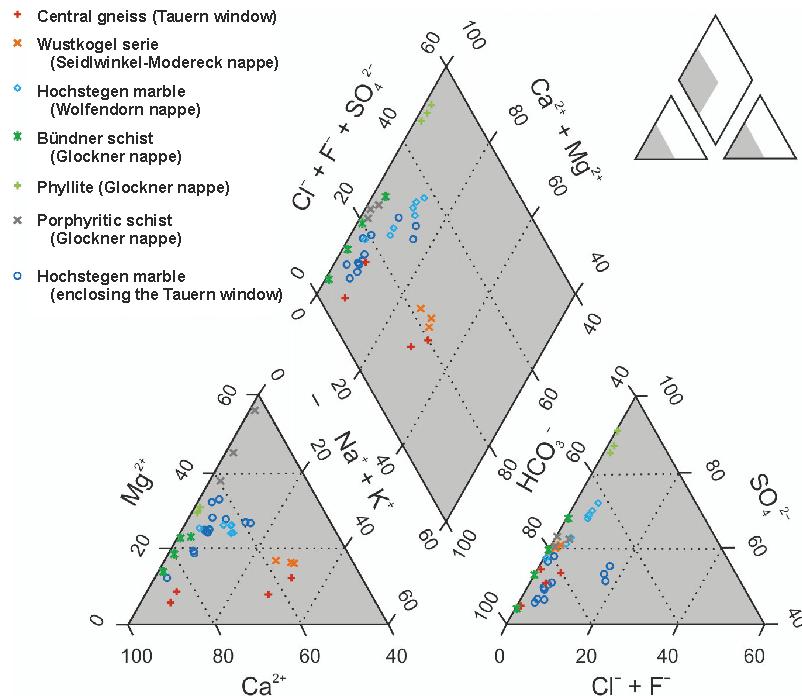
More than 30 caves are known around the Olperer massive (3,476 m a.s.l.; about 17 km SE of Finkenberg) towards Finkenberg. Some of these caves reach passage lengths of up to 100 m. Melting waters of glaciers have recently built new caves (Spoetl 2009). Speleothems in these caves have been dated with U/Pb and U/Th methods with ages of  $340 \pm 2$  ka and  $353 \pm 9$  ka (Cliff et al. 2010). The karst system of the Hochstegen Formation is relatively old and was also active during the glaciations, as shown by speleothem growth, and was possibly fed by groundwaters or meltwaters of the Tux Ferner (Spoetl et al. 2007, Spoetl and Mangini

2010). This means that the karst system has been active up to the present time, overlapping periods of changing hydraulic potentials and influenced by erosion and dynamic morphological changes.

## KARST HYDROCHEMISTRY

Stiff diagrams provide a convenient method to compare waters based on their their main solvates. Stiff diagrams of the waters from the Tux Valley are grouped by host rock types and tectonic nappes in Fig. 1. This study demonstrates that the spring water chemistry is directly linked to structural units. One of the conclusions is that there are minor deep groundwaters involved.

The waters of the Hochstegen Formation are divided into two subgroups. In a carbon dioxide content of the soil air of 3 vol. % (Hesterberg and Siegenthaler 1991) and a water temperature of 10°C can be about 3 mmol / 1  $\text{Ca}^{2+}$  released (Dreybrodt 2008). Hydrochemical analyses show six perennial springs in Finkenberg (Eberl spring, Loeschwasser spring, Sporer spring, Grazerau spring, Kainzer spring, and Gredler spring; Fig. 2) and the permitting spring Lindenheim, in which the spring waters are saturated or oversaturated with carbonate with 3.2 to 3.7 mmol/l  $\text{Ca}^{2+}$ . At the Lindenheim spring, about 750 m NE of the drillings, tufa is also found due to  $\text{CO}_2$  degassing and lime precipitation. At the end of the Tux Valley near Hintertux, about 15 km southwest of Finkenberg, the springs (Kaiserbruendl, “Quelle an der Pfereweide” and thermal springs of hotel Kirchler) are undersaturated in terms of carbonate with 1.0–1.7 mmol/l  $\text{Ca}^{2+}$ . The mineralization generally increases towards Finkenberg.



**Fig. 3: Waters of the Tux Valley in modified Piper diagram.**

A modified Schoeller diagram shows the predominant ion ratios (Fig. 3). The spring waters originating from the Hochstegen Formation have ionic compositions which cannot be found in ground waters from other tectonic nappes.. However, nonconforming solvates were detected in some springs of the Hochstegen Formation. In the cold springs around Finkenberg the waters are about 150–250 mg/l more mineralized than the thermal springs in Hintertux. Different sodium, chloride, and sulfate concentrations were obtained from water samples of the Hintertux springs and from the Finkenberg springs, indicating that some of the Finkenberg waters originate from infiltration in the upper nappes.

The flow path from Hintertux (Hintertux springs light blue in Fig. 1) to Finkenberg (dark blue in Fig. 1) indicates recent karst reaction in the Hochstegen marble; the concentrations of calcium, magnesium, bicarbonate and potassium stay in characteristic relations but double in concentration. The Hochstegen Formation was therefore to be considered as karstified in the entire Finkenberg catchment area. As an example, the catchment area of the springs in Finkenberg extends to N until Penkenjoch (about 2,000 m a.s.l.) far into the rocks of the Schieferhuelle. Different measured nitrate concentrations are probably geologically unrelated, but are primarily due to the influence of cattle farming in the entire valley.

## RESULTS OF THE PRESERVATION OF EVIDENCE

In Finkenberg at the Dorfer spring (Fig. 2), about 350 m NE of the geothermal wells, the discharge ranges between 4.2–9.7 l/s. The large variations of discharge and its fast reaction after precipitation clearly shows the influence of a karst system. It should be tested whether the drilling works at the geothermal field affect the springs continuously. For the preservation of evidence, all springs which could be possibly influenced were monitored since March 2012, two months before start of the first construction phase until August 2013, four months after completion of the heat exchanger field. The time variation curves will help to give a more detailed description of the karst system.

During rainfall, an increase in spring discharge arrives after a few hours while the quantity is reduced after periods of drought. Depending on weather conditions rainfall can increase the spring temperatures significantly. Thus, there is a significant meteorological impact on water temperature and discharge.

The redox potential of all sources monitored from late March to early May 2013 were about 100 mV lower than in the months before and after. This observation can be correlated with the period of snow melting in 2013. Meltwaters infiltrated above the Finkenberg, in the area of the Penkenjoch massive.

A direct anthropogenic influence on the hydrochemistry is detectable (Fig. 2) in the Grazerau spring located down the Mayrhofen-Hintertux highway. In comparison to the other sources in Finkenberg, the Grazerau spring has twice to three times higher concentrations of sodium and chloride. This is the greatest difference in the observed spring water qualities. This anomaly is caused by deicing of the Tuxer Valley road by salts added in the winter.

An impact on the spring water quality in terms of changes in ionic activities during and after the drilling was not observed. Indeed the turbidity parameter for one specific spring showed evidence for a hydraulic connection to drilling and grouting operation. Unaffected spring waters have typical turbidity values of 0.1 to 0.8 FNU. The Tuxbach and its tributaries can reach opacities of 1–75 FNU. During heavy rainfall events or snowmelt and inflow of coarse particles and sediments in the creek bed, opacities in the same streams increased to 100–785 FNU. During drilling, especially with bentonite mud (which was not applied in Finkenberg because of pneumatic drilling technique) the turbidity can reach over 1000 FNU.

A hydraulic contact with the drillings could be detected by increased turbidity in levels of up to 103 FNU only in the Loeschwasser spring, the closest spring at about 120 m horizontal distance from the drillings. The maximum of this temporary interference falls within the temporal peak of the drilling operations. After grouting the BHE wellbores of the Loeschwasser spring reached normal levels within three days. However, the Eberl spring, which is only 50 m away from the closest drill site, showed no increase in turbidity over the natural limit throughout the drilling phase. Thus, karstification and groundwater flow within the Hochstegen Formation appears to be highly variable on a small scale and the conduits in the karst differs significantly. This is even more remarkable, because the Loeschwasser spring and the Eberl spring are along the strike direction of the main fault systems and a structural link is to therefore to be expected.

Overall, the scientific studies in Finkenberg showed the feasibility of a medium depth geothermal project in a karst aquifer, recognizing the applicability of methods to analogues and verifying the regional hydrogeological prognosis. Therefore, it was found that the results of the hydrogeological investigation provided a basic explanation to the large-scale groundwater situation.

## ACKNOWLEDGEMENTS

We thank Josef Stock, Sporthotel Stock GmbH, for financial and practical support of research closely related to a commercial project. Furthermore, we thank the volunteers of the Fire Department Finkenberg, the Water Rescue Tyrol, Finkenberg, the District Commission Tyrol and the Provincial Government of Tyrol and their respective employees for minor and major assistances. We thank gratefully the DAAD and the NaturPur Institute for the partial funding of this research work. We also thank Sebastian Homuth for reviewing this paper.

## LITERATURE

Bakalowicz, M.: Karst Groundwater: A Challenge for new Resources, *Hydrogeol J*, **13**, (2005), 148-160.

Cliff, R., Spoetl, C. and Mangini, A: U–Pb Dating of Speleothems from Spannagel Cave, Austrian Alps: A High Resolution Comparison with U–Series Ages, *Quaternary Geochronology*, **5**, (4/2010), 452-458.

DIN EN ISO 14689-1: Geotechnische Erkundung und Untersuchung – Benennung, Beschreibung und Klassifizierung von Fels – Teil 1: Benennung und Beschreibung, (2011).

Dreybrodt, W.: Von der Kluft zum Urkanal – Chemie und Physik der Hohlenentstehung, In: Kempe, S. and Rosendahl, W. (eds.): Höhlen – Verbogene Welten, (2008), 168 p.

Frisch, W.: Zur Geologie des Gebietes zwischen Tuxbach und Tuxer Hauptkamm bei Lanersbach, Zillertal, Tirol, *Mitt Ges Geol Bergbaustud*, **18**, (1968), 287-336.

Frisch, W.: Tectonic Progradation and Plate Tectonic Evolution of the Alps, *Tectonophysics*, **60**, (1979), 121-139.

Geologische Bundesanstalt (GBA) [eds.]: Geofast 1 : 50 000, 149, Lanersbach. (2005a).

Geologische Bundesanstalt (GBA) [eds.]: Geofast 1 : 50 000, 150, Mayrhofen. (2005b).

Goldscheider, N. and Drew, D.: Methods in Karst Hydrogeology, In: *Int Contributions to Hydrogeology*, **26**, (2007), 264 p.

Goldscheider, N., Mádl-Szoenyi, J., Eroess, A. and Schill, E.: Review: Thermal Water Resources in Carbonate Rock Aquifers. *Hydrogeology J*, **18**, (2010), 1303-1318.

Hesterberg, R. and Siegenthaler, U.: Production and stable Isotopic Composition of CO<sub>2</sub> in a Soil near Bern, Switzerland. *Tellus*, **43B**, (1991), 97-205.

Kießling, W. and Zeiss, A.: New paleontological Data from the Hochstegen Marble (Tauern Window, eastern Alps), *Geol Palaeont Mitt Innsbruck*, **18**, (1992), 187-202.

Kurz, W., Neubauer, F., Genser, J. and Dachs, E.: Alpine Geodynamic Evolution of Passive and Active Continental Margin Sequences in the Tauern Window (eastern Alps, Austria, Italy): a Review, *Geol Rundschau*, **87**, (1998), 225-242.

Lehr, C. and Sass, I.: Thermo-optical Parameter Acquisition and Characterization of geologic Properties: a 400-m deep BHE in a karstic alpine marble Aquifer, *Env Earth Science* (2014, online)

Misstear, B., Banks, D. and Clark, L.: Water, Wells and Boreholes, 2<sup>nd</sup> ed., (2006), 498 p.

Rosenberg, C.L. and Schneider, S.: The western Termination of the SEMP Fault (Eastern Alps) and its Bearing on the Exhumation of the Tauern Window. In: Siegesmund, S., Fuegenschuh, B. and Froitzheim, N. (eds.): Tectonic Aspects of the Alpine-Dinaride-Carpathian System, Geol Soc London Special Publications, (2008), 197-218.

Sass, I. and Lehr, C.: Design Parameter Acquisition of an underground Heat Storage and Extraction System – A deep BHE array in a karstic alpine marble Aquifer for 1 GWh Power, *Proceedings*, 38th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA (2013).

Sass, I., Heldmann, C.-D. and Lehr, C.: Erschliessung eines Marmorkarstvorkommens als mitteltiefer Erdwärmesondenspeicher, Tuxertal, Tirol, *Grundwasser*, (2014, submitted).

Schmid, S. M.; Scharf, A., Handy, M. R. and Rosenberg, C. L.: The Tauern Window (Eastern Alps, Austria): a new tectonic Map, with Cross-Sections and a tectonometamorphic Synthesis, *Swiss J Geosci*, **106**, (2013), 1-32.

Silverstone, J.: Petrologic constraints on Imbrication, Metamorphism and Uplift in the Tauern Window, Eastern Alps, *Tectonics*, **4**, (1985), 687-704.

Spoetl, C. and Mangini, A.: Paleohydrology of a high-elevation glacier-influenced Karst System in the Central Alps (Austria), *Austrian J of Earth Sciences*, **103/2**, (2010), 92-105.

Spoetl, C., Offenbecher; K.-H., Boch, R., Meyer, M., Mangini, A., Kramers, J. and Pavliza, R.: Tropfsteinforschung in österreichischen Höhlen – ein Überblick, *Jb Geol BA*, **147**, (2007), 117-167.

Toechterle, A.; Brandner, R. and Reiter, F.: Strain Partitioning on major Fault Zones in the north-western Tauern Window – insights from the investigations to the Brenner Base Tunnel, *Austrian J of Earth Sciences*, **104/1**, (2011), 15-35.

Veselá, P. and Lammerer, B.: The Pfitsch-Moerchner Basin, an Example of the post-Variscan sedimentary Evolution in the Tauern Window, *Swiss J. Geoscience*, **101**, suppl. 1, (2008), 73-88.