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Extreme Radon Concentrations in a High-Yield-Aquifer of the Austrian Alps – Origin, Transport and Health Impact

Extreme Radonkonzentrationen in einem ergiebigen Aquifer in den Österreichischen Alpen – Ursprung, Transport und Gesundheitsauswirkungen

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Inhalt

1. Introduction

The study area is located in the Western Central Alps, Austria and belongs geologically to the Ötztal-Stubai crystalline complex, which is composed of para and ortho gneisses. These poly-metamorphic rocks were altered by Caledonian to Alpidic tectonisms. Typically for the Ötz Valley is its stair-like morphology. Rock falls from both sides gave rise to the formation of basins and narrows.

This study is related to the basins of Umhausen and Längenfeld, which were formed by the rock fall of Köfels/Umhausen. These basins are filled with thick limnic-fluviatile, unconsolidated sediments and, thus, are expected to represent the main groundwater reservoir of the area under investigation. The glacially moulded slopes of the main valley are covered with a rather thin layer of debris. The mica schists and biotite-pla-

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gioclase-gneisses do not display a significantly deep reaching infiltration of meteoric water. However, the granite gneisses, eklogites and amphibolites may facilitate a higher and deeper reaching infiltration due to the larger openings of their joint system, the position of the joint planes and the intensive cutting.

The river Ötztaler Ache is acting as the main drainage system. Obviously, potential groundwater reservoirs of larger extent are mainly expected in the thick valley and basin fillings.

At clearly defined areas of the basin of Umhausen and in certain parts of the village Umhausen, high radon concentrations were detected in soil-gas samples and in indoor-air samples respectively. The values in houses reached up to 370,000 Bq/m^3. (The international activity limits for indoor-air concentration are between 200 Bq/m^3 and 1000 Bq/m^3 – adopted by the WHO, ICRP, IAEA, and EU). Local health statistics emphasize a roughly 5-fold increase of lung-cancer-risk in the village Umhausen (2.4/1000 per inhabitant and year) in comparison to the average value of the whole province of Tyrol (0.5/1000 per inhabitant and year).

Preliminary mineralogical investigations suggest that this radon anomaly is related to the gigantic rock fall of Köfels ($\cong$ 2 km^3 of rock masses). Systematic geological and hydrogeological investigations using various techniques, revealed high radon concentrations also in groundwater (up to 1.1 Mio. Bq/m^3), identified the different sources of radon, the transport paths and transport mechanism of this noble gas, and finally tried to determine the radon balance (of interest for civil engineers).

This study is part of the water management programme for the Tyrol province and aimed at providing the political authorities with basic information required to guarantee the protection of the water resources of that valley with respect to the water supply of future generations. The programme is devided into two phases.

In the first phase, a hydrogeological exploration project (in the Ötz Valley) and a project entitled "Geology, Tectonics and Deep Waters in the Ötztaler Alps" have been implemented. The latter project provided basic data on geology and tectonics of both sides of the valley.

For the second phase, detailed studies are planned, which are expected to provide more information on the aquifer itself and its capacity, on the dynamics and quality of the groundwater, and on the recharge (catchment) area.

The water resources management authorities are especially interested in:

– evaluating the groundwater potential within particular sections of the valley and basin (quantitativ and qualitativ results),
– ensuring an autonomous water supply for the local population in the near future with particular emphasis on water quality, in order to enable the protection of human beings,
– working out a reliable data base on the temporal and spatial variations of radon in the study area in order to enable the protection of human beeings.

Experts in medical physics, radiochemistry, mineralogy and petrography previously studied the phenomena of the high radon emanation. They identified extremely high radon concentrations in houses of Umhausen and emphasized the need to protect the public against this high radiation level. These studies, however, did not involve hydrogeology, because the experts disregarded the presence of groundwater in the area of Umhausen. Therefore, hydrogeologists and geologists proposed an interdisciplinary approach in studying origin, production and transport (paths and mechanisms) of radon.

2. Preliminary investigations

Investigations carried out by various scientists led to the following results:

a) The gigantic rock fall of Köfels involved about 2 km^2 of rock masses and is the largest one in the crystalline part of the Central Alps. Due to C-14 age determinations, it took place about 9,800 years ago. Processes initiated by this rock fall and the specific petrographic composition of the rocks are the causes of the high radon production.
b) Downstream of the rock fall, the high radon values are associated with the old alluvial Fan of the river Ötztaler Ache.
c) The spatial variability of the (in-house) radon concentration in the village Umhausen is most likely controlled by the petrographic composition of the underlying fans: the high permeable Ache Fan, the lower permeable Horlach Fan (east of the Ache Fan) and the low permeable Murbach Fan (northeast of the Ache Fan).
d) Mineralogical investigations suggest that the high Rn-concentrations are caused by the intensive shattering and break up of the rock (granitic gneisses) during the rock fall event. This resulted in high values of the specific surface of the rock and thus high radon emanation rates due to diffusion and migration from the rock matrix.
e) It was suggested, that whenever the coarse grained material of the Ache Fan is linked to the rock fall, radon migrates within the aerated zone from the rock fall into the fan and from there it emanates into the air (and houses). However, if the coarse grained material is covered by younger fine grained material radon cannot as easy emanate to the surface .

Although there is no doubt about the close relation between the rock fall and the high radon anomaly of soil gas in its vicinity, it is difficult to explain the migration of radon via soil gas over a distance of about 1,000 m from the rock fall to Umhausen. This is mainly because of the comparatively short radon-222 half-live of 3.8 days . Therefore, it appeared more likely that the radon transport is facilitated by migration through the deep reaching fault system and/or movement of groundwater as a carrier of radon.

Figure 1 shows the tectonic network of the area under consideration, dominated by deep reaching N–S and E–W running lineaments.

Based on the results of previous morphological and tectonic investigations, soil-gas sampling was established along four sections. These sections were perpenticularly oriented to the valley axis and had a total lenght of 5 km. The samples for radon measurements were taken from a depth of 1 m and the sampling distance was 20 m (Fig. 2).

To identify the origin of the radon anomalies (faults, shallow or deep-seated sources), the soil gases carbon dioxide, methane, oxygen, nitrogen, helium and argon were also sampled and analysed. The results of the radon measurements are given in Fig. 2, and a plot of the radon values obtained by interpolation of the concentrations measured along the three profiles around Umhausen is shown in Fig. 3. The figures show that the highest radon concentrations occur in direction NNW–SSE (parallel to the river) and NW–SE.

Tectonic features (faults) seem to control this radon distribution. In the case of the NW–SE orientation of the high radon concentrations, a spatial coincidence with a contact of two different fans (Ache and Horlach Fan) is also possible. In general, the radon concentrations (with maxima up to 176,000 Bq/m³) tend to decrease with distance from the rock fall.

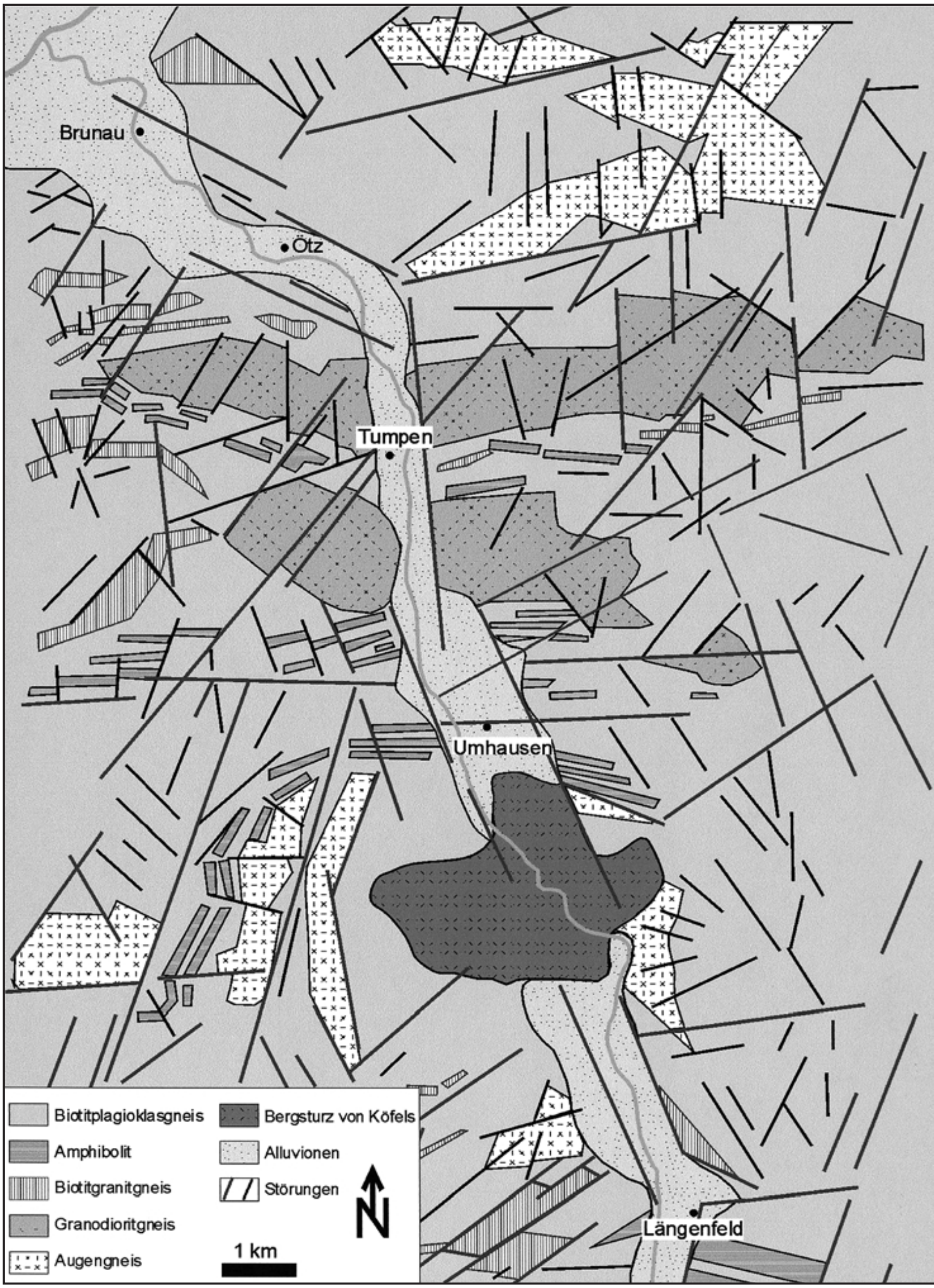


Fig. 1: Tectonic network in the Lower Oetz Valley/Tyrol.
Tektonische Übersichtskarte des Unteren Ötztales.

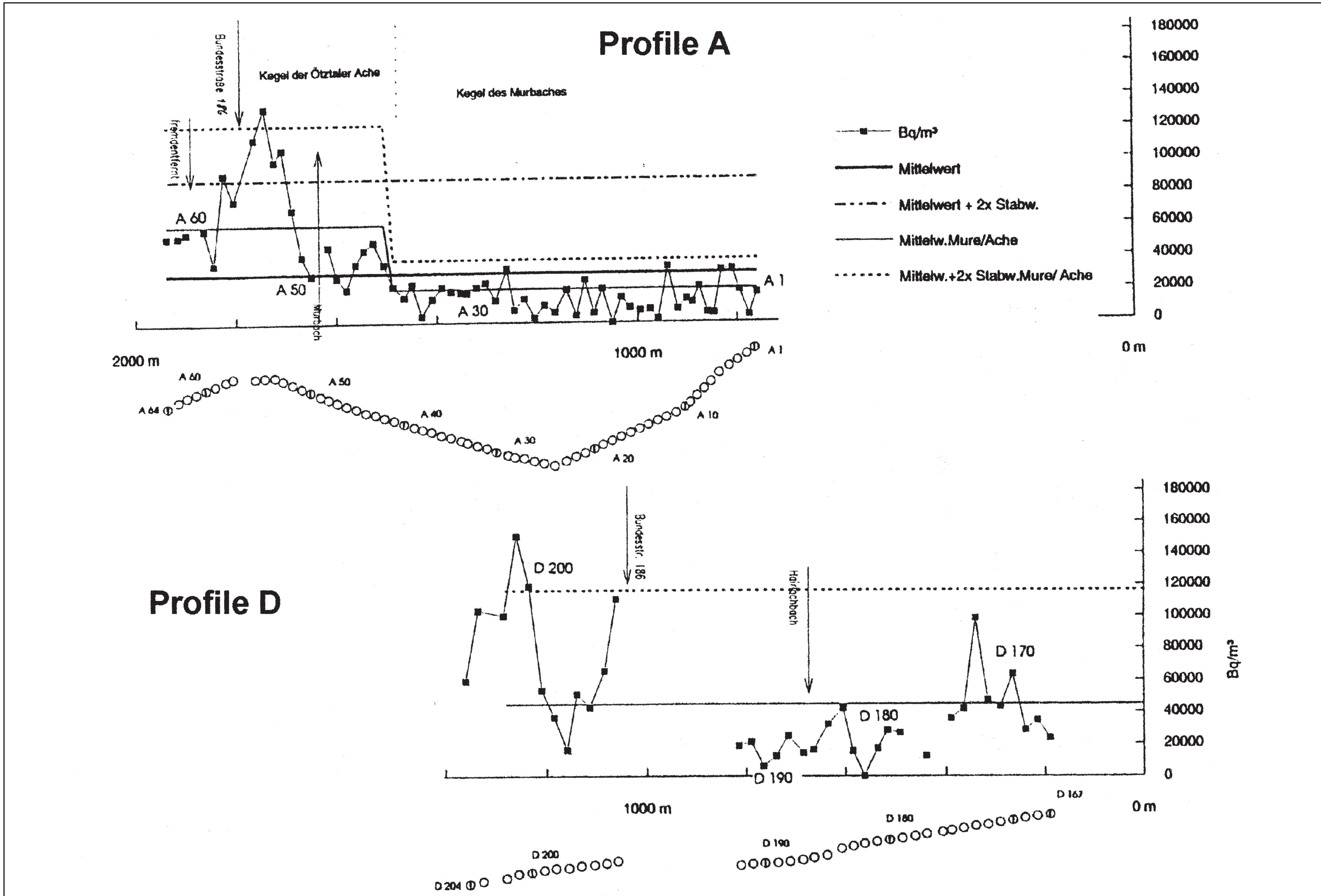
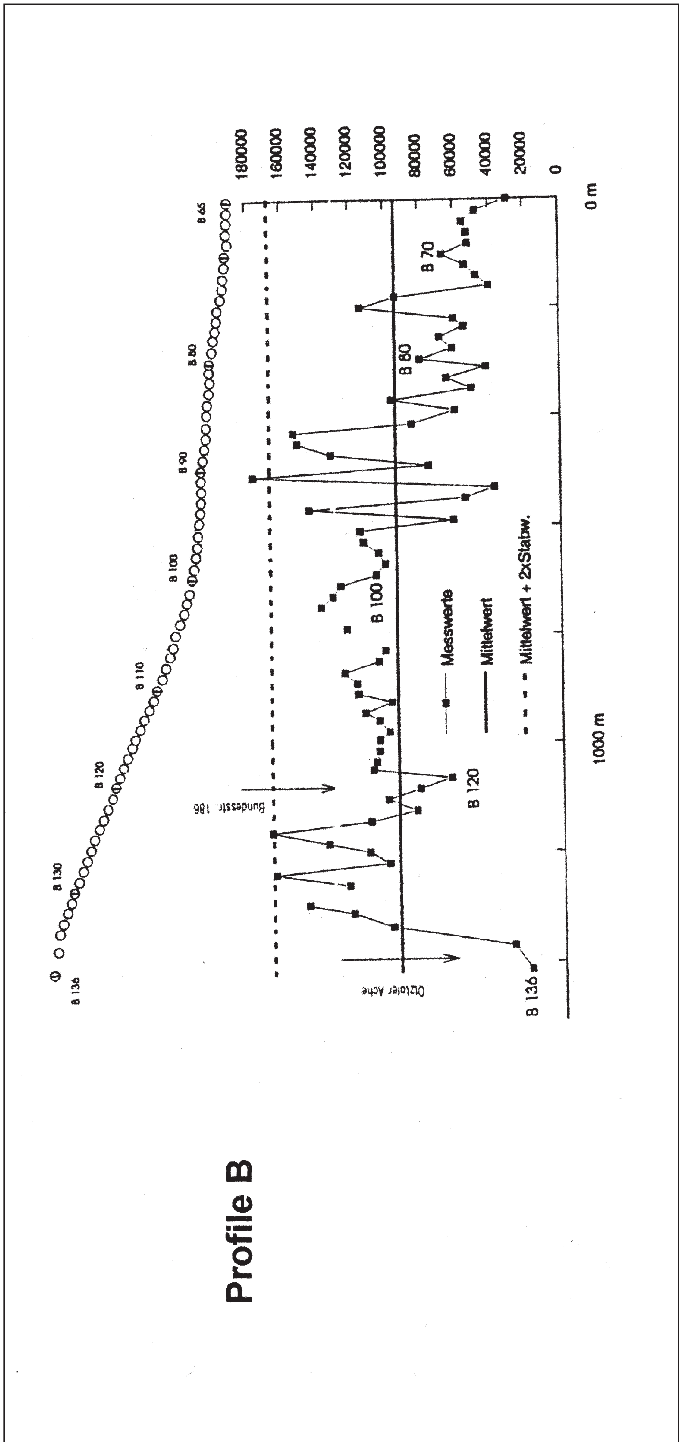


Fig. 2: Results of radon measurements in soil gases along the profiles A, D, B. (Continuation p. 66)
Ergebnisse der Radonmessungen in Bodengasen entlang der Profile A, D, B. (Fortsetzung S. 66)


Profile B
Messwerte
Mittelwert
Mittelwert + 2xStabw.
Bundesstr. 186
Ötztaler Ache
0 m
1000 m
180000
160000
140000
120000
100000
80000
60000
40000
20000
0
B 136
B 130
B 120
B 110
B 100
B 90
B 80
B 70
B 65

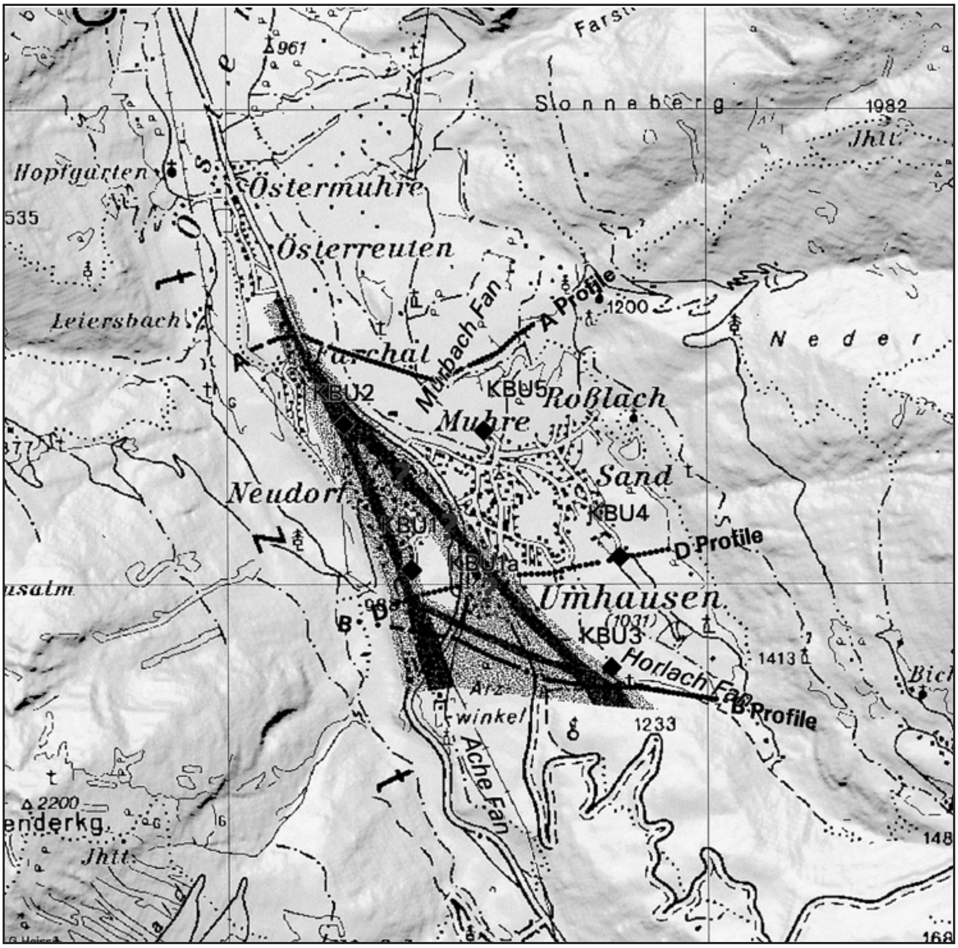


Fig. 3: Lineaments of radon anomalies in the basin of Umhausen; location of profiles (A, D, B), boreholes (KBU) and fans.
Verlauf der Radonanomalien im Becken von Umhausen; Lage der Profile (A, D, B), Bohrungen (KBU) und Schuttfächer.

3. Boreholes

In addition to soil-gas measurements, six boreholes with a total length of 590 m were drilled in order to substantiate the existence of groundwater and to measure the vertical distribution of radon in the unsaturated as well as in the saturated zone. The drilling sites were determined on the basis of tectonical, geological and morphological considerations and soil-gas measurements. The results can be summarized as follows:

1. Owing to the blocky material and lack of a fine-grained matrix, core drilling was extremely difficult in the basin fillings.
2. In each of the boreholes groundwater was found (reaching more than 50 m in thickness in case of the Ache Fan).

3. The groundwater table lies rather deep (between –28.6 and –82.8 m) which may justify the opinion of local people that "there is now water around".
4. In one of the boreholes, radon measurements have been carried out at various depths during drilling (the instrument used, always registrated the summe of Rn-226 and Rn-222 activity per volume unit of air). In all other boreholes this measurement was done after casing with filter tubes and blank pipes. In order to monitor the long-term behaviour of the radon emanation, the measurements were repeated in six to eight weeks intervals (in total for 14 month). In one case, measurements were made several times during one day to examine the short-term variation.
5. The radon concentrations in the air of the boreholes in the Ache, Horlach and Murbach Fan are higher compared to the equivalent soil gas (maximum of 326,000 Bq/m^3).
6. Repeated measurements in one specific borehole displayed extreme variations of the radon concentrations, ranging from 11 to 259,000 Bq/m^3.

4. Groundwater

The high radon concentration in room air and in soil air of the village of Umhausen was known for a long time and confirmed by our systematic measurements. Prior to our investigation, groundwater was not known to exist there and therefore it was not considered as possible source of high radon concentrations. To study the possible role of groundwater as source and carrier of radon, we launched a long-term programme for sampling and analysis of radon in groundwater from boreholes and springs.

The following results were obtained:

a) Groundwater in the Ache Fan shows higher radon concentrations than in the Horlach and Murbach Fan.
b) Groundwater from springs inside the rock fall of Köfels or at its boundary has generally medium to high radon concentrations; the highest value found in the area of Maurach was 1,326 Bq/l (1.3 MBq/m^3).
c) Groundwater from recharge areas outside the fans and the rock fall are generally low in radon (maximum 43 Bq/l). However, an exception has been found downstream the fans near Habichen and Brunau (up to 192 Bq/l), which is most likely caused by the rock fall of Tumpen.
d) The variation of Rn-concentrations in water is significantly lower than in the soil air.

So far the International Commission on Radiological Protection (ICRP) recommends no international limit of the radon activity concentration in water, since the main radiation pathway of radon is assumed to be inhalation. But some governments have defined the limit of the radon-222 activity concentration in the range between 500 and 1000 Bq/l to avoid high inhalation doses. In connection with natural radionuclides in groundwater, radium-226 is of special interest, because it is the parent nuclide of radon-222. For radium-226 an activity limit of 0.123 Bq/l is internationally adopted.

In addition to the described radon analyses in water, **gamma spectrometric measurements of dry residues of water samples** (80 l) have been carried out (Tab. 1).

It should be emphasized that in all water samples a high excess of uranium over radium (15 : 1) was found. This high $^{238}U/^{226}Ra$ ratio is most likely caused by a selective absorbtion of radium during transport (see also below) and can be very often observed in areas with high radon emanation.

Tab. 1: Example of gamma spectrometry of spring water: sample No. MA2-G3932, "Schießstand", 15 May 1996.
Beispiel einer gammmaspektrometrischen Aufnahme von der Quellwasserprobe Nr. MA2-G3932, „Schießstand", 15. Mai 1996.

Nuclide	Activity concentration [Bq/l]
Cs-137	< 0.0004
K-40	0.079 ± 0.014
Pb-210	0.130 ± 0.010
Ra-226	**0.010 ± 0.001**
Ra-228	< 0.0020
U-238	**0.160 ± 0.010**

5. Borehole measurements, property of the aquifer

Geophysical measurements including natural gamma logging were carried out in all boreholes. In comparison with the geological profiles (from core drilling) it was found that the high gamma peaks, which repeatedly appeared in the vertical profile, were not related to potassium-40 (K-40) but to radium , predominantly Ra-226.

The analysis of the core samples by gamma spectrometry, geochemistry and sieve analysis showed that there is nearly no clay between the blocky material. This finding is in accordance with the high permeability of up to 0,12 m/s observed in the sediments of the Ache Fan. Furthermore, our geochemical observations suggest a relation between iron or manganese oxids and radium, which points to trapping of radium by these amorphous oxides.

By **gamma spectrometry of core samples** (Tab. 2) the predominance of radium over uranium turned out which is exactly the opposite relation observed in the groundwater itself. The data of most of the nuclides also show the trend with higher values in the groundwater fluctuation zone than in the deeper part of the aquifer. This is probably also the result of the higher oxygen supply in the ventilation zone together with increased groundwater flow in the upper part of the groundwater body.

Tab. 2: An example of gamma spectrometry of core samples; relative uncertainty of measurements ± 10 %.
Beispiel einer gammaspektrometrischen Aufnahme von einer Kernprobe; relative Messungenauigkeit ± 10 %.

Sample No.	Depth [m]	Activity concentration [Bq/kg]				
		K-40	Pb-210	**Ra-226**	Ra-228	**U-238**
KBU2-G3672	25.5	1150	129	**138**	8	**83**
KBU2-G3673	34.5	1160	199	**148**	< 3	**98**
KBU2-G3674	57.1	1050	120	**117**	20	**89**
KBU2-G3675	76.1	1040	58	**64**	< 2	**73**

6. Modelling

As allready mentioned, the radon concentration measured in houses or in soil-gas samples is the sum of two components representing two sources: a) radon transported by groundwater and b) radon produced by radium trapped in iron/manganese oxids deposited in the Ache Fan. The model in Fig. 4 summerizes the radon balance and the radon dynamics for the Ache Fan in the area of the village Umhausen.

The in-door radon concentration (Rn-226 and Rn-222) in dwellings and houses of Umhausen ranges between 75,000 and 325,000 Bq/m^3. It is even lower than the mean concentration of the groundwater underneath Umhausen, which is most likely due to the dilution, convection and decay processes in the thick overburden.

The calculated ratio of the mean radon concentration in groundwater and in the borehole air ranges between 2.2 and 6.3 and, thus, exceeds the theoretical equilibrium of ~0,4 for water temperatures between 5 and 10 °C (H. L. CLEVER, 1985) by five to 16 times. This seems to indicate that the radon measurements in boreholes were carried out too far away from the groundwater table.

Due to the specific situation in the area of the Ache Fan – like favourable morphological features (e. g. high and steep terrace-slope), high permeability of the sediments in the unsaturated as well as in the saturated zone (K_{max} = 0,12 m/s), high groundwater velocity (in the area of the rock fall more than 200 m/d; R. V. KLEBELSBERG, 1951), extreme climatic contrasts within very short distances (caused by the deep and cold river course, gently inclined and dry basin surface, sun exposed rock fall terrain) and the

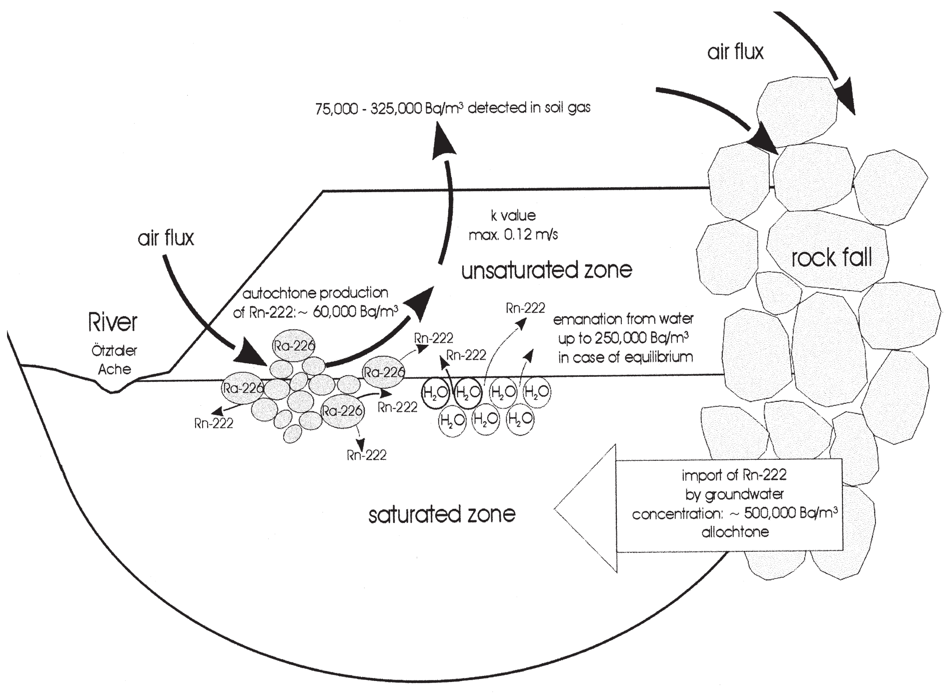


Fig. 4: Model of radon balance (dynamics and distribution).
Modell der Radonbilanz (Dynamik und Verteilung).

immediate contact to the extremely permable rock fall (with so-called "weather shafts") – high radon concentrations can rapidly develop and be strongly ventilated through the unsaturated zone at given weather conditions (chimney-effect).

In any case, it is evident that **high radon concentrations in the soil gas correlate perfectly with high radon concentrations in groundwater.**

Summarizing the geophysical and hydrogeological results, it can be assumed that the radon anomalies in the soil gas are connected with the groundwater flow. According to that two possible groundwater branches have to be considered in the southern part of the basin of Umhausen: one is running parallel to the river Ötztaler Ache and the other one is assumed to originate in the Horlach Fan underneath and covered by the rock fall of Köfels (or might be that groundwater flow, which still follows the paleo-river course of the valley).

A radon source from deep reaching faults, primarily assumed, can now be excluded.

These results have to be implemented now into an integrated water and land use concept for the municipality of Umhausen in particular and of the Middle and Lower Ötz Valley in general.

Summary

The research area under investigation is situated in the Western Central Alps, Austria. Geologically it belongs to the Ötztal-Stubai crystalline complex, composed mainly of para and ortho gneisses, moulded by Caledonian to Alpidic tectonisms.

Typically for the Ötz Valley is its stair-like morphology. Rock falls from both sides gave rise to the formation of basins and narrows. The river Ötztaler Ache is acting as the main drainage system.

This study is related to the rock fall of Köfels/Umhausen (about 10,000 years b.C.) by which two basins filled with unconsolidated sediments were formed. The glacially formed slopes of the main valley, however, are covered with a rather thin layer of debris.

Mica schists and biotite-plagioclase-gneisses have an insignificant yield, their drainage systems are too narrow and shallow. In granite gneisses, eklogites and amphibolites, on the other hand, a higher hydraulic conductivity and partly deep reaching drainage systems can be expected. Potential groundwater reservoirs of larger extent are mainly expected in the thick valley fillings. Actually, a groundwater body of more than 40 m thickness and a width of about 1 km was found in the basin of Umhausen. The groundwater turnover rate in this body was found to be rather high.

In well-defined areas of this basin and in certain parts of the village Umhausen, extremely high radon concentrations of up to 370,000 Bq/m^3 were detected in houses. Local health statistics emphasize a roughly 5-fold increase of lung-cancer-risk in the village Umhausen in comparison to the average value of the Tyrol province.

Preliminary mineralogical investigations indicated that there is a relation between the gigantic rock fall of Köfels/Umhausen and the radon anomaly in its surroundings. Systematic geological/ hydrogeological investigations, using various techniques, confirmed the high radon values (e. g. in the groundwater up to 1.1 Mio. Bq/m^3), identified the different sources, transport paths and transport mechanisms of that noble gas and, finally, arrived at a radon balance of the studied system.

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Zusammenfassung

Das Untersuchungsgebiet liegt in den westlichen Zentralalpen von Österreich. Geologisch gehört dieses dem Ötztal-Stubai-Kristallin an, das hauptsächlich aus Para- und Orthogneisen besteht, die durch die kaledonische bis alpidische Tektonik geformt wurden.

Typisch für das äußere Ötztal ist seine treppenförmige Tallandschaft. Bergstürze von beiden Talflanken waren die Ursache für das Entstehen von steilen Talbarrieren und den dahinter folgenden flachen Talbecken. Die Ötztaler Ache bildet im Untersuchungsgebiet die Hauptvorflut.

Die Studien konzentrierten sich auf den Bergsturz von Köfels/Umhausen, der die Bildung zweier Becken verursachte. Während die Becken mit Lockersedimenten z. T. mächtig gefüllt sind, lagern auf den glazial geprägten Hängen des Haupttales nur dünne Schuttdecken.

Glimmerschiefer und Biotit-Plagioklas-Gneise sind unbedeutend in ihrer Bergwasserführung, zu eng und nicht tiefreichend genug sind die Entwässerungssysteme. In den Granitgneisen hingegen, in Eklogiten und Amphiboliten, kann mit einer höheren hydraulischen Leitfähigkeit auch bis in größere Tiefen gerechnet werden.

Aquifere mit guter Ergiebigkeit sind hauptsächlich an die mächtigen Talfüllungen gebunden. Ein sich rasch erneuernder Grundwasserkörper von über 40 m Mächtigkeit und etwa 1 km Breite wurde im Becken von Umhausen gefunden.

Im selben Becken jedoch, in begrenzten Bereichen des Ortes Umhausen, wurden in Wohnhäusern extrem hohe Radonkonzentrationen gemessen (bis zu 370 000 Bq/m^3). Laut örtlicher Gesundheitsstatistik ist das Lungenkrebsrisiko in Umhausen etwa 5-mal höher als im Land Tirol.

Mineralogische Analysen ergaben den Zusammenhang zwischen der gigantischen Bergsturzmasse und der Radonanomalie in seiner Umgebung. Systematische geologisch-hydrogeologische Untersuchungen mit unterschiedlichen Methoden wiesen die hohen Radonwerte (z. B. bis zu 1,1 Mio. Bq/m^3 im Grundwasser), die Lage der Radonanomalien, den unterschiedlichen Radonursprung, den Transportweg und Transportmechanismus diese Edelgases und schließlich die Bilanz der Radonproduktion nach.

Keywords: radon, radon in groundwater, radon emanation, origin of radon, radon and health risk

Stichwörter: Radon, Radon im Grundwasser, Radonemanation, Radonherkunft, Radon und Gesundheitsrisiko