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Influence of variable stress on underground radon concentrations

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RESUMEN

Los esfuerzos aplicados a las rocas de la corteza generan deformaciones locales. Para medir una señal de radón debida a esfuerzos variables y tensión en la roca, se utilizó un laboratorio natural bajo un tanque de almacenamiento de la planta de energía de Vianden (Luxemburgo). Dependiendo de las demandas de energía, los tanques artificiales que se encuentran en lo alto de una colina sufren fluctuaciones diarias de hasta 16 metros en los niveles del agua y ejercen presiones variables en las rocas donde están asentados. Las concentraciones de radón se miden continuamente en pozos cavados en la roca debajo de los tanques. Se observan algunas variaciones importantes en las concentraciones transitorias de radón inducidas por las fluctuaciones de los niveles del agua. El tanque está compuesto por dos tanques independientes que se vaciaron durante cierto periodo de tiempo. El patrón de comportamiento del radón depende de la localización de los pozos de medida bajo el tanque y es distinto si los dos tanques trabajan simultáneamente, o si uno de los tanques está vacío. Los patrones observados pueden explicarse considerando caminos variables de los fluidos, sobrepresión del fluido y por el flujo dinámico en las fracturas.

PALABRAS CLAVE: Transporte de radón, deformación de la corteza, esfuerzo-deformación de rocas.

ABSTRACT

Stresses applied to rocks of the Earth's crust cause local deformation of the crust. In order to monitor a radon signal due to variable pressures and rock stresses we use a natural laboratory under a reservoir of the Vianden (Luxembourg) pumping storage power plant. Depending on energy demands, the artificial reservoirs at the top of a hill experience daily variations in water levels of up to 16 meters, thus exerting variable pressures on the underlying rocks.

Radon concentrations are continuously measured in boreholes drilled into the bedrock under water reservoir. We observe some very strong variations in transient radon concentrations induced by variations of water level. The reservoir consists of two independent reservoirs that were emptied individually for some period of time. The observed radon pattern depends on the location of the boreholes under the reservoir and is different if both basins are working together, or if one of the reservoirs is empty. The observed patterns can be accounted for by variable pathways of fluids, fluid overpressure and a dynamic flow in cracks.

KEY WORDS: Radon, radon transport, crustal deformation, stress-strain in rocks.

INTRODUCTION

Radon is an omnipresent radioactive noble gas; it may be used as a natural tracer in geophysics, hydrology and geology, as an interesting alternative to other investigation tools. Dynamic phenomena occurring in the rock mass due to earthquakes, volcano activities, tremors, shocks, coal or rock bursts, may be related to outbursts of gas and changing radon concentrations (Trique 1999; Wysocka 1999). We report underground radon monitoring in connection to local stress and strain changes. Radon measurements were initiated under a large water reservoir in order to investigate the possible influence of changing water loads, resulting in changing volumetric stresses. The elastic properties of rocks, the local fracture system and the compressibility of rock pores may define the magnitude of stress-strain-induced variations (Holub 1981). We have shown the influence of earth tides on underground radon concentrations (Kies, 1999). Here we study the possible influence of changing loads on radon levels. A pumped storage facility in the north of Luxembourg affords a well-quantified driving force that produces variations in radon emission by changes in the reservoir load or the weight of water. This is in opposition to the poorly-understood processes in connection with earthquakes or volcano outbursts.

A further aim of our investigations is the possibility to use, for the site of Vianden, radon as a study gas for possible time evolutions of load-induced kinematical processes under the reservoir. Paired with other geophysical observations, this may be a part of safety control tasks.

THE VIANDEN STORAGE POWER STATION

The power station of Vianden is situated in the Devonian of northern Grand Duchy of Luxembourg (Figure 1). Water is pumped regularly from the lower river reservoir into an upper reservoir. This water feeds electric power turbines. The upper reservoir consists of two artificial reservoirs R1 and R2, with a useful water capacity of 3.0 Mm^3 (R1) and 3.8

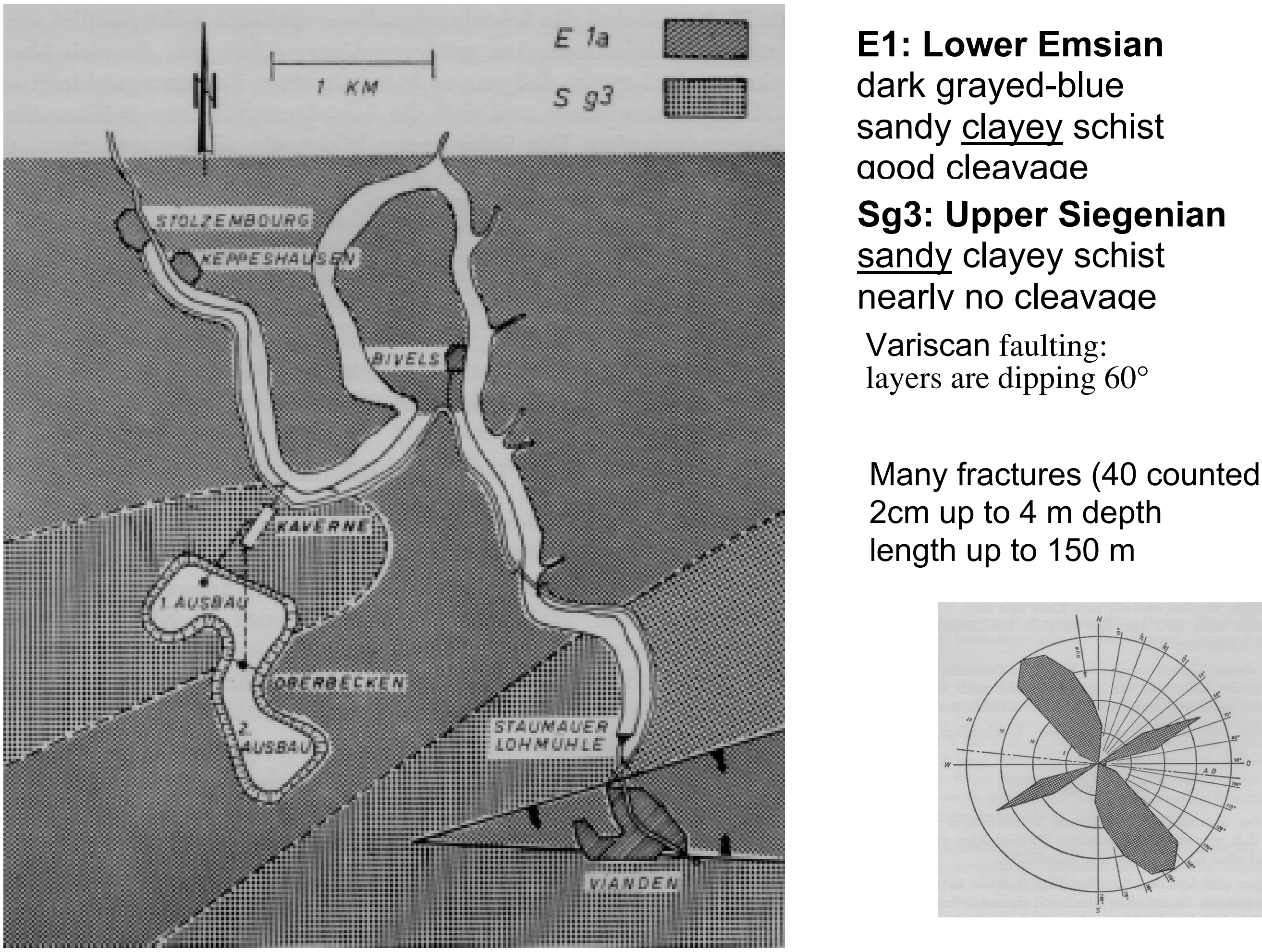

Fig. 1. Geological map of the Vianden pumped power station area (Bintz 1964).

Mm³ (R2) respectively, over a combined area of 0.5 km². The minimum and maximum water heights vary between 494.0 m and 510.3 m, a water level variation of 16.3 m. Normally the connection between R1 and R2 is open and the water levels are identical. Over our investigation period, due to routine works on the basins, either R2 or R1 were emptied for a few months at a time.

Before our investigations, a geophysical network with gravimeters and tiltmeters studied gravitation effects and microkinematical processes due to displacement of the water masses and changing water loads. It was found that gravitationally induced vertical displacements of equipotential surfaces (leveling) locally exceed 0.1 mm (Bonatz and Sperling, 1995; Bonatz, 1997).

EXPERIMENTAL SET-UP

The two artificial basins of the upper reservoir are formed by rockfilled embankments, which surround the plateau of Mount Saint-Nicolas and almost perfectly follow the natural contour. During the banking up (navvying), the upper part of the original hill had to be removed and leveled. The underlying rocks are of Lower Devonian age. For reservoir 1, the rocks are composed of Lower Emsian dark grayed-blue clayey sandy schist with good cleavage. The basement for reservoir 2 is mainly underlain by Upper Siegenian sandy clayey schist with nearly no cleavage. As a result of Variscan faulting and subsequent erosion, layers are dipping by some 60°. Up to 40 fractures had been counted during the leveling. Under the waterproofed bottom of the reservoir are located drainage systems and accessible galleries, partly cut into the rock, that collect the seepage waters so that their discharge rate may be measured.

In a first study, radon was measured at different places in one of these galleries. Even after stopping the forced ventilation it was difficult to show any influence of changing water levels, the main reason being temperature-induced air movements (Kies and Massen, 1999).

In order to get rid of such factors, 1 meter deep vertical boreholes of 10 cm diameter were drilled through the concrete floor of the gallery into the bedrock. In the tightened boreholes, radon in air concentrations were measured indirectly with Aware RM-80 Geiger-Mueller counters. Comparison with Alphaguard and Sarad radon monitors in the radon room at the Centre Universitaire and simultaneous measurements with a flow-through Radim radon monitor (Radim) in a borehole showed a very good correlation between radon concentrations and the gamma dosage from the Geiger counters. The sensibility and resolution of Radim radon monitors and Aware Geiger counters are similar. An advantage of the use of passive Geiger counters is ease of installation and the lack of active pumping with the resulting pressure perturbations in the borehole. Any influence of exterior factors such as temperature or atmospheric pressure can be neglected.

RESULTS AND DISCUSSION

The results of our investigations are presented in two parts. The first part concerns radon concentrations measured in a borehole under R2, where for more than 2 years radon has been measured continuously. The second part presents the results obtained from the other recently drilled boreholes.

Radon (dose-rate) measured under basin 2.

The observed variations of radon levels depend strongly on the water levels of both reservoirs 1 and 2.

(a) During a first measurement period, *reservoir 1 was empty*. A small influence of water level on radon levels could be shown (Figure 2). We notice an anti-correlation between water level and radon concentration. Decreasing water levels lead to the decrease of the vertical load in the bulk of the rocks and this may open supplementary pathways for radon and induce an increase of radon transport through the rocks.

(b) Figure 3 shows the results of measurements in the same borehole with *reservoirs 1 and 2 working* together. The anti-correlation of radon versus water level changes to a strong correlation. Furthermore the amplitudes of the variations are much more significant. It seems that decreasing common loads from reservoirs 1 and 2 are able to open radon pathways that have a diluting effect on radon concentrations measured in the vicinity of the borehole. Another explanation could be changing water levels in fractures and cracks. With both reservoirs operating, the small anticorrelating effect of case (a) is masked by a stronger effect.

(c) R*eservoir 2 was emptied*. According to previous observations radon concentrations in the borehole were decreasing with decreasing water level. Once reservoir 2 is emptied, radon concentrations experience an exponential increase with a 10 h time constant to stable equilibrium concentrations, as experienced under full load. It is very interesting to notice that now the changing water levels of reservoir 1 do not influence radon concentrations.

In general a response time of 2 to 3 hours is observed between a decrease of water level and the variation of radon concentrations. When both reservoirs were working, often a nonlinear effect was observed in the sense that if the water

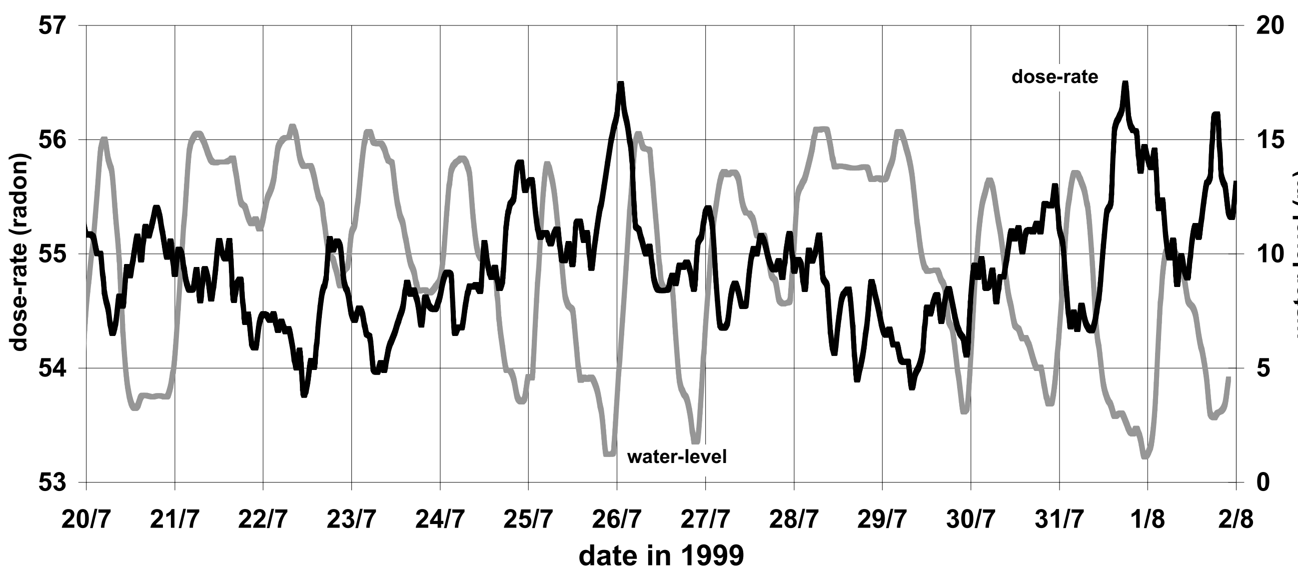

Fig. 2. Radon (dose-rate) in the borehole under reservoir 2 and water level variations in reservoir 2. For the investigated period, reservoir 1 was empty.

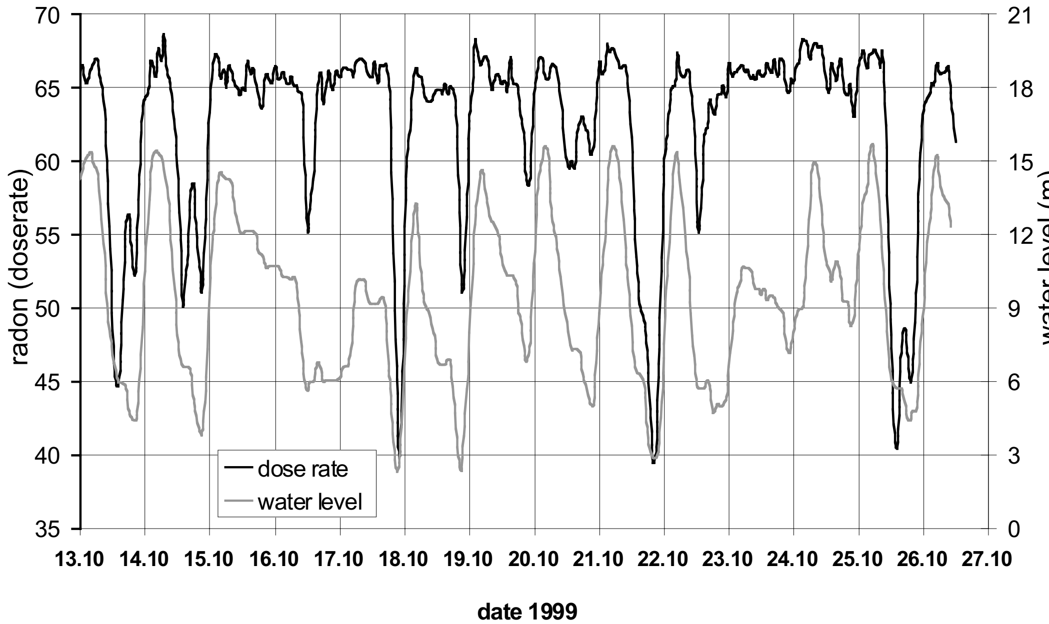

Fig. 3. Radon (dose-rate) in the borehole and identical water level variations in the reservoirs 1 and 2.

level decreased less than 6 m, spikes of very low radon levels occurred.

For interpretation we may assume spatial heterogeneity in the rocks, with different correlation lengths. In a simple way we may assume small-scale grain-grain interactions and a macroscale network of clustered cracks and fractures and percolation defects. A model of stress-energy framework suggests that crustal stress-energy decouples between different scale lengths (Leary 1997).

In case (a) radon could be influenced by small-scale grain-grain interactions, where grain-scale defects interact with stress energy. In case (b) long scale effects are dominant. Crack and microfracture density must be an important factor in the explanation of the observed pattern. This density is essential for the possibility of fracture-fracture communication of fluids, it makes communication of fluids more likely, and intergranular fluids percolate through the rock matrix. Furthermore, rock may be considered as a critical point system. In a model of crack induced anisotropy, defects have a formation energy and interact with other defects at a certain energy level. Opening and closing of interacting fractures and cracks may account for the radon behaviour of case (b), thus explaining the observed radon lows.

In case (c), the long-scale effect is inhibited; without any load from R2 no pathways from R1 to the borehole under R2 are active. At present no convincing explanation could be proposed.

The geology of the rocks under the reservoirs may be of great importance. Coarse sandy clayey schist underlies R1 whereas R2 is built on more clayey schist with a pronounced layering. The main fracture directions of the observed faults extend in the direction given by Figure 1. We may suppose that a decrease of the load of reservoir 1 opens, supplementary entry pathways for radon, due to reversible elastic shear stress situations in the bedrock under both reservoirs.

Early results of radon concentrations measured in three boreholes under R1 show for one borehole a correlation with water load with the same time lag of 2-3 hours, but amplitudes of the variations of radon levels are less important than in case (b). For these measurements R2 was empty. In the future, further investigations, done in different locations under the reservoirs, paired with geophysical investigations may give a more clear view of the rocks affected by reversible stress-strain situations.

CONCLUSION

Variable water levels induce a significant change in radon concentrations in boreholes under a large water reservoir of a pumped storage station. Depending on the distribution of the loads over the measuring point, the effects are different. In the case of localized loads, a small effect on radon concentrations is anti-correlated with water levels, modeled by small-scale interactions with a high response time. Changing water levels of both reservoirs have a much higher influence on radon levels. This time radon concentrations exhibit a direct correlation with water levels. In the case of an extended pressure field, a large effect on radon concentrations is directly correlated to changing water levels. Long-scale interactions through a macroscale network of clustered cracks and fractures and percolation defects may be responsible for these observations.

Emptying the part of the reservoir above the borehole leads to a constant radon concentrations unaffected by water levels of the reservoir.

For the interpretation of the observations the fact that the two reservoirs are situated on different geological structures must be considered.

Unfortunately, until now, no simultaneous measurements of radon concentrations and other geophysical parameters have been performed. Further measurements are planned, in parallel with other geophysical investigations that may permit a better modelling of the stress induced variations of radon concentrations under the reservoir of the Vianden pumped storage station and to draw more general conclusions regarding radon output under various stress conditions.

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