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Calculating flux to predict future cave radon concentrations

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ABSTRACT

Cave radon concentration measurements reflect the outcome of a perpetual competition which pitches flux against ventilation and radioactive decay. The mass balance equations used to model changes in radon concentration through time routinely treat flux as a constant. This mathematical simplification is acceptable as a first order approximation despite the fact that it sidesteps an intrinsic geological problem: the majority of radon entering a cavity is exhaled as a result of advection along crustal discontinuities whose motions are inhomogeneous in both time and space. In this paper the dynamic nature of flux is investigated and the results are used to predict cave radon concentration for successive iterations. The first part of our numerical modelling procedure focuses on calculating cave air flow velocity while the second part isolates flux in a mass balance equation to simulate real time dependence among the variables. It is then possible to use this information to deliver an expression for computing cave radon concentration for successive iterations. The dynamic variables in the numerical model are represented by the outer temperature, the inner temperature, and the radon concentration while the static variables are represented by the radioactive decay constant and a range of parameters related to geometry of the cavity. Input data were recorded at Driny Cave in the Little Carpathians Mountains of western Slovakia. Here the cave passages have developed along splays of the NE–SW striking Smolenice Fault and a series of transverse faults striking NW–SE. Independent experimental observations of fault slip are provided by three permanently installed mechanical extensometers. Our numerical modelling has revealed four important flux anomalies between January 2010 and August 2011. Each of these flux anomalies was preceded by conspicuous fault slip anomalies. The mathematical procedure outlined in this paper will help to improve our understanding of radon migration along crustal discontinuities and its subsequent exhalation into the atmosphere. Furthermore, as it is possible to supply the model with continuous data, future research will focus on establishing a series of underground monitoring sites with the aim of generating the first real time global radon flux maps.

1. Introduction

Radon (^{222}Rn) is a radioactive noble gas that results from the decay of solid radium (^{226}Ra). The release of radon is controlled by the alpha particle recoil mechanisms that expel radon from radium. Whether a newly formed radon atom remains in the mineral grain or whether it enters the intergranular pore space is determined by the position of the radium atoms and the direction of radon atom recoil (Appleton, 2013). The vast majority of radon atoms remain within the mineral grain only to decay once again into a solid product while the tiny minority that enter the intergranular pore space then begin the process of migration towards the surface. Migration is controlled largely by the water retention and fluid transmission characteristics of the bedrock (Åkerblom and Mellander, 1997). The latter include its permeability, its porosity, and its pore size distribution as well as the nature of any crustal discontinuities such as faults, fractures, and joints (Appleton, 2013). It is far more common for radon to be emitted into a liquid phase rather than into a gas phase. Radon

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migration in the liquid phase occurs with the help of carrier fluids and the radon will remain in the liquid phase until a gas phase is introduced. Clearly radon migration in the liquid phase is going to be influenced by factors such as groundwater circulation whereas migration in the gas phase is going to be influenced by factors such as the diffusion characteristics of the gas.

Radon is generally abundant in confined underground spaces such as caves, tunnels, and mines (Stannard, 1988). The numerical model presented in this paper is based on input data recorded in a cave. Measurements of cave radon concentration reflect the outcome of a perpetual competition which pitches flux against ventilation and radioactive decay (Wilkening and Watkins, 1976). In the absence of ventilation it is possible for the radon concentration in such settings to approach that characteristic of soil gas (Wilkening, 1990). Cave radon clearly accumulates as a result of exhalation from the confining rock mass but it is important to have a basic understanding of the contributions made by diffusive transport and advective transport. The distances over which radon atoms can be transported by diffusion are limited by the short half life of radon ($t_{1/2} = 3.82$ d) while the distances over which they can be transported by advection along structural discontinuities is significantly further, perhaps more than one hundred metres (Appleton, 2013). Exhalation by diffusion from solid limestone containing 2.2 mg kg^{-1}U may be expected to result in cave radon concentration measurements in the order of 100 Bq/m^3 (Appleton, 2013). The fact that radon concentration measurements in such settings are generally greater by at least one order of magnitude emphasises the importance of exhalation by advection along structural discontinuities. This importance may be heightened in caves compared to other underground settings as their passages often develop along precisely the same faults and fractures as those used for radon migration.

Faults and fractures permit the efficient transmission of radon to the surface due to the fact that fluids readily migrate along such crustal discontinuities. Consequently many studies have used high radon concentration measurements to infer the presence of discontinuities under soil or glacial drift. High radon concentration is more likely to be encountered if the discontinuities are active (Swakoń et al., 2005; Ielsch et al., 2010; Neri et al., 2011). Discontinuities in the near surface environment may be thought of as active if they are subjected to thermal expansion as this leads to dilation and constriction whereas those at greater depths tend to be more susceptible to slip caused by either gravitational or tectonic processes. The EU-TecNet fault displacement monitoring network has been making direct experimental observations of fault slip at more than one hundred sites across central Europe. More than a decade of data demonstrate that fault motion in this intracratonic region is commonly characterised by steady progressive creep trends: these may be horizontal (strike-slip), vertical (dip-slip), or a combination of the two (oblique-slip). However, the steady progressive creep trends are sometimes interrupted by short periods of anomalous activity, interpreted to reflect a short term perturbation in the regional stress field (Stemberk et al., 2010; Košťák et al., 2011; Briestenský et al., 2015). During these periods the progressive creep trends may be subjected to, for example, a conspicuous reversal; a sudden enduring displacement; or a series of oscillatory displacements. It follows that significant displacements should also be evidenced by radon anomalies especially given that numerous studies have related radon concentration anomalies with other geodynamic phenomena such as earthquakes (Igarashi et al., 1995; Briestenský et al., 2014; Hwa Oh and Kim, 2015).

Once radon has been exhaled into a confined underground space it is then subject to the processes responsible for liberating it into the atmosphere. The most comprehensive recent account of underground meteorology is that of Badino (2010). Air exchange is strongly influenced by convective circulation caused as a result of internal-external buoyancy pressure differences and barometric circulation caused as a result of internal-external pressures differences. The former is particularly important for caves with more than one entrance at different heights whereas the latter is more important for caves with only one entrance or for caves with only extremely small entrances. Diurnal and seasonal circulation changes often result in diurnal and seasonal fluctuations in natural gas and aerosol concentrations (Bezek et al., 2012). The effects of such changes on radon concentration are particularly well known because radon is commonly used as a tracer for cave ventilation modelling (Cunningham and Larock, 1991; Hakl et al., 1997; Tanahara et al., 1997; Przylibski, 1999; Perrier et al., 2004; Kowalczk and Froelich, 2010; Gregorič et al., 2014). However, although the processes governing air exchange are well understood, the mass balance equations used to model changes in radon concentration through time routinely treat flux as a constant. This mathematical simplification sidesteps an intrinsic geological problem: the majority of radon exhalation occurs as a result of advection from crustal discontinuities whose motions are clearly inhomogeneous in both space and time. In this paper the dynamic nature of flux is investigated and the results are used to predict cave radon concentration for successive iterations.

2. Study area

The input data used for our numerical model were recorded at Driny Cave in the geodynamically active Little Carpathian Mountains of western Slovakia (Fig. 1). This mountain range trends SW–NE along the southeastern margin of the Bohemian Massif and forms part of the Alpine-Carpathian Orogenic Belt (Lenhardt et al., 2007). It comprises a mesh of clearly defined morphostructural units (Marko et al., 1991) bordered to the northwest by the Vienna Basin and to the southeast by the Pannonian Basin (Plašienka et al., 1997). The range is characterised by moderate seismicity: the strongest earthquake, with a magnitude of $M_s = 5.7$, occurred in the

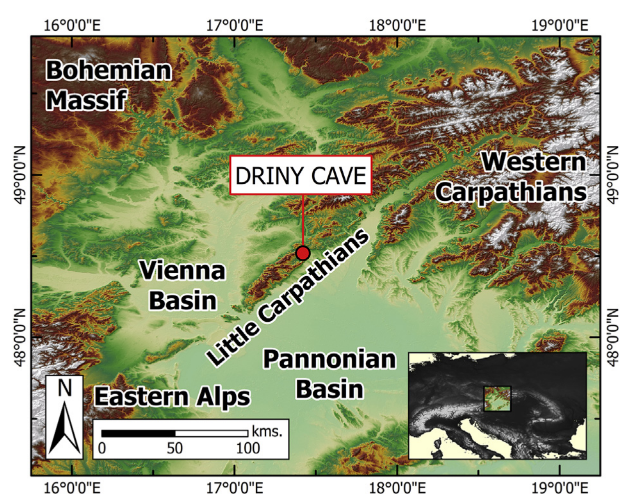

Fig. 1. The location of Driny Cave in the Little Carpathians Mountains of western Slovakia. This range trends SW–NE along the southeastern margin of the Bohemian Massif and forms part of the Alpine-Carpathian Orogenic Belt. The cave passages have developed along splays of the NE–SW striking Smolenice Fault, which hereabouts marks the contact between the Little Carpathians and the Pannonian Basin, and a series of transverse faults striking NW–SE. Detailed information about the cave and its layout is presented in Michalík et al. (1992) and Bella (2006).