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Understanding and modelling dissolved gas transport in the bedrock of three Fennoscandian sites

Paolo Trinchero [a,*], Anne Delos [a,1], Jorge Molinero [a], Marco Dentz [b], Petteri Pitkänen [c]

[a] AMPHOS 21 Consulting S.L., Passeig de Garcia i Faria, 49-51, 1-1, 08019 Barcelona, Spain
[b] Departamento de Geociencias, Instituto de Diagnostico Ambiental y Estudios del Agua (IDAEA-CSIC), C/Jordi Girona 18-26, 08034 Barcelona, Spain
[c] Posiva Oy, Olkiluoto, FI-27160 Eurajoki, Finland

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SUMMARY

The origin and transport of dissolved gases in the geosphere is of interest for assessment studies of nuclear waste repositories. In this paper, we analyse available field measurements of helium, methane and hydrogen at three Fennoscandian sites: Forsmark and Laxemar in Sweden and Olkiluoto in Finland. The field data are interpreted using different analytical models all based on the one-dimensional diffusion equation. The results of the different models provide estimates about the amount of deep gas flux, the in situ production and the groundwater residence time of the considered sites. The computed helium fluxes, which fall within the lower range of crustal degassing fluxes reported by Torgersen (2010), are strictly related with the high tightness of the considered fracture media. The very high estimates of groundwater residence time indicate that, at the considered depths, there are only very few flowing fractures while in the rest of the fractured domain groundwater has been almost motionless during a whole glacial cycle.

1. Introduction

In safety assessment studies of nuclear waste repositories, the release and transport of dissolved gases in deep geological formations has a double interest. On the one hand, noble gases (namely He, Ne, Ar, Kr and Xe) are commonly used as markers of the paleo-hydrogeological evolution, and are good tracers of hydrogeological conditions and groundwater residence times (Andrews and Lee, 1979; Castro et al., 1998; Aeschbach-Hertig et al., 1999; Lippmann et al., 2003; Peeters et al., 2003; Phillips and Castro, 2003). On the other hand, reactive gases, such as CH_4 and H_2, are reducing agents which may consume oxygen and/or be involved in microbial sulphate reduction processes (Pitkänen et al., 1998; Pedersen, 2005).

Naturally occurring helium has traditionally been used as environmental tracer in different investigations focused on very different spatial and temporal scales. Palaehydrogeological studies, which account for the past hydrogeological evolution over time scales that span hundreds thousand years, use helium data to infer the groundwater residence time of regional aquifer systems (Andrews and Lee, 1979; Torgersen, 1980; Andrews et al., 1982; Bottomley et al., 1990; Marty et al., 1993). Helium profiles have been also used to study specific local features of subsurface water bodies, e.g. the rate and spatial variability of leakage from a confining aquitard (Hendry et al., 2005; Mazurek et al., 2011; Gardner et al., 2012), the location and amount of groundwater discharge (Gardner et al., 2011) and recharge (Solomon and Sudicky, 1991). Helium data has also been extensively used to study the residence time in planned nuclear waste repository host rocks (Marine, 1979; Balderer and Lehmann, 1989).

In some of the different existing layouts of nuclear waste repositories (e.g. the KBS-3 concept used in Finland and Sweden), the spent fuel is stored in copper canisters, which might be corroded by sulphide ions present in the groundwater. Thus, several studied has focused on the presence of hydrogen and methane at repository depth and they role in microbially mediated sulphate reduction processes (Pitkänen et al., 1998; Pedersen, 2005; Pitkänen and Partamies, 2007; Delos et al., 2010; Neretnieks, 2013; Wersin et al., 2014).

Here, we analyse available field measurements of helium, methane and hydrogen at three Fennoscandian sites: Forsmark and Laxemar in Sweden and Olkiluoto in Finland. The field data are interpreted using different analytical models that provide

* Corresponding author. Tel.: +34 935 830 500; fax: +34 933 075 928.
E-mail address: paolo.trinchero@amphos21.com (P. Trinchero).
[1] Present address: ARCADIS, 127 Boulevard de Stalingrad, 69100 Villeurbanne, France.

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estimates about the amount of deep gas flux and in situ production and the groundwater residence time at the considered sites.

2. Sites description and field observations

2.1. Geological, geochemical and hydrogeological settings

Olkiluoto, in Finland, and Forsmark, in Sweden, have both been selected as sites for geological disposal of high-level radioactive waste (spent fuel).

The Finnish nuclear waste company Posiva Oy submitted the construction licence application of the deep geological repository of Olkiluoto at the end of 2012.

The Forsmark site was selected by the Swedish Nuclear Fuel and Waste Management Company (SKB) in June 2009 as the site for a final repository, after detailed site investigations both at Forsmark and at a second candidate site, the Laxemar site. A license application for underground construction was submitted to Swedish government in March 2011.

The three aforementioned sites, which are shown in Fig. 1, share common hydrogeological patterns as all of them are located in low permeable fractured crystalline bedrocks. In these types of media, most of the flow takes place in a network of fractures and deformation zones whose density and transmissivity typically decrease dramatically with depth (SKB, 2005a,b; Fransson, 2009).

2.1.1. Olkiluoto site (Finland)

Olkiluoto is located on the coast of Gulf of Bothnia in southwestern Finland. The two main lithological units of the Olkiluoto site are (1) high grade metamorphic rocks and (2) igneous rocks. The host rock is strongly reducing being characterised by extensive hydrothermal sulphidisation and graphite in bedrock (Posiva, 2009). Next to the east of Olkiluoto site occurs an anorogenic Rapakivi granite batholith, which has probably caused significant hydrothermal alteration at the site.

Different groundwater types can be identified with increasing depth. Down to 100 m depth, brackish-HCO_3 groundwater results from the mixing between meteoric and former Littorina Sea derived waters, where organic matter oxidation, calcite precipitation, sulphate reduction, and pyrite precipitation have been reported to occur. Between 100 and 300 m depth, a sulphate-rich groundwater mainly originating from the Littorina Sea is encountered. The enrichment of salinity increases strongly below about 400 m, suggesting the effects of deep, highly saline groundwater, which has apparently been influenced by extremely old brine (Pitkänen et al., 1998; Pitkänen and Partamies, 2007; Posiva, 2009). A similar increase of the salinity versus depth slope has been observed in the Canadian Shield where Gascoyne et al. (1987) have interpreted it to indicate a change of hydrological condition from advection to diffusion; i.e. to fairly stagnant groundwater conditions.

It is worthwhile noting that, at Olkiluoto, an interface between brackish SO_4-rich and SO_4-free brackish and saline groundwaters

Fig. 1. Map of Scandinavia with the location of the three sites under study.