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Characterisation and modelling of mixing processes in groundwaters of a potential geological repository for nuclear wastes in crystalline rocks of Sweden

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HIGHLIGHTS

- Laxemar (Sweden) groundwater is the combined result of several mixing events.
- Water–rock interaction processes explain the remaining variability.
- Four end-members and four conservative tracers have been used in the mixing analysis.
- Mixing analysis has been carried out with M3, a statistical multivariate technique.
- A correlation between water type and fraction of each end-member has been established.

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ABSTRACT

This paper presents the mixing modelling results for the hydrogeochemical characterisation of groundwaters in the Laxemar area (Sweden). This area is one of the two sites that have been investigated, under the financial patronage of the Swedish Nuclear Waste and Management Co. (SKB), as possible candidates for hosting the proposed repository for the long-term storage of spent nuclear fuel. The classical geochemical modelling, interpreted in the light of the palaeohydrogeological history of the system, has shown that the driving process in the geochemical evolution of this groundwater system is the mixing between four end-member waters: a deep and old saline water, a glacial meltwater, an old marine water, and a meteoric water. In this paper we put the focus on mixing and its effects on the final chemical composition of the groundwaters using a comprehensive methodology that combines principal component analysis with mass balance calculations. This methodology allows us to test several combinations of end member waters and several combinations of compositional variables in order to find optimal solutions in terms of mixing proportions. We have applied this methodology to a dataset of 287 groundwater samples from the Laxemar area collected and analysed by SKB. The best model found uses four conservative elements (Cl, Br, oxygen-18 and deuterium), and computes mixing proportions with respect to three end member waters (saline, glacial and meteoric). Once the first order effect of mixing has been taken into account, water–rock interaction can be used to explain the remaining variability. In this way, the chemistry of each water sample can be obtained by using the mixing proportions for the conservative elements, only affected by mixing, or combining the mixing proportions and the chemical reactions for the non-conservative elements in the system, establishing the basis for predictive calculations.

1. Introduction

In the framework of the site characterisation programme carried out by the Swedish Nuclear Fuel and Waste Management Company (Svensk Kärnbränslehantering AB; SKB) two sites have been studied as possible candidates for hosting the deep geological repository for the final disposal of spent nuclear fuel: Forsmark and Laxemar (Andersson et al., 2013) both located in the eastern coast of Sweden (Fig. 1). The host rock and the groundwater system were first characterised to provide information for a site selection, which was based on a

Abbreviations: AM, Altered Meteoric end member; BC, before Christ; DS, Deep Saline end member; Gl, Glacial end member; ICVs, input compositional variables; Lit, Littorina end member; Ma, million years; m.a.s.l., metres above sea level; MM, mixing model; pc, principal component; SFR, Swedish final repository for low and intermediate level radioactive waste; SKB, Svensk Kärnbränslehantering AB; TDS, total dissolved solids; V-SMOW, Vienna Standard Mean Ocean Water.

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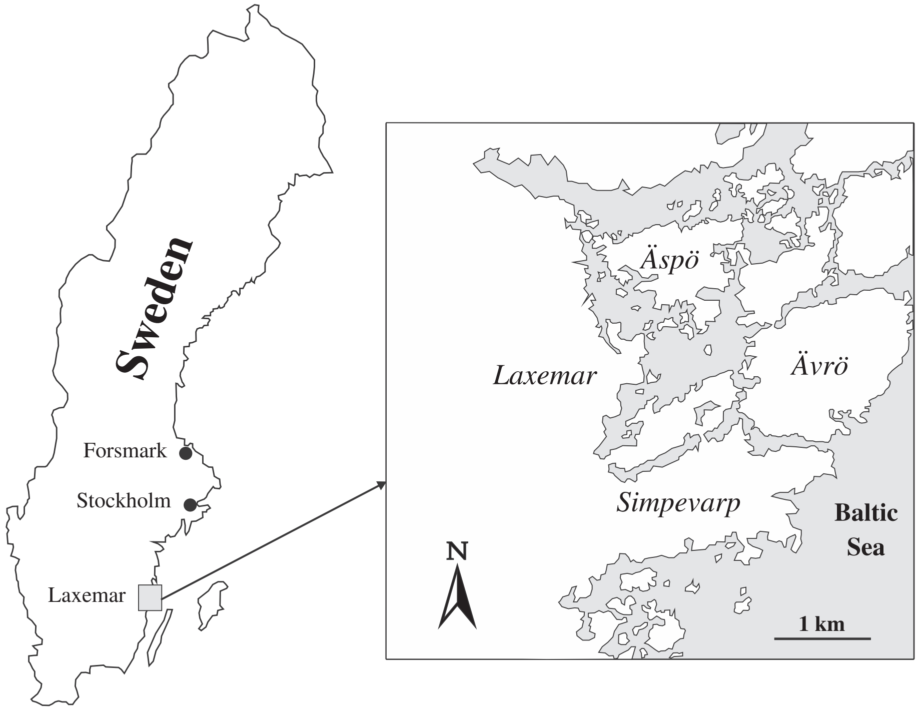

Fig. 1. Location map of the different localities cited in the text, including a detail of the Laxemar area including the subareas of Laxemar, Simpevarp, Äspö and Ävrö.

preliminary evaluation of the long-term safety of equivalent spent fuel repositories on each of the two sites. After the selection of the Forsmark site, the characterisation results have been used to provide input to SKB's licence application to construct a repository at that site.

From the hydrogeochemical point of view, the main aim of the characterisation programme was to understand the present undisturbed hydrogeochemical conditions in the deep (500–1000 m) geological environment of the potential repository and how these conditions may change in the future. To that aim groundwater samples were collected from more than 100 drilled boreholes by SKB. The data were then analysed within a hydrogeochemical study that took into account the general geological knowledge of the system and applied different hydrogeochemical tools, and the results of the evaluation were presented in several technical reports published by SKB (for example, Gimeno et al., 2008, 2009). A characterisation of the main processes controlling the hydrogeochemistry of the groundwater system was necessary in order to reach the goals of the site characterisation programme. Some of these processes are studied here in the Laxemar area, with special emphasis on mixing, as a complement to another paper focusing on the water–rock interactions which will be published elsewhere.

As previously reported in Gimeno et al. (2008, 2009), the evaluation of mixing processes in the Laxemar and Forsmark groundwater systems has confirmed the existence of, at least, four end member waters: an old deep saline water, a glacial meltwater, an old marine water (ancient Littorina Sea) and a modern meteoric water (Altered Meteoric, where "altered" means a meteoric water after reacting with the first metres of the overburden, that is, a shallow and dilute groundwater). As a result, mixing can be considered the prime irreversible process responsible for the chemical evolution of these groundwater systems; the successive disequilibrium states resulting from mixing conditioned the subsequent water–rock interaction processes and, hence, the re-equilibration pathways of the mixed groundwaters (Gimeno et al., 2008, 2009).

The main purpose of the modelling work presented here is to obtain the contribution of each end member to the chemical composition of every water parcel in the system. Once the first-order effect of mixing has been taken into account via the mixing proportions, water–rock interaction can be used to explain the remaining variability. In this way, the hydrogeochemistry of the system is characterised by combining the effects of mixing and reactions allowing the prediction of the future evolution and composition of the system.

To attain this general objective, the key issue is to find a reliable mixing model for the system. Because at least four end-member waters are involved and hundreds of samples are included in the database, traditional geochemical codes are not very useful to grasp the complexity of the system. In consequence, a specific methodology has been designed and implemented, as it is explained in Section 3. Basically the procedure can be summarised in two points: 1) analyse the groundwater dataset of the Laxemar area with the multivariate geochemical code M3 (Gómez et al., 2006) in order to identify the end-member waters needed to explain their chemistry; and 2) define the best mixing model and compute the mixing proportions in terms of the selected end-member waters.

These results, combined with those from water–rock interaction modelling, will define the main processes controlling the groundwater chemistry. This methodology has already been tested in two different sites: the Yucca Mountain groundwater system (USA; Gómez et al., 2011) and the final repository for low and intermediate level radioactive waste, SFR, at Forsmark (Sweden; Nilsson et al., 2011).

2. Geological and hydrogeological features of the Laxemar groundwater system

The general geological description of the Laxemar area has been extensively provided elsewhere (Ström et al., 2008; Laaksoharju et al., 2008c, 2009b; Gimeno et al., 2009; SKB, 2009; Rhén and Hartley, 2009). Only those aspects pertaining to the palaeohydrogeology of the site will be summarised here. The Laxemar area is located close to the shoreline of the Baltic Sea (Fig. 1) and immediately adjacent to the Oskarshamn nuclear power plant and the Central Interim Storage Facility for Spent Nuclear Fuel (Clab). The predominant rock-types in the area are granite and quartz-monzodiorite (Tullborg et al., 2008; Drake et al., 2009). Most of the bedrock was formed between 1900 and 1800 Ma ago and it has undergone both ductile and brittle deformation.