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Research paper

Large-scale tracer profiles in a deep claystone formation (Opalinus Clay at Mont Russelin, Switzerland): Implications for solute transport processes and transport properties of the rock

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ABSTRACT

Natural tracers (Cl^- and stable water isotopes) in pore water of the Opalinus Clay and adjacent formations were studied in the motorway tunnel at Mont Russelin, Switzerland. The Opalinus Clay occurs in the core of an anticline which is cut by a complex system of thrust faults. Concentration profiles of natural tracers were taken from 17 boreholes along a 363 m long section. Pore waters of drillcore samples were analysed with indirect and direct methods. The Cl^- and stable water isotope distribution in the pore water shows a regular and well defined profile, with a conspicuous decrease towards the overlying Dogger limestone aquifer. The highest Cl^- values (approximately 23,000 mg/L) are found in the core of the anticline in Liassic claystones underlying the Opalinus Clay. To quantify the large-scale transport properties of the Opalinus Clay formation, a 2D transport model was constructed and used to reproduce the observed concentration profiles. The calculations indicate that the observed tracer distributions are consistent with diffusion as the dominant transport process. Groundwater flow in the overlying Dogger aquifer was initiated about 2–4 Ma ago, which is long after the folding of the Jura Mountains and probably coincides with the exposure of the aquifer to freshwater recharge following continued erosion of the anticline. The calculations suggest that tracer distributions are controlled by 1) the timing of freshwater recharge in the overlying limestone aquifer, 2) the shape of the anticline and 3) the magnitude and the anisotropy ratio of diffusion coefficients.

1. Introduction

The evaluation of low-permeability rocks as potential host rocks for radioactive waste repositories requires knowledge of large-scale solute transport mechanisms and transport properties. Natural tracers in pore water offer a unique possibility to quantify these properties because they may reflect the hydrogeological evolution of these rocks over millions of years, i.e. at time and space scales comparable with or larger than those needed for a safety assessment.

Early work on pore-water tracers in argillaceous rocks was focused on Quaternary surficial clay deposits (e.g. Desaulniers et al., 1981; Desaulniers and Cherry, 1989). More recently, a clay-rich till aquitard in Saskatchewan, Canada, was studied in great detail (e.g. Hendry et al., 2000; Hendry and Wassenaar, 2004; Hendry and Woodbury, 2007). In deep indurated shales, studies are available from the Toarcian–Domerian at Tournemire, France (Patriarche et al., 2004a,b; Savoye et al., 2008), Opalinus Clay at Benken and Mont Terri, Switzerland (Gimmi et al., 2007; Rübel et al., 2002). These studies use conservative pore-water tracers (anions, water isotopes, and dissolved noble gases) to explore the palaeo-hydrogeological evolution and transport mechanisms across the formations. Transport modelling led to the conclusion that observed tracer distributions can be explained by diffusion-dominated transport.

Here we study natural tracers in the pore water of the Opalinus Clay (Aalenian, 174 Ma) at Mont Russelin in Switzerland. A suite of drillholes were drilled from the Mont Russelin motorway tunnel system near St. Ursanne in the Folded Jura Mountains. Opalinus Clay has been the subject of previous geochemical research at different localities in Switzerland, most importantly in the Mont Terri underground research laboratory (Pearson et al., 2003; Rübel et al., 2002), situated approximately 3 km northwest of Mont Russelin, and in Benken (north-eastern Switzerland; Gimmi et al., 2007). These studies showed that the profiles of natural, non-reactive tracers (stable water isotopes, Cl^-, Br^- and He) show regular and well defined variations across the thickness of the Opalinus Clay. These profiles constitute the main constraints for numerical transport models that were used to understand and quantify solute transport in Opalinus Clay. The tracer profiles at Mont Terri and at Benken are consistent with diffusion as the dominant transport process. Differences in the shapes of the profiles can be attributed to the different palaeo-hydrogeological evolutions of each site. The research campaign at Mont Russelin was initiated to further strengthen the evidence that transport in the Opalinus Clay is diffusion-controlled. Unlike in the Mont

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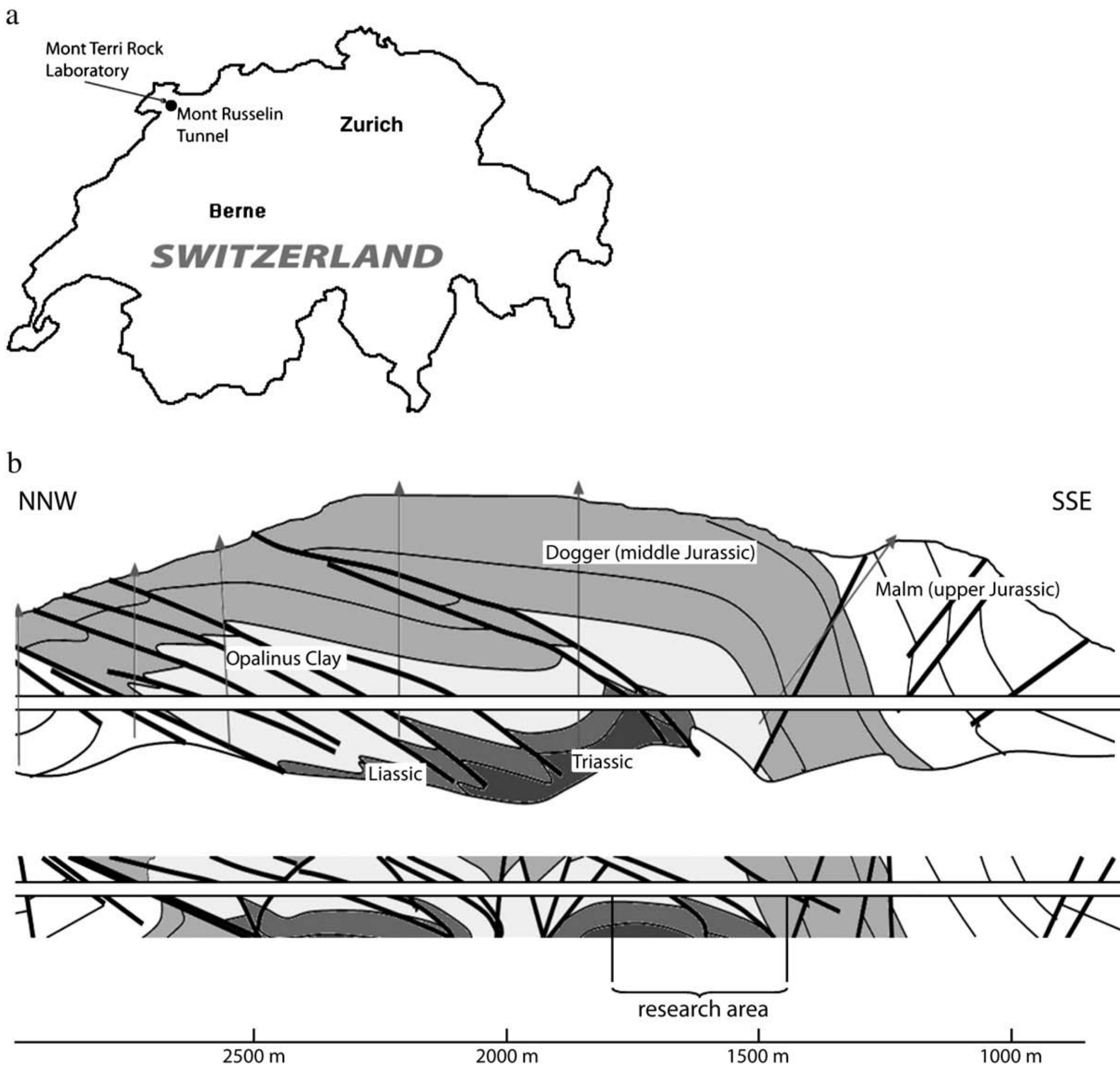

Fig. 1. a) Location of the Mont Russelin motorway tunnel. b) Vertical geological cross-section through the Mont Russelin anticline. Top: Predicted profile on the basis of surface mapping and borehole data available before tunnel construction. Bottom: Profile in the vicinity of the main tunnel based on actual findings. Adapted from Bureau Technique Norbert (1993). Thick lines indicate major faults; thin straight lines with triangles at the ground surface indicate boreholes.

Terri research laboratory, the anticline at Mont Russelin is strongly affected by brittle deformation, and so one of the main objectives of the project was to determine if and how faults and fractures impact on the transport of solutes. For this purpose, we determined Cl^- concentrations and $\delta^{18}O$ and $\delta^{2}H$ values in pore water from core samples taken from a 363 m long section of Opalinus Clay and adjacent formations. Further objectives of the project were: (1) to constrain pore-water compositions using indirect and direct methods, (2) to assess the main transport mechanism in the low-permeability rocks, (3) to constrain the hydrogeological evolution of the Mont Russelin anticline and how it relates to the geological evolution of the Jura Mountains, and (4) to assess the long-term evolution of the pore water.

2. Geological and hydrogeological setting

A motorway tunnel penetrates the Mont Russelin in anticline, which is part of the thin-skinned belt of the Jura Mountains (north-western Switzerland). The Opalinus Clay at Mont Russelin is positioned in the

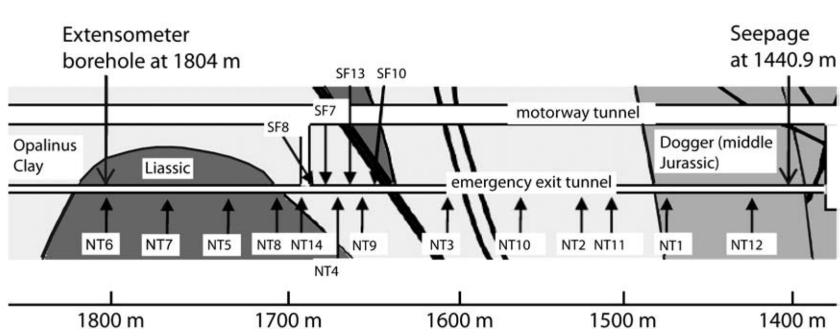

Fig. 2. Schematic horizontal section (map view) along the Mont Russelin tunnel showing the locations of boreholes. Adapted from Bureau Technique Norbert (1990).