Journal of Hydrology 545 (2017) 395–409

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Using noble-gas and stable-isotope data to determine groundwater origin and flow regimes: Application to the Ceneri Base Tunnel (Switzerland)

Yama Tomonaga [a,b,c,*], Roberto Marzocchi [d,e], Sebastian Pera [d], Hans-Rudolf Pfeifer [e], Rolf Kipfer [b,f,g], Laurent Decrouy [h], Torsten Vennemann [h]

[a] Institute of Geological Sciences, University of Bern, Baltzerstrasse 1+3, CH-3012 Bern, Switzerland
[b] Eawag, Swiss Federal Institute of Aquatic Science and Technology, Department of Water Resources and Drinking Water, Überlandstrasse 133, CH-8600 Dübendorf, Switzerland
[c] Atmosphere and Ocean Research Institute, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa-shi, Chiba 277-8564, Japan
[d] IST, Institute of Earth Science, University of Applied Sciences and Arts of Southern Switzerland (SUPSI), Campus Trevano, CH-6952 Canobbio, Switzerland
[e] IMG-Centre d'Analyse Minérale, Faculty of Geosciences and Environment, University of Lausanne (UNIL), Anthropole, CH-1015 Lausanne, Switzerland
[f] Institute of Biogeochemistry and Pollutant Dynamics, Swiss Federal Institute of Technology (ETH), CH-8092 Zürich, Switzerland
[g] Institute of Geochemistry and Petrology, Swiss Federal Institute of Technology (ETH), CH-8092 Zürich, Switzerland
[h] IMG, Laboratoire des Isotopes Stables, Faculty of Geosciences and Environment, University of Lausanne (UNIL), Anthropole, CH-1015 Lausanne, Switzerland

ARTICLE INFO

Article history:
Received 4 August 2016
Received in revised form 17 October 2016
Accepted 21 November 2016
Available online 23 November 2016
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Bartolomé Andreo-Navarro, Associate Editor

Keywords:
Groundwater
Tunneling
Noble gases
Tritium
Stable isotopes

ABSTRACT

Tunnel drilling provides a unique opportunity to sample and study deep groundwaters that are otherwise difficult to access. Understanding deep groundwater flow is of primary importance in assessing the possible impacts of tunnelling on hydrogeological systems. During this study, water was sampled for noble-gas analysis from tunnel inflows in the AlpTransit Ceneri Base Tunnel (Canton Ticino, southern Switzerland), which passes through an area mainly characterized by metamorphic rocks (gneiss). Furthermore, water was sampled from springs located in the same geological environment.

Based on the measurement of noble-gas concentrations and isotope ratios, tritium concentrations, the stable isotope composition of hydrogen (δ^2H) and oxygen ($\delta^{18}O$), and the concentrations of major ions in the water, a conceptual hydrogeological model was established for this case study that allowed the most probable origin of the groundwaters sampled at different locations to be determined. The measured abundances of ^3He, ^4He, and ^{20}Ne allow the geochemical characterization of old groundwaters strongly enriched in terrigenic helium of crustal origin and the identification of mixing with water that circulates preferentially through cataclastic structures. Noble-gas concentrations and isotope ratios as well as tritium are useful proxies for the characterization of faults that may be critical for tunnel drilling because of their active hydrogeological role and their influence on the mechanics of the rocks.

1. Introduction

Characterization of groundwater circulation in massifs is challenging because of the intricacy of these systems and the very limited means to acquire hydrogeochemical information at depth. Tunnel drilling offers a unique opportunity to sample groundwaters that are otherwise extremely difficult to access. Tunneling can also result in the diversion of significant volumes of water from deep aquifers hydrologically connected to surface springs and thus changes in the spring water yield might occur. This can have direct consequences for human activities (e.g., drinking water production) and for the overall water budget of the adjacent biotopes. In assessing the hydrogeology of construction sites, the chemistry of the groundwater is often used to investigate the residence time, origin, and flow pattern of the groundwater in fractured rock (Cook et al., 2003; Teed et al., 2005; Demlie et al., 2008). Nevertheless, the complexity of rock-water interaction means that straightforward data interpretation and comprehensive conceptual understanding of the underground water circulation is not always possible.

Noble gases (He, Ne, Ar, Kr, and Xe) are chemically inert and are, therefore, ideal proxies to study physical processes and flow dynamics in aquifers (e.g., Andrews and Lee, 1979; Stute and Deák, 1989; Beyerle, 1999; Morikawa, 2004; Klump et al., 2006). Deviations from the expected atmospheric equilibrium concentrations (e.g., due to

* Corresponding author at: Institute of Geological Sciences, University of Bern, Baltzerstrasse 1+3, CH-3012 Bern, Switzerland.
E-mail address: yama@tomonaga.ch (Y. Tomonaga).

http://dx.doi.org/10.1016/j.jhydrol.2016.11.043
0022-1694/

the accumulation of radiogenic and terrigenic noble-gas species) can therefore be used to understand the transport dynamics of aquatic systems (Ozima and Podosek, 1983; Kipfer et al., 2002; Brennwald et al., 2013). Groundwaters are known to accumulate non-atmospheric noble gases, in particular He, that may be found in concentrations exceeding the expected equilibrium concentrations. Non-atmospheric He in aquifers can be tritiogenic ^{3}He, which is produced by the decay of tritium (^{3}H), or terrigenic ^{4}He and ^{3}He emanating from the solid earth (e.g., Schlosser et al., 1988; for reviews see Solomon, 2000; Solomon and Cook, 2000). An additional source of noble-gas excess with respect to the expected equilibrium concentrations is the so called "excess air" resulting from the partial dissolution of entrapped air bubbles within the quasi-saturated zone (Heaton and Vogel, 1981; Wilson and McNeill, 1997; Holocher et al., 2002, 2003; Ingram et al., 2007; Klump et al., 2007). Noble-gas concentrations and their isotope ratios have been used, for instance, in lakes and groundwaters to determine residence times, mixing processes, and the origin of water and geogenic fluids (Tolstikhin et al., 1996; Mahara and Igarashi, 2003; Althaus et al., 2009; Holzner et al., 2009; Tomonaga et al., 2011). Experimental evidence indicates that emission of terrigenic He into the atmosphere is focused on particular geological structures such as faults (Oxburgh and O'Nions, 1987; O'Nions and Oxburgh, 1988; Kennedy et al., 1997; Mahara and Igarashi, 2003; Kulongoski et al., 2003; Kennedy and Van Soest, 2007; Pik and Marty, 2009).

Enrichment with tritiogenic ^{3}He can be useful in dating groundwater that was recharged during the last 50 years. Because tritium was released into the atmosphere in large amounts during nuclear bomb testing in the mid-1960s, groundwaters that infiltrated during this time were highly enriched in ^{3}H, which then underwent radioactive decay, forming ^{3}He. On the other hand, terrigenic ^{4}He and ^{3}He can be useful to understand the origin of deep groundwater and can indicate the presence of geological structures fostering migration of fluids from the lithosphere. Furthermore, the ^{3}He/^{4}He ratios allow identification of the source of terrigenic He (from mantle and crust) and hence of deep fluid emission (Kipfer et al., 1994; Tomonaga et al., 2011, 2014). Where tritium is present in groundwater samples, its analysis can provide a quantitative estimation of water age, at least for relatively recent groundwaters (Solomon et al., 1992; Cook and Solomon, 1997; Aeschbach-Hertig et al., 1998; Massmann et al., 2008; Althaus et al., 2009).

Major ions represent the largest share of dissolved solids in groundwaters. In general the most abundant cations are Ca^{2+}, Mg^{2+}, Na^+, and K^+ while the most abundant anions are HCO_3^-, Cl^-, and SO_4^{2-}. The concentrations of major ions is used to classify the respective waters into ionic types depending on the dominant dissolved species (e.g., Back, 1966; Schmassmann et al., 1984). Furthermore, major ions can be used to characterize rock-water interactions (e.g., weathering, ion exchange) that provide initial insights on the residence times of water masses within an aquifer.

The stable-isotope composition of water is another important research tool in the field of hydrogeology, as well as in hydrology, climatology and paleoclimatology (Maloszewski et al., 2002; Maréchal and Etcheverry, 2003; Ofterdinger et al., 2004; Paternoster et al., 2008). This is because differences in the isotope composition of water molecules are related to isotope fractionation during any physico-chemical reactions (Sheppard, 1986; Gat et al., 2001). Measurements of the stable-isotope composition of water can be useful in understanding aquifer recharge, the transit time of water in the rock, and groundwater mixing (Eichinger et al., 1984; Maloszewski et al., 1990; Blavoux and Letolle, 1995).

In this study, noble-gas concentrations, tritium, major-ion concentrations, oxygen and hydrogen isotope compositions were measured in samples collected from inflows to the Monte Ceneri railway tunnel (also known as the AlpTransit Ceneri Base Tunnel) and from springs located in the same geological environment in order to develop a conceptual hydrogeological model (CHM) for the area investigated, which is located in Canton Ticino (southern Switzerland).

2. Geological setting of the sampling site

The Ceneri Base Tunnel is entirely located within the south-alpine crystalline basement (Fig. 1). The tunnel project crosses two different tectonic zones: (i) the Strona-Ceneri zone (amphibolites, Ceneri orthogneiss, Giumello paragneiss) to the north and (ii) the Val Colla zone (S. Bernardo orthogneisses, Stabiello paragneisses, schists and phylonites) to the south. These two zones are separated by the Val Colla Line (known also as Caslano – Taverne – Gazzirola Line), which has a thickness of approximately 600 m (Pini and Rossi, 2009). According to the classification by Buergi et al. (1999), this geological structure is composed mainly of Palaeozoic mylonites.

The tunnel has been drilled from different access points and in different directions. The main construction site is the Sigirino access tunnel, from which the base tunnel is being excavated both to the north and to the south. At the two ends of the tunnel (i.e., the Vigana portal in the north and the Vezia portal in the south) two more construction sites are planned. The north portal of the base tunnel (Fig. 2) is located near the village of Vigana. The first part has been excavated through unconsolidated material. After about 20 m, the tunnel traverses fractured rocks, in particular the Ceneri orthogneiss (100–150 m) followed by the Ceneri paragneiss, which outcrops widely in this region. The thickness of the rock above the tunnel increases from about 10 m (near the north portal) to about 100 m (at a distance of about 400 m from the north portal). From the hydrogeological point of view, orthogneiss and paragneiss generally show low hydraulic conductivity; values between 10^{-7} m/s and 10^{-10} m/s were in fact measured in prospective boreholes (Marzocchi et al., 2010). The main water inflows are linked to two main cataclastic zones that cross the tunnel at 170 m and 300 m, respectively, from the north portal (Fig. 2). These zones, according to Buergi et al. (1999), are classified as kakirites. Kakirites show in general high water conductance and hence are expected to allow relatively fast groundwater flows.

The Sigirino access tunnel was excavated entirely through fractured rocks. In particular it passes through Ceneri orthogneisses and gneisses, hornfels, amphibolites and Giumello paragneisses (Fig. 3). The permeability of these rocks is generally low and the tunnel was excavated mainly in dry conditions. Only occasional lateral drippings were observed in the first 100 m of rocks (with high discharge related to precipitation), as well as downstream and upstream of the main cataclastic structures (mylonites and kakirites) being crossed by the tunnel. Mylonites are metamorphic rocks characterized by a much lower hydraulic conductivity compared to kakirites. The position and dip of these structures are shown in Fig. 3.

3. Methods

Eight water inflows at the Vigana (VIG 1–4) and Sigirino (SIG 630, SIG 958, SIG 1030, SIG 1580) sites were sampled for noble-gas and geochemical analysis (Figs. 2 and 3). At the Vigana site the water discharge was moderate to high (1 L/min. up to 360 L/min.; Table 1) while at the Sigirino site the volume of water percolating from the tunnel fractures was rather limited (0.1 L/min. up to 0.2 L/min.; Table 1). Samples from two springs (Sp-N and Sp-S) located in the same geological environment (fractured gneiss) were also collected. The two springs are situated at the