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Hydrochemical considerations for identifying water from basaltic aquifers: The Israeli experience

P. Möller[a,*], E. Rosenthal[b], N. Inbar[b], F. Magri[a,c,d]

[a] GFZ German Research Centre for Geosciences, Section 5.3—Hydrogeology, Potsdam, Germany
[b] Tel Aviv University, Department of Geophysics and Planetary Sciences, Tel Aviv, Israel
[c] Helmholtz Centre for Environmental Research (UFZ), Department of Environmental Informatics (ENVINF), D04318 Leipzig, Germany
[d] Freie Universität Berlin, Hydrogeology, 12249 Berlin, Germany

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In memory of Asaf Pekdeger to his 65th birthday.

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ABSTRACT

Study region: Yizre'el-Harod-Bet She'an valley, Lower Galilee and Golan Heights, Israel.
Study focus: Identification of pure groundwater that infiltrated the widespread alkali olivine basalts in the replenishment areas of the study region.
New hydrological insights for the region: The groundwater is characterized by equivalent ratios such as Na/Cl > 1; $Na/HCO_3^- < 1$; SO_4^{2-}-fraction < 0.1; $HCO_3^-/(Ca+Mg+Na) \geq 0.7$; $HCO3^-/(Ca+Mg) > 1$; 1000Br/Cl in the range of 1–2.5; $\delta^{34}S_{sulfate} < 5$‰ (CDT). Bowl-shaped-normalized REY distribution patterns are indicative for recharge over basaltic outcrops. These aquifers are recharged not only by direct precipitation on volcanic exposures but also by water from underlying confined limestone aquifers. Groundwater from the limestone aquifers is characterized by Na/Cl < 1; $HCO_3^-/(Ca+Mg) < 1$; $HCO_3^-/(Ca+Mg+Na) < 0.7$; 1000Br/Cl in the range of 1.6–10; $\delta^{34}S_{sulfate}$ range from 20 to 25‰ (CDT). The wide spread of these parameters characterizes mixing of groundwater from both limestone catchments and aquifers in different stages of hydochemical evolution. The REY patterns of these groundwaters resemble those of limestones. If $\delta^{34}S_{sulfate}$ and/or REY distribution patterns are not available, the unmixed water from basaltic-rock aquifers show up in the field of $HCO_3^-/(Ca+Mg) > 1$ and $HCO_3^-/(Ca+Mg+Na+K) > 0.7$. Application of these parameters to analyses showing only the main constituents of groundwater reveals that in the study area the contribution of unmixed groundwater from basaltic catchments is largely restricted to the Golan Heights. Mixing of groundwater by interaquifer flow is a common phenomenon all over the area.

1. Introduction

When attempting to define the hydrological properties of volcanic rocks, two main groups are immediately sorted out—sequences of hard basalt flows and accumulations of tuffs and scoria. The hydrological properties of the latter are similar or close to those of coarse clastics and gravel. Contrarily, groundwater flow through sequences of hard basalt is usually characterized by very low hydraulic conductivities (10^{-8}–10^{-13} m/s) because the pores, generated by release of volatiles from the lava, are not interconnected (Freeze and Cherry, 1979). Therefore groundwater flow through sequences

* Corresponding author at: GFZ German Research Centre for Geosciences, Section 5.3—Hydrogeology, 14473 Potsdam, Germany. Fax: +49 331 2881529.
E-mail address: pemoe@gfz-potsdam.de (P. Möller).

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of basalt flows is anisotropic, mainly through cooling cracks and fissures and through horizons of gravel and paleosoils formed between different lava flows during temporary cessation of volcanic activity. Perched water horizons are common in phreatic basalt aquifers. Although primary porosity is insignificant, fractured basalts are permeable. The production from wells in basalts is unpredictable; it may yield either high or low volumes. Nevertheless, this type of basaltic-rock aquifer is the only reliable source of water supply on volcanic islands (e.g., Canary Islands, Hawaii) and in areas covered by large basaltic flows such as the Columbia Plateau-, Pacific Northwest-, Snake River Plain basalts USA (Miller, 1999), basalts of the Blackburn Hills volcanic field of western Alaska (Moll-Stalcup and Arth, 1991), the Upper Cretaceous to Eocene Deccan Traps of India (Singhal and Gupta, 1999), the Atherton Tablelands, Australia (Locsey, 2004), the Early Jurassic basalts of the Karoo Province, South Africa, the Middle Paleozoic to Mesozoic basalts of the Siberian Traps, Russia, and the Lower Cretaceous Parana Volcanics of Brazil (Singhal and Gupta, 1999), the Mexican Trans-volcanic Belt (Edmunds et al., 2002), the Tertiary basalts of the Gedaref Basin in eastern Sudan (Hussein and Adam, 1995), basalts of the Ethiopian Rift Valley (McKenzie et al., 2001), the plateau basalts in north-eastern Jordan (Lloyd, 1965; Abu Jaber, 2001). In these areas basaltic aquifers are the only reliable sources for water supply and large volumes of groundwater are withdrawn from them.

The distinction between different groundwater bodies flowing in regional multi-aquifer systems, which include basalts and over- or underlying aquiferous formations, is hydrologically challenging. Such multi-aquifer systems are widespread in Israel, e.g., in the Lower Eastern Galilee, in the Yizre'el and Harod valleys (Rosenthal, 1988) and on the Golan Heights (Dafny, 2003) (Fig. 1). In order to define the source of groundwater, it is necessary to define hydrochemical criteria which would allow discerning between groundwater deriving from either volcanic or carbonate aquifers of origin. A different case of problematic identification is encountered in Israel, in areas which are part of the Jordan-Dead Sea Rift valley or are adjacent to it. Large parts of these areas are covered by basalts from which groundwater is extracted (Fig. 2). These waters are often characterized by equivalent ratios of Mg/Ca > 1. Such ratios (which are often encountered for water from volcanic aquifers) also characterize certain brackish and saline waters and brines which had no "basaltic history" but are widespread in the area. For purposes of regional water management, it is necessary to define chemical parameters which would enable to distinguish and eventually separate between the two (chemically) resembling waters and define their origin and flow-paths. In previous papers, Rosenthal (1988) proposed to use Na/Cl and Mg/Ca values to distinguish between water deriving from basaltic and carbonate aquifers. However, high Mg/Ca ratios were encountered in numerous groundwaters, prevalently from brackish and saline sources absolutely unrelated to basalts. Additional parameters such as $\delta^{34}S$ in sulfate were suggested to distinguish between sulfate of marine origin and oxidation of igneous sulfides (Siebert et al., 2012). Rare earth (REE) and yttrium (Y) distribution patterns (henceforth termed REY) were used to characterize the catchment lithology (Möller et al., 2003; Siebert et al., 2014). REY and $\delta^{34}S$ information, however, are only available for recent analyses. To make use of the wealth of old analyses without Br and REY concentrations and $\delta^{34}S$ of sulfate, the necessary information about the origin of groundwater has to be extracted only from the major elements. Comparison of both REY interpretations and $\delta^{34}S$ of sulfates is not always congruent with major element interpretation of the origin of groundwater because REY behave differently in catchments and in aquifers (Möller et al., 2003; Tweed et al., 2006).

2. Geological setting

The Neogene northern basin (Picard, 1932) includes the Yizre'el-Harod-Bet She'an-Mehola valleys (henceforth referred to as the Valley) and the Lower Galilee plateau (Fig. 1). It extends between the Carmel and Gilboa Mts. in the southwest, the Upper Galilee in the north and the Jordan-Dead Sea rift in the east. According to Fleischer and Gafsou (2003), the original structure of this basin (top Upper Cretaceous Judea Group as structural key horizon) is a deep NNE plunging syncline. The formation of this basin is related with the opening of the Red Sea during the Late Oligocene or Early Miocene which caused shearing along the Jordan valley-Arava/Aqaba lineaments (Quennell, 1956; Gvirtzman et al., 2010). It was accompanied by eruptions of alkali olivine basalts leading to the subsequent severance of Arabia from the African Plate (Hirsch, 2005). The stratigraphic section of the basin includes the Middle Miocene Lower Basalt, the Upper Miocene Intermediate Basalt and the Pliocene/Pleistocene Cover Basalts (Shaliv, 1991). The basaltic flows and tuffs of the Lower Eastern Galilee and in the Valley partially interfinger with fluvio-lacustrine beds of the Hordos formation (Picard, 1943; Schulman, 1959). The sequence of the Lower Basalts (K–Ar age 9–17.5 Ma) attains the thicknesses up to 660 m, whereas the thickness of the Cover basalts (5.3–3.3 Ma) is in the 150–200 m range (Shaliv, 1991; Eppelbaum et al., 2004). The Intermediate basalts (6.2–8.4 Ma) do not exceed a few tens of meters. The distribution of basalts is not restricted to the exposures in the Lower Galilee but were identified by drilling and by geophysical explorations in the subsurface of the Valley (Rosenthal, 1980; Segev et al., 2006; Meiler et al., 2011) (Fig. 2).

In the Golan Heights the alkali olivine basalts and other volcanic rocks of Plio–Pleistocene age comprise the Bashan Group (Dafny, 2003). At the time of its eruption, the lava that formed the Bashan Group volcanics, a broad syncline, whose relief was formed by tectonics and erosive processes, extended in the area between the Hermon anticline in the north and the Ajloun anticline in the south (Fig. 1). The Bashan Group basalts covered unconformably the relief, filled the syncline and created an elevated plateau. The total thickness of the volcanic sequence exceeds 524 m (Dafny, 2003). In 2013 a new well was drilled to a depth of 600 m and did not reach to the bottom of the volcanic sequence. Most of the Bashan Group volcanics are stratigraphically equivalent to the Cover Basalt and only its uppermost horizons are younger, i.e., of Quaternary age.

The Lower and Cover Basalts are separated by the Bira (Upper Miocene) and Gesher (Late Miocene to Early Pliocene) Formations. The Bira Fm is a sequence of +350 m of clay, chalk, marl, gypsum and halite, rich in pyrite and organic matter