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Groundwater recharge and flow on Montserrat, West Indies: Insights from groundwater dating

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ABSTRACT

Study region: Montserrat, Lesser Antilles, Caribbean.
Study focus: Analysis of δ^2H and δ^{18}O isotopes, and chlorofluorocarbon (CFC) anthropogenic tracers in Montserrat groundwater provides insights into the age and provenance of the spring waters.
New hydrological insights: δ^2H and δ^{18}O analysis indicates uniform recharge elevations for groundwaters on Montserrat. CFC-11 and CFC-12 analysis reveals age differences between isotopically similar, high elevation springs and low elevation aquifer waters. Low CFC concentrations within a confined low elevation aquifer suggest water ages of ~45 years. High CFC concentrations in the northern and western springs are explained by rapid infiltration of cool (high CFC concentration) rainfall into saturated compartments, with flow through the vadose zone to the phreatic zone dominated by compartment flow. Lower CFC concentrations in a number of aligned warmer springs suggest a contribution from older, warmer waters from depth. Temperatures and CFC concentrations indicate older component supply rates of up to 8 L/s to the highest yielding spring on Centre Hills, with contributions of up to 75% in the warmest spring waters.

1. Introduction

Despite high rainfall on the tropical, volcanic island of Montserrat, Lesser Antilles (Fig. 1a), surface water is limited and the deeply incised drainage channels (known locally as ghauts) are largely ephemeral. The only permanent streams are sourced from springs which emerge at elevations ranging from 200 and 400 m (amsl) (Hemmings et al., 2014). The freshwater demands of the entire island are met by potable supply from six productive springs on the flanks of the extinct volcanic complex of Centre Hills (CH) (Fig. 1b). In 2013 the combined discharge from the six supply springs was in excess of 50 L/s (Montserrat Utilities Ltd. (MUL), unpublished data). Supply at this rate easily meets the current demands of the population, (~19 L/s). However, consumptions rates are expected to rise as population and agriculture recover, during a period of relative quiescence, after >15 years of destructive and disruptive volcanic activity at Soufrière Hills Volcano. An expected increase in future freshwater demands, together with historical fluctuations in spring discharge (Hemmings et al., 2014), demonstrates the fragility of the freshwater resource on Montserrat.

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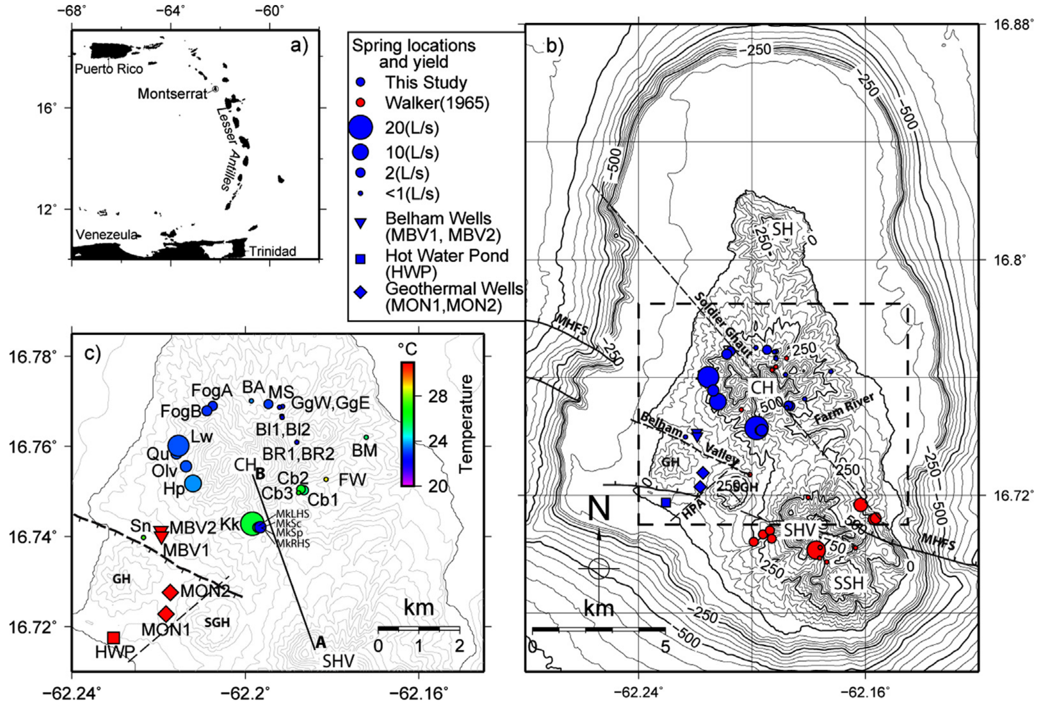

Fig. 1. (a) Location of Montserrat within the Lesser Antilles arc. (b) Spring locations and discharge with major volcanic complexes (SH, Silver Hills; CH, Centre Hills; SHV, Soufrière Hills Volcano; SSH, South Soufrière Hills.) Also marked are GH, Garibaldi Hill; SGH, St George's Hill and the major active (solid lines) and inferred (dashed lines) fault systems: MHFS, Montserrat-Havers Fault System and Belham Valley fault, from Feuillet et al. (2010); Soldier Ghaut fault, inferred by Hautmann et al. (2010); HPA, the NE trending fault inferred by Ryan et al. (2013) from earthquake hypo-centres. (c) Temperatures of spring waters and Belham Valley artesian well waters (inverted triangles) Hemmings et al. (2014). Also marked is Hot Water Pond (HWP, square) at 56 °C and the locations of the two geothermal boreholes (MON1 and MON2, diamonds). Spring codes relate to springs in Table 1. Circle radius is proportional to spring discharge. The line A–B is the surface trace of the schematic cross-section presented in Fig. 8.

Fragile water resources are familiar to many island populations, particularly on volcanic islands where high surface permeabilities are typical and groundwater flow is critical to supply. Understanding the complex groundwater systems that exist in these settings is essential for effective and sustainable resource management. The results of this study highlight and illuminate the complexity that exists in volcanic island hydrology, particularly volcanic arc islands. The methods we describe will be useful for study of groundwater systems in other volcanic island settings. In a recent study on the basaltic ocean island of Hawaii, Kelly and Glenn (2015) combined anthropogenic tracers (Chlorofluorocarbons, CFCs) and isotope analysis to explore the residence times and recharge areas of groundwater in coastal drinking water aquifers. Here, we analyse CFCs and stable isotopes δ^2H and δ^{18}O, in Montserrat groundwater, aiming to provide insights into the age and provenance of the island's vital spring waters.

1.1. CFCs as groundwater tracers

Chlorofluorocarbon (CFC) analysis, particularly CFC-11 and CFC-12, have proven to be a valuable tool for dating groundwater younger than 60 years (Stuart et al., 2010). It also has the potential to provide insights into the extent of mixing between groundwater components of different age (Gooddy et al., 2006). The use of CFCs for dating of groundwater is based on known concentrations in the atmosphere over the last 60 years, together with observations that they are globally well-mixed, and the assumption that their solubility in water follows Henry's Law at the temperature of recharge (Darling et al., 2012). CFC concentrations in groundwater are assumed to be proportional to the partial pressure, p_i, of the gas in the atmosphere at the time of recharge (Dunkle et al., 1993; Plummer et al., 2006):

$$C_i = K_{H_i} p_i, \tag{1}$$

where C_i is the concentration of a particular CFC compound in water, and K_{H_i} is the Henry's Law coefficient for that CFC compound. K_H is a function of both temperature and salinity and has the form (Warner and Weiss, 1985),

$$\ln K_H = a_1 + a_2\left(\frac{100}{T}\right) + a_3 \ln\left(\frac{T}{100}\right) + S\left[b_1 + b_2\left(\frac{T}{100}\right) + b_3\left(\frac{T}{100}\right)^2\right], \tag{2}$$

where T is temperature in degrees kelvin and S is salinity in parts per thousand by weight. a_1, a_2, a_3, b_1, $b_2$and b_3 are least squares fitting parameters, determined by and detailed in Warner and Weiss (1985).