Use of Geochemical Tools to Study Groundwater Salinization in Volcanic Islands: a Case Study in the Porto Santo (Portugal) and Santiago (Cape Verde) Islands

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ABSTRACT

Porto Santo (Portugal) and Santiago (Cape Verde) are two volcanic islands of the Macaronesia region with scarce freshwater resources that rely on groundwater and seawater desalination plants to guarantee public water supply and irrigation needs. Rainfall is less than 400 mm/year and unreliable, as it usually occurs as short heavy events that may produce flash floods and strong landscape erosion (locally called 'badlands').

Volcanism in the studied regions occurred intermittently since at least Palaeogene (in Santiago) and Lower Miocene (Porto Santo) in an environment characterized by dramatic eustatic and isostatic sea-level fluctuations and active tectonics. Periods of prolonged volcanic activity under submarine or subaerial conditions alternated with phases of volcanic quiescence dominated by intensive erosion and deposition of sedimentary formations. The islands are mainly composed of basaltic-trachytic-rhyolitic lava flows and some alkaline rocks, with a subordinate amount of pyroclastic and sedimentary rocks.

Studied volcanic formations are often very heterogeneous from the hydrogeological point of view. The principal hydrogeological formations are formed by the modern unconsolidated sedimentary formations (alluvium, conglomerates and eolianites) that outcrop downstream the principal spring-fed creeks or by volcanic formations with interstratified high permeability levels of pillow lavas, breccia and hyaloclastites. Groundwater recharge is by rainfall infiltration in the higher part of the islands. The water infiltrates and moves downward in the interior of the islands with preferential flow occurring along zones with faults, fractures and dykes. The aquifers discharge to several springs, wells, boreholes and along the shoreline where increasing salinities are becoming a major constraint on groundwater utilization.

Detailed hydrogeochemical investigations have been carried out in both islands to characterize groundwater quality, to determine the origin of groundwater salinization processes and to identify the principal areas in risk of seawater intrusion in order to develop mitigating measures to reduce contaminating risk. The geochemical results obtained point to two different sources of groundwater salinization, one due to prolonged water-rock interaction in aquifer formations which have high natural background salinities; and, the other one due to seawater intrusion along low-lying alluvial valley aquifers and other shallow coastal aquifers. Seawater intrusion is aggravated in these aquifers by overpumping for tourism (in Porto Santo) and agriculture (in Santiago) and also by illegal removal of alluvium materials for construction.

Keywords: volcanic islands, salinization, groundwater quality, natural background

INTRODUCTION

Fresh water resources in volcanic islands located in semiarid regions are limited and extremely vulnerable to climate changes and management practices. Surface water circulation is often confined to the highest parts of the islands and/ or to short periods after the heavy rainfall events, which occasionally occur during the wet season. Groundwater resources are usually the principal source of fresh water for local populations and agriculture. However, due to the common water shortage problems that affect these regions, the emphasis is placed on groundwater availability rather than quality and groundwater resources face an increasing risk of contamination.

The main risk of groundwater contamination in volcanic islands is salinization, which may result from natural rock-water interaction processes (cation exchange, dissolution, precipitation, surface complexation) between circulating groundwaters and volcanic materials that are enriched in several geochemical elements (Cl, Na, Si, As, F); or, from seawater intrusion due to non sustainable groundwater abstraction. Strong evaporation may also contribute for salt reconcentration in areas with shallow water levels.

STUDY AREAS

The present study was carried out in two volcanic islands located in the Atlantic Ocean along the west coast of Africa – Porto Santo (Portugal) and Santiago (Cape Verde), which have very limited natural resources, including serious water shortages, and where groundwater is the principal source of freshwater. Both islands have a semi-arid to sub-tropical climate with unreliable and erratic rainfall leading in some years to prolonged droughts.

Porto Santo is a small volcanic island (42.26 km^2) located in the northeast part of the Madeira archipelago between 32º 59’ and 33º 07’ N parallels of latitude and 16º 16’ and 16º 24’ W meridians of longitude. The island has a relatively steep relief in its northeast and southwest extremes, which are over 450 m above sea level, and a low lying flattened area in its central part, which is approximately 150 m high.

Santiago is a mountainous volcanic island located in the south part of the Cape Verde archipelago between 15º 20’ and 14º 50’ N parallels of latitude and 23º 50’ and 23º 20’ W meridians of longitude. It is the largest island, both in size (991 km^2) and population (236 627 inhabitants), and where the capital, Praia, is located. Water resources in the island of Santiago are limited and due to its characteristically steep relief and eroded soils, most surface water drains into the ocean immediately after the occasional rains. Less than one-third of the Santiago population is connected to any type of water supply system and safe drinking water is, therefore, in short supply.

HYDROGEOLOGICAL SETTING

The two studied volcanic islands are very heterogeneous from the geological and hydrogeological point of view. In Porto Santo groundwater resources are limited in general to the principal sedimentary formations - the calcoarenites from the eolinite formation and the old and modern beach sand deposits. Most of the volcanic formations have low permeability but in some parts of the island interstratified levels of hyaloclastites and submarine volcaniclastic deposits increase locally the permeability and create conditions for spring occurrence.

In Santiago the principal hydrogeological formations are the submarine pillow lava formations and the modern alluvium and conglomerate formations located along the principal creeks. Groundwater recharge is by rainfall infiltration in the higher part of the island. The water

infiltrates and moves downward in the interior of the island with preferential flow occurring along zones with faults, fractures and dykes. The aquifer discharges to several springs, wells, boreholes and along the shoreline where increasing salinities are becoming a major constraint on groundwater utilization.

METHODS

Groundwater samples were collected from springs, wells and boreholes located within the two studied islands. A multiport flow-through cell connected in-line to the sampling points was used to obtain reliable geochemical field. Groundwater samples were taken from the discharge during pumping conditions and once stabilisation of the principal field parameters (pH, T, Eh, DO) was observed for subsequent major, minor, trace element and stable isotopic analysis. On-site measurements included the determination of alkalinity by acid colorimetric titration.

RESULTS AND CONCLUSION

Groundwater samples collected in Porto Santo are all very mineralized (EC>1.6 mS/cm) and with characteristic pH values above 7.5. Groundwater along the coastline and near the saline intrusion interface is characterized by higher electrical conductivity (>4.78 mS/cm), lower Na/Cl ratios and slightly higher Ca/Mg ratios compared to the groundwater sampled in areas further away from coastline (Figure 1). It suggests that Na in these samples is being partially removed from the groundwater and replaced by Ca, which is confirmed by the higher Ca/Na ratios. The samples collected in a short distance from the coastline present Br/Cl very close to seawater mixing line (0.0016) but samples collected inland show enrichment in Br and Si over Cl and Br, respectively, which may be attributed to rock-water interactions.

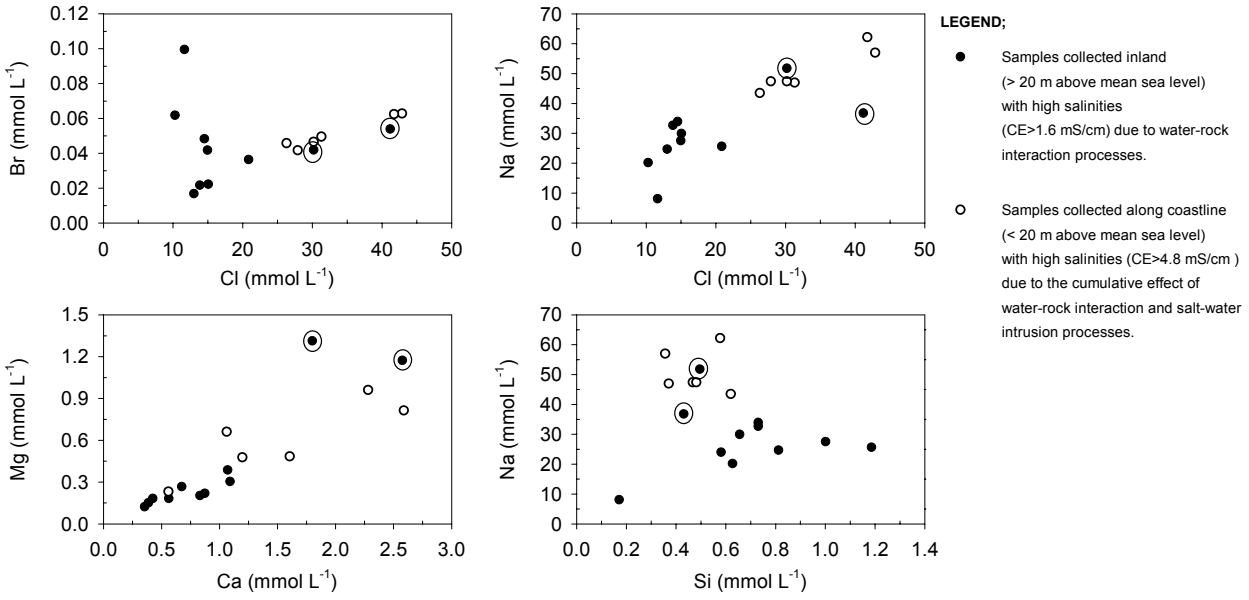

Figure 1. Chemical molar ratios determined in groundwater samples collected in Porto Santo island showing differentiated values depending on the origin of salinity.

Groundwaters in Santiago display a great variability in their chemical and physical features. They range from dilute waters (EC=362 µS/cm) with an average temperature of 26ºC to groundwaters that are generally more saline (CE~1 000–12 000 µS/cm). Groundwater samples collected along the coast have often Cl concentrations exceeding 500 mg/l as a result of saline

intrusion. Stable isotopic data shows a slight enrichment in shallow high salinity groundwater samples which may indicate a contribution of evaporation for increasing salinities.

Thus the geochemical results obtained show that different processes – evaporation, water-rock interaction and sea water intrusion are contributing for groundwater salinization and limiting its use for public supply.

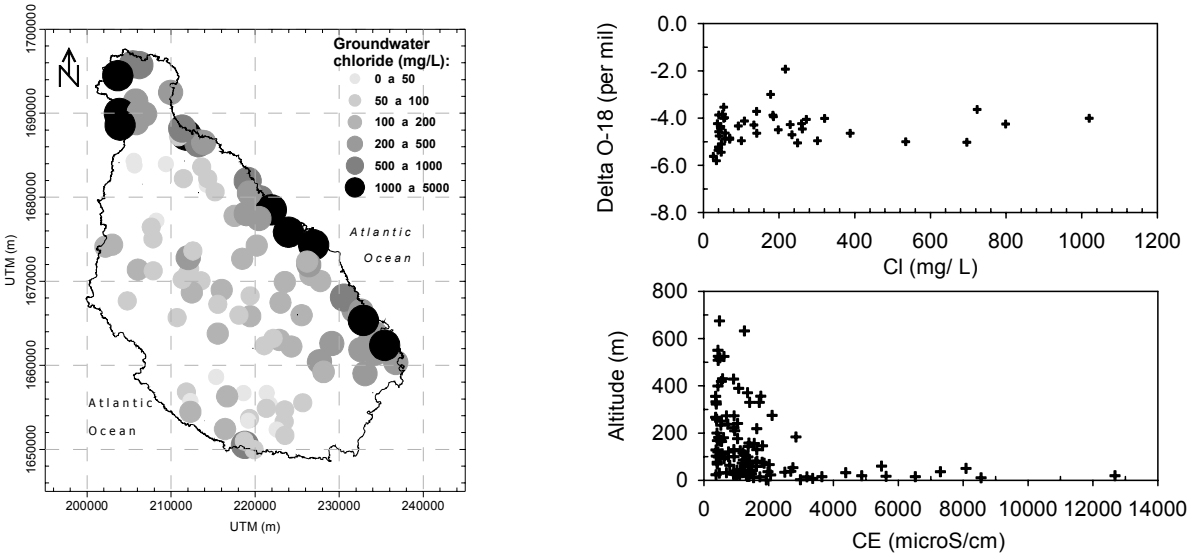

Figure 2. Groundwater chloride distribution and evolution of stable isotopic content as a function of groundwater salinity in Santiago.

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