

OLD MARINE WATER IN FUERTEVENTURA ISLAND DEEP FORMATIONS

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ABSTRACT

During the SWIM meeting in Miedzyzdroje, Bolin Island, Poland, first results on the origin of saline groundwater in volcanic Fuerteventura, Canary Islands, Spain, were presented. Now they are completed with the final results of the doctoral thesis of the first author (Herrera, 2001), under the tuition of the second one. The study considers the central part of the island, where there are the maximum elevations (ca. 800 m) and the submarine formations and intrusive rocks underlying the volcanic edifices crop out. Groundwater presents high dissolved solids content and the concentration increases downwards. An Upper Unit contains groundwater of 2.5 to 5.5 mS cm⁻¹ and 18 to 25° C, of the sodium-chloride type, with moderate alkalinity, sulphate and silica contents, and often with quite high nitrate contents of anthropic origin. A Lower Unit yield groundwater of 5.5 to 24.0 mS cm⁻¹ and 25 to 30°C, of the sodium chloride-sulphate type, high in dissolved silica and nitrate free. The high salinity of the Upper formation is due mostly to the climatic aridity of the island, in which average rainfall varies between 100 a 200 mma⁻¹. Chemical composition of groundwater from the Upper Unit can be easily explained by rainfall water evaporation with a secondary mineral contribution from water-rock interaction, which mostly results in a sodium increase due to plagioclase weathering. However, to explain the dissolved solids contents of Lower Unit other contributions have to be considered. Considering the Cl/Br ratio, the water isotope composition, the most characteristic ion ratios and chemical modelling, there is a marine water component, which is assumed to be relict seawater trapped in the intrusive rock bodies. It penetrated during stages in which the island was at a lower elevation, possibly before the last Quaternary volcanic eruptions. The very small bulk permeability of these intrusive rocks, in spite of local heterogeneities that allow some boreholes to yield significant water flows, may explain that some marine water is still not flushed, even above sea level. The high sulphate content of these waters is due to igneous sulphur dissolution, as shown by S isotope composition.

INTRODUCTION

Fuerteventura is one of the Eastern islands of the Canarian Archipelago, Spain, in the Atlantic Ocean and facing the Saharan Coast (Figure 1). Fuerteventura is the second largest island, with ca. 1650 km². It is oriented NNE – SSE and relatively low (max. 800 m altitude), which does not favours the production of rain by intercepting the dominant trade winds. Average yearly rainfall in the highlands badly attain 200 mm, and in the costal lowlands may be as low as 70 mm. Rainfall events, sometimes short, intense showers, concentrate between November and March.

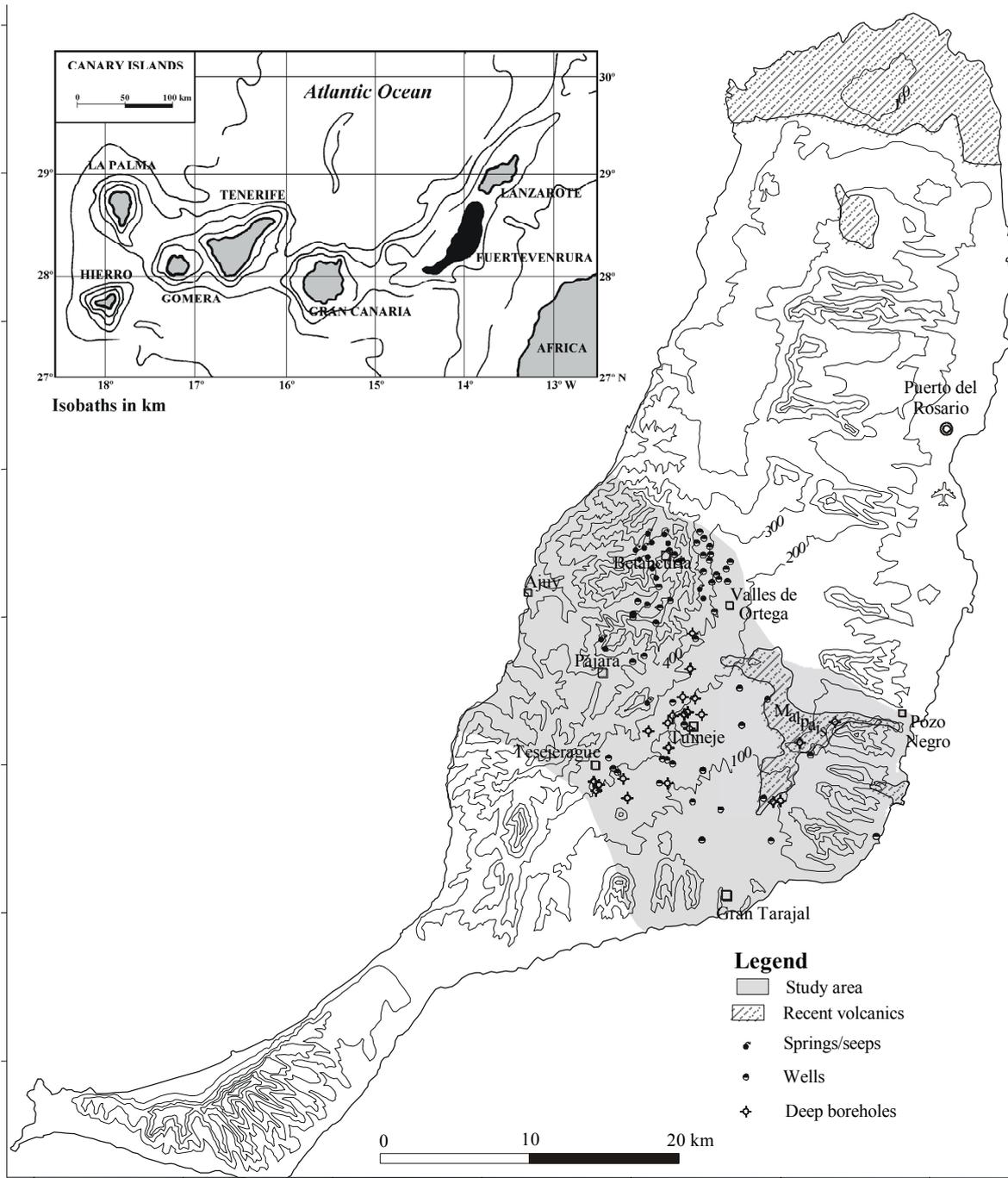


Figure 1 Situation of Fuerteventura and of the study area (shaded area). Contours show the elevation in m

In Fuerteventura groundwater is mostly for agricultural and farming uses. It is obtained from recently drilled boreholes and traditional large diameter, excavated shaft-wells. Since the 1980's, deep boreholes were drilled, up to 300 m depth, by means of cable-tool and bottom-hammer percussion drills. In what follows, both boreholes and shaft-wells are designed as wells, if details are not needed.

GEOLOGICAL BACKGROUND

Fuerteventura is the oldest of the volcanic Canary Islands. The deep marine sedimentary basement crops out in some reduced areas, and on top of it submarine vulcanites pile up, intruded by dominantly basic magmatic bodies and a very dense swarm of mostly basaltic dykes. This submarine complex (Basal Complex), from Upper Cretaceous to Lower Miocene, has been uplifted and intensively eroded. This island, jointly with the Cape Vert archipelago is the only ones with carbonatites outside a pure continental environment (Demény et al., 1999). On top of the submarine formations a high, large subaerial basaltic shield complex (Gran Tarajal stratovolcano) of Miocene age developed, which was later on deeply eroded and subjected to major landslides (Stillman, 1999).

The study area is the central part (Figure 1) and comprises the highest elevations. In the centre of the study area there is a recent and rather extense lava field (Malpais), of Pliocene–Holocene age and small thickness, with fingers towards the coast, following the main creeks (barrancos). They rest on older volcanics or its denudation products, and some poorly sorted alluvium.

Hydrochemical characteristics of groundwater

Local groundwater shows a wide range of chemical characteristics. Generally groundwater salinity increases with increasing depth as shown by the electrical conductivity and temperature logs of the saturated length of wells not in use. They are uncased boreholes, with poor or inexistent lithological logs. This does not allow defining a clear relationship between water types and the rock characteristics in which they are. However, it is observed that the shallowest groundwaters from wells less than 50 m deep, drilled in the Basal Complex volcanic rocks, are less saline than waters from deeper wells. The most saline waters often come from intrusive rocks from the Basal Complex. The greatest salinity increases are produced in the area of Tesejerague, where electrical conductivity increases from 2.5 mS cm⁻¹ near the water table up to 24 mS cm⁻¹ in the deepest tracts.

The temperature gradients of the upper saturated zone of the boreholes are very small (sometimes less than 0.01 °C m⁻¹) and below the normal thermal gradient. This fact may be due to vertical downward flows inside the boreholes, mostly induced by the deep wells in the area. In the deeper, more mineralized part of the boreholes the thermal gradients are generally higher and close to the normal value, which indicates that now vertical flows does not disturb significantly the natural stratification.

Two hydrogeological units can be defined: 1) the Upper Unit, which contain the less saline water (EC= 2.5 – 5.5 mS cm⁻¹; T= 18 – 25 °C) and the Lower Unit (EC= 5.5 – 24 mS cm⁻¹; T= 25-30 °C). Groundwater from the Upper Unit is of the sodium chloride type and present ionic ratios that partly follow rainwater chemistry. Figure 2 shows the ionic ratios rNa/r Cl, rSO₄/rCl, rMg/r Cl and rCl/(rHCO₃+rCO₃), relative to chloride content, for rainfall, the Upper Unit and the Lower Unit (r means that concentration is in meqL⁻¹). The ratios for groundwaters of the Upper Unit follow precipitation values. However, the high nitrate content of some samples indicates an anthropogenic groundwater chemical component.

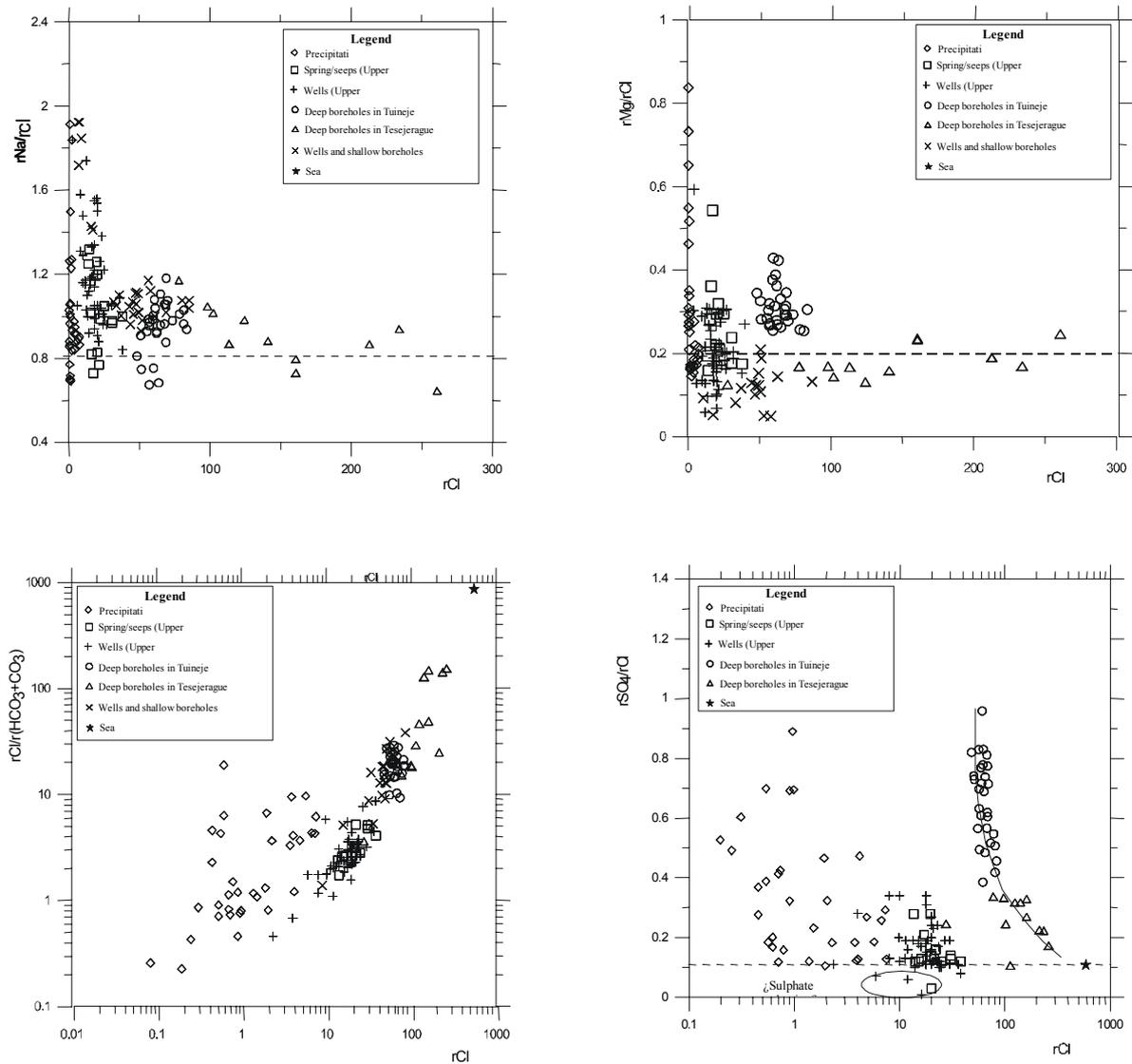


Figure 2 Ionic ratios vs. Cl for different waters (see the legend).
The prefix *r* means that concentrations are given in meq L^{-1} .

Chemical modelling using the programme PHREEQC (Parkhurst and Appelo, 1999) shows that most of the ionic contribution to the Upper Unit groundwater is due to climatic aridity. Simple evaporation of rainfall produces good results for the Upper Unit, but they improve if processes such as plagioclase weathering, and calcite and quartz precipitation are added. They are produced either in the unsaturated zone or in the upper part of the saturated zone.

Groundwaters with a higher salinity of the Lower Unit are of the sodium chloride-sulphate type, with high silica content and nitrates almost absent but for possible mixing with water coming from the Upper Unit. In the Lower Unit –differently from what happens in the Upper Unit– there are inputs of soluble salts, which produce a high sulphate concentration.

The ratio $r\text{SO}_4/r\text{Cl}$ has a median value of 0.54 for the Lower Unit, which is much higher than the value for rainwater (0.18) and seawater (0.11). Sulphate content in groundwater from the Lower Unit varies between 24 and 58 meq L^{-1} , which are very high values. This may be explained as a lithological contribution, possibly associated to sulphate mineral dissolution. Sulphates have been described by Demeny et al., (1999) for intrusive rocks of the Basal Complex. As chloride concentration increases in both the Upper and the Lower Units (Figure 2), the value of $r\text{SO}_4/r\text{Cl}$ approaches the value for seawater. It is deduced that the sulphates from the Lower Unit have an origin that is not meteoric, and that has possibly a marine component.

Bromide and chloride content has been measured in rainwater samples integrating wet and dry deposition, as well as in groundwater. The relationship Cl/Br vs. rCl/rBr for rainwater and groundwater is presented in figure 3. It can be deduced:

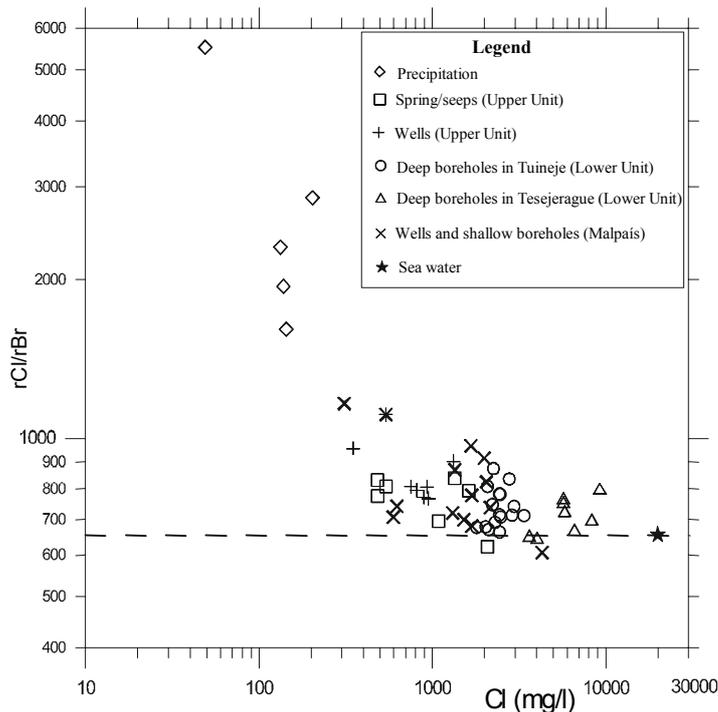


Figure 3 Radio rCl/rBr vs. Cl for different waters.
See the legend. (After Custodio and Herrera, 2000).

- Groundwater from deep boreholes representing the Lower Unit shows an rCl/rBr ratio between the marine value (660) and ca. 800. There is not a clear trend with salinity but the set evolves towards the marine values as Cl increases.
- Waters from the small springs in the most abrupt part of the island (they are mostly seeps) and from shallow wells in the Upper Unit show relatively high rCl/rBr ratios, even with relatively large changes in chloride. Also in the Malpais the ratio varies between the marine value and close to 1500, which is a high one.
- Rainwater and water from a well close to a 'gavia' (small permeable dam to retain runoff from the gullies) have relatively high ratios, between 1000 and 5500, in the same range as the wells in the Malpais.

The high ratio rCl/rBr for rainwater and its relatively high chlorinity can be explained as incorporation of particulate wind-borne halite crystals. This halite is assumed to be formed near the coast after partial evaporation of marine spray, where the sea is rough, the coast abrupt and wind intense. The phenomenon is still to be studied, although it is also known in coastal areas of other islands (Gran Canaria, La Palma).

Saline groundwater at high depth seem marine to some extent, with addition of salts from the rock. It should have a very low turnover rate.

SALINITY AND ENVIRONMENTAL ISOTOPE CHARACTERISTICS

In figure 4, $\delta^{18}\text{O}$ and $\delta^2\text{H}$ data of rainwater and groundwater from the study area have been plotted, as well as the World Meteoric Line ($\delta^2\text{H} = 8\delta^{18}\text{O} + 10\text{‰}$), and local meteoric line which has a deuterium excess of + 15‰. This slight displacement to the left seems to respond to a higher kinetic fractionation of seawater evaporation due to the relatively dry and warm environment close to the Saharan Belt. The same effect explains the deuterium excess of rainwater in the Mediterranean Sea (Herrera and Custodio, 2000).

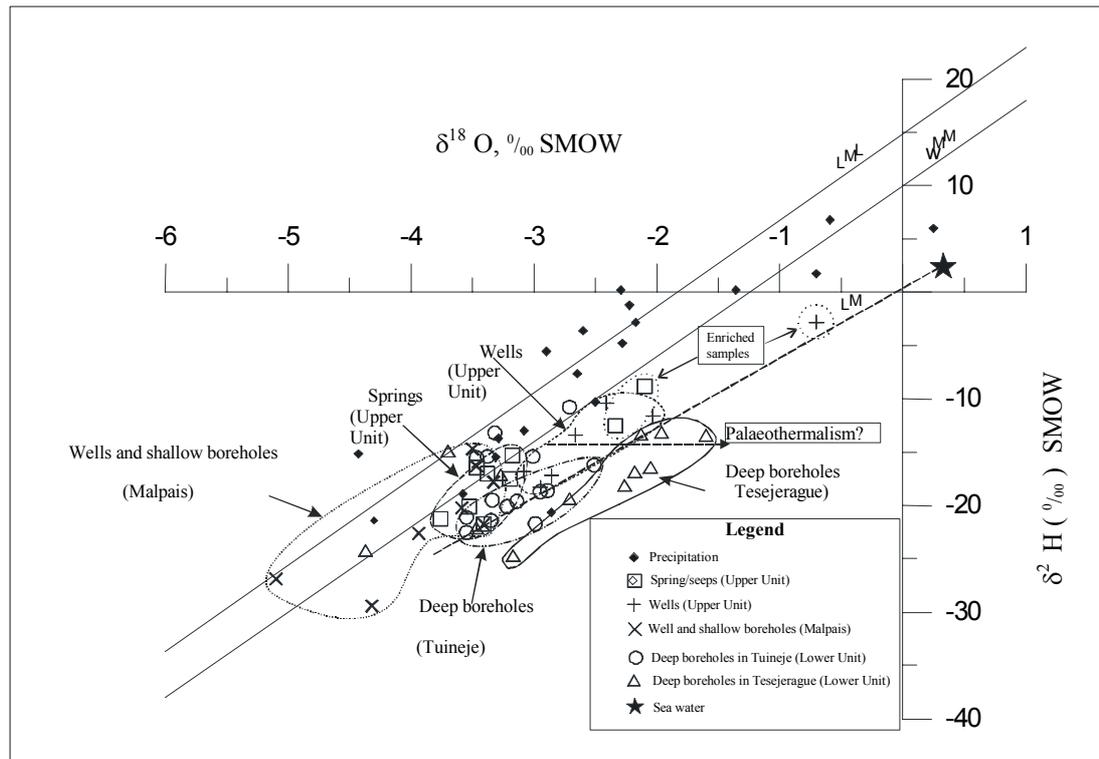


Figure 4 $\delta^{18}\text{O}$ VS. $\delta^2\text{H}$ for local waters, as shown in the legend.
Different groups are identified.

WMM = World meteoric line; LMM = local meteoric line; LM = mixing with seawater.

Most groundwater analyses plot below the local meteorological line. This means either evaporation (from the soil or before sampling) or mixing with marine water, or both, although some palaeo-thermal effect for the deep groundwater cannot be excluded. It can be deduced:

- Rainwater from heavy precipitation – that which is able to produce some recharge and runoff – is characterized by $\delta^{18}\text{O} = -4.5$ to -3.5 ‰, and $\delta^2\text{H} = -20$ to -15 ‰.
- The small springs tend to be around the heaviest corner of intense rains (some evaporation), and the shallow wells from the Malpais are closer to light rainfall.
- Groundwater from the Upper Unit tend to show some evaporation
- Groundwater from the Lower Unit seem local water with some thermal effect (or evaporated water from colder events), with some mixing with water of marine origin. The effect is clearer for Tesejeregue than for Tuineje.

The study of the $\delta^{34}\text{S}$ of dissolved sulphate in groundwater points to two different families: a) waters from two springs and a shallow borehole in the Malpais show a mean value of $\delta^{34}\text{S}$ of +17.1‰; it can be related with the value of sulphate in rain, that contains an important fraction of wind-borne marine salts ($\delta^{34}\text{S} = +20\text{‰}$); b) groundwater from deep boreholes in Tuineje and Tesejerague, with a mean value of $\delta^{34}\text{S} = 8.1 \text{‰}$. These ^{34}S values exclude a significant marine contribution (Herrera and Custodio, 2000), and may be explained by two hypothesis: a) dissolution of sulphate of igneous origin, associated with the important magmatic activity existing in all the area; these values are close to that measured by Demeny et al. (1999) in sulphates from the carbonatites of Ajuy-Solapa, and b) contributions of endogenic H_2S or SO_2 .

The data on $\delta^{13}\text{C}$ of soil CO_2 and dissolved organic carbon in groundwater is insufficient to show the cycle of carbon in groundwater.

DISCUSSION

The high salinity of groundwater from the Upper Unit can be explained as the result of the high evapoconcentration of rainwater, which has an important contribution of marine airborne salts. However, for the saline waters from the Lower Unit other origin of salinity have to be considered.

Since chloride behaves conservatively, its increase with depth needs some source, like:

- a) Infiltration of highly concentrated irrigation return flows
- b) Contribution from some lithologies or from halite dissolution
- c) More arid epochs in the past.
- d) Mixing with modern marine water due to seawater encroachment
- e) Mixing with relict marine water.

The hypothesis of increasing the chloride content as a consequence of contamination by infiltrating irrigation return flows seems very unlikely, since the effect does not shows up near the water table, and short-circuits are improbable except for vertical flows inside the boreholes.

The contribution of chloride as the result of igneous rocks weathering is not a common process due to the low concentrations of chlorine in these rocks. However, research in ultramafic rocks affected by serpentinization seems to show that chloride is more concentrated in these rocks (Rucklidge and Patterson, 1977). A significant part of the ultramafic rocks present in the island are affected by serpentinization, but their influence cannot be decided due to the lack of chloride measurements in these rocks. Recent studies of Kent et al. (1999) in Loihi island, Hawaii archipelago, also show chloride contents somewhat high in rocks of submarine origin, but without defining clearly if the increased chloride concentration is due to chloride-rich mineral phases or to sea-derived brines trapped in these rocks. This is something to be considered in later studies. In any case this Cl^- is of marine origin.

The high chloride concentration in groundwater from the Lower Unit may be the result of halite dissolution. In fact the chloride content increase corresponds to a significant increase of sodium content, in approximately equivalent amounts. However, the values of the $r\text{Cl}/r\text{Br}$ ratio from these water samples indicate that this is probably not the explanation, since they are close to or slightly above the seawater value (640-800), which are much lower than the high values to be expected from halite dissolution (Custodio and Herrera, 2000).

It is difficult to prove a chloride increase representing the recharge to the system under more arid conditions that present ones. This situation does not agree with the results from palaeoclimatic studies of the island, that in general terms point to more wet periods in the past, but never more arid that the current situation (Paguet et al., 1989; Meco and Petit-Maire, 1997; Zazo et al., 1997). In any case, if past times were in some moments more arid than now, they did not contribute significantly to recharge.

The hypothesis of mixing of meteoric-originated water with modern marine water from seawater encroachment is difficult to prove due to the fact that water of the Lower Unit, which has a high mineralization, is found sometimes up to 150 m above sea level. Furthermore, groundwater with the highest mineralization is found in the central part of the island, far away from coastal zones where seawater encroachment should mainly show up. However this encroachment may be the cause of the high mineralization of some water wells emplaced very close to the coastline, in the area of Gran Tarajal.

It seems that the hypothesis of a mixture of meteoric-originated water with old seawater trapped in the low permeability intrusive formations may be acceptable. In fact the ratios r_{Na}/r_{Cl} , r_{Mg}/r_{Cl} , r_{SO_4}/r_{Cl} and $r_{Cl}/(r_{HCO_3} + r_{CO_3})$ tend to the marine water value when groundwater mineralization increases. Although these ratios for the Upper Unit groundwater also tend to the seawater ratios as the importance of airborne salts increase, there is an important dispersion of the results. Conversely, the values for the Lower Unit approach better the marine values. Also, as groundwater chloride concentration increases, the ratio $r_{Cl}/(r_{HCO_3} + r_{CO_3})$ increases sharply towards the seawater value. Furthermore, the ratio r_{Cl}/r_{Br} varies between the seawater value and 800, but they tend to the marine value as salinity increases.

As a further indication, the water isotope values of groundwater from the Lower Unit seem to correspond to a mixture of meteoric-origin water similar to that of the Upper Unit, with seawater (figure 4). As water samples are more enriched in heavy isotopes also chloride increases. Although this change of isotope contents of the Lower Unit groundwater may be explained by an evaporative isotope fractionation, this is improbable since the water isotopic composition of the Upper Unit that represent recharge do not show a significant evaporative fractionation. Also, the groundwater samples from deep boreholes of Tuineje seem to start from original meteoric water, which is different from that of the deep boreholes of Tesejerague. This produces different slopes of the mixing lines with seawater (Figure 4). The higher (more enriched) $\delta^{18}O$ values of Tesejerague samples may also show a palaeothermal effect, affecting meteoric-originated groundwaters from this area, before the mixing with sea-originated water.

The current geological and hydrogeological knowledge of Fuerteventura island and the lack of specific boreholes do not allow to formulate a robust conceptual model to explain the origin of marine water present in the intrusive rocks of the Basal Complex. One possibility is that this marine water could be trapped in these formations during the uprising of the island, since the overlaying volcanic rocks are submarine ones. However, this hypothesis is difficult to be proved since geologic information show that the main uprising was produced in the Late Miocene, although a secondary one is probable when the last Pleistocene-Holocene lavas of the Malpais were poured out. This implies a long time during which the relict waters trapped in these formations could be washed out by recharge water. However, as seen in the temperature and electrical conductivity logs, groundwater flow could be relatively important in volcanic rocks of the Upper Unit, whilst flow is probably much less important in the Lower Unit.

It can be hypothesised that recharge water, once attains the water table, has a preferential horizontal movement through the volcanic rocks of the Basal Complex, following its way to the discharge area in the coast, without leaving the volcanic formation. In this way, the leaching of salts from the Lower Unit may be very small, which means that eventually trapped marine water and even chloride-rich minerals have been able to resist flushing out. The slow displacement and leaching of marine water from the intrusive rocks has been also favoured by the persistent climatic aridity prevailing in Fuerteventura Island, that implies a small recharge rate.

This explanation, which implies a very low permeability Lower Unit, may seem not fully in agreement with actual data. In fact some deep wells penetrating the Lower Formation produce up to 5 L s^{-1} (ITGE, 1991). But it has to be taken into account that only a few of the deep boreholes drilled in the island produce significant yields from the intrusive formations. Most of them yield very small flows and for a very short period. The existence of some boreholes able to yield a relatively high flow, jointly with boreholes with negligible water yield, points to a structural control in groundwater flow. Although it is not known the role of the dykes that cross the formation, they may play a relevant local drainage role, as seems to happen in other places in the Canaries (Custodio, 1989). It cannot be discarded that dykes behave as drains that facilitate the capture of groundwater from the intrusive rocks, which are held in small fissures. As groundwater is pumped out from productive boreholes, there is water flow and a head drawdown in the fissures associated to the dykes penetrated by the boreholes. They induce the low drainage from the rock to the fissures. The dykes may be up to several km long. This idea could explain how the abstraction of relict marine water in the intrusive rocks is the result of current abstraction pattern. Of course, this explanation means that groundwater pumped from the Lower Unit is progressively exhausted. The result is the depletion of the borehole yield or the progressive replacement of deep water by groundwater from the Upper Unit, if it is able to contribute enough water.

REFERENCES.

- Custodio, E. (1989). Groundwater characteristics and problems in volcanic rock terrains. In *Isotope Techniques in the Study of the Hydrology of Fractured and Fissured Rocks*. Intern. Atomic Energy Agency, Vienna: 87-137.
- Custodio, E., Herrera, C. (2000): Utilización de la relación Cl/Br como trazador hidrogeoquímico en hidrología subterránea. *Bol. Geol. Min.*, Madrid, 111: 49-67.
- Demény, A., Ahijado, A., Casillas, R., Boyce, A. J. Fallick, E. (1999): Crustal contamination of carbonatites indicated by $\delta^{34}\text{S}$ - $\delta^{13}\text{C}$ correlations (Fuerteventura, Canary Islands). *Rev. Soc. Geol. España*, 12(3-4):453-460.
- Herrera, C. (2001). Caracterización hidrogeoquímica del macizo de Betancuria, Fuerteventura, archipiélago de Canarias. Doctoral Thesis. Technical University of Catalonia (ETSICCP), Barcelona.
- Herrera, C., Custodio, E. 2000. Saline water in central Fuerteventura Island, Canary Islands, Spain. *Proc. Salt Water Intrusion Meeting, Miedayzodroje. Wolin Island. Poland. Nicholas Copernicus Univ.* 80: 81-86 (Publi. 2001)
- ITGE (1991): Estudio hidrogeológico de la isla de Fuerteventura. In: *Proyecto de Actualización, Infraestructura Hidrogeológica, Vigilancia y Catálogo de Acuíferos Memoria Inst. Tecnológico y Geominero de España*. Madrid (internal report)
- Kent, A., Clague, D., Honda, M., Stolper, E., Hutcheon, I., Norman, M. (1999): Widespread assimilation of a seawater-derived component at Loihi seamount, Hawaii. *Geochimica et Cosmochimica Acta*. 63 (18): 2749-2761.
- Parkhurst, D.L., Appelo, C.A.J. (1999). User's guide to PHREEQC (versión 2). Report 99-4259, U.S. Geological Survey, Water Resources. Washington D.C.
- Rucklidge, J.C., Patterson, G.C. (1977): The role of chlorine in serpentinization. In *Contribution to Mineral and Petrology*. 65, 39-44.
- Stillman, C.J. (1999): Gian Miocene landslides and the evolution of Fuerteventura, Canary Islands. *Journal of Volcanology and Geothermal Research*. 94: 89-104.
- Zazo, C., Hillaire-Marcel, CL., Goy, J.L., Ghaleb, B., Hoyos, M. (1997): Cambios del nivel del mar-clima en los últimos 250 ka: (Canarias Orientales, España). *Bol. Geol. Min.*, Madrid 108 (4 -5) 487-497.