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Geochemical characteristics of the main high-temperature geothermal fluids presently highlighted in Caribbean islands

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Abstract

The Caribbean being part of the Lesser Antilles volcanic arc such as Guadeloupe, Martinique, Dominique, Montserrat, Saint Lucia, etc., must face the fragility of their energetic system and environment, given their insularity. However, these territories, which are home to young volcanic systems, possess a huge potential for power generation from High-Temperature (HT) geothermal energy. This energy is continuously available and economically competitive. However, so far, it remains difficult to develop in these islands. Indeed, even though the first exploration works have been carried out in the 1970s in some of these territories, the HT (260°C) Bouillante geothermal power plant in Guadeloupe, exploited since 1986, is currently the unique example of electricity production (15 MWe and about 6% of the annual electricity needs of the Island) in the Caribbean area. The main objectives of this study are to present, for the first time, the main geochemical characteristics of the deep fluids from the geothermal wells and some thermal springs existing in Guadeloupe, Martinique, Dominica, Montserrat and Saint Lucia. New auxiliary chemical thermometric relationships such as Na-Li, Na-Rb, Na-Cs, K-Sr, K-Fe, K-Mn, K-F and K-W, and Li isotopes, were also tested on these deep fluids, which can be useful for future works of geothermal exploration in these islands. In order to reach these objectives, this paper has exploited two types of geochemical data: 1) data obtained after an extensive literature review and 2) data acquired in Guadeloupe (with new analyses on old stored fluid samples) and Martinique (with a campaign of fluid sampling carried out in 2022), during this study. If in the past, some deep wells drilled in the Saint Lucia and Martinique islands had to be abandoned and closed, the results of this study integrating new exploration works and deep wells recently drilled in Dominica and Montserrat suggest promising geothermal developments in the Caribbean area.

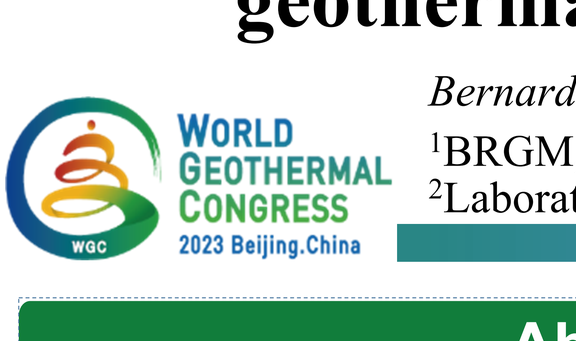
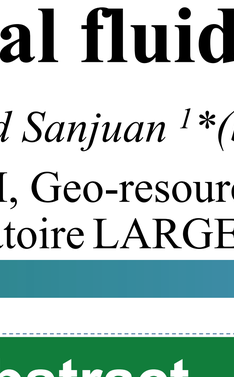
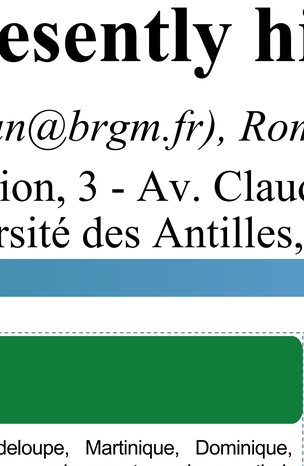


Plate boundaries from Bird (2003). Uncertainty in the position of the North American (NAM) - South American (SAM) plate boundary is indicated by white shading. Plate motion vector is for Atlantic seafloor relative to the Caribbean plate.

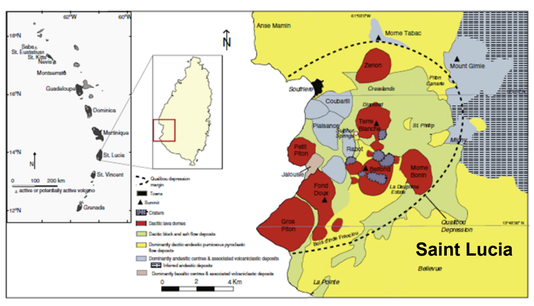


Map of the main active volcanic centers of the Lesser Antilles (from Joseph, 2008; right).



Map of the Lesser Antilles island arc, showing the ages of the exposed rocks and the positions of the volcanic front during the Eocene-Oligocene (red line), Pliocene (blue line), and Pleistocene (black line) (from Robertson, 2009).

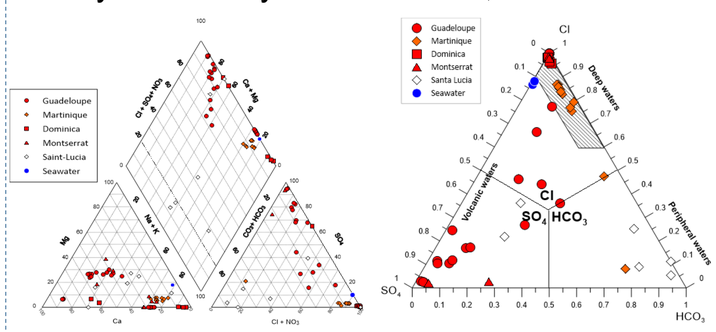
Results and Discussion



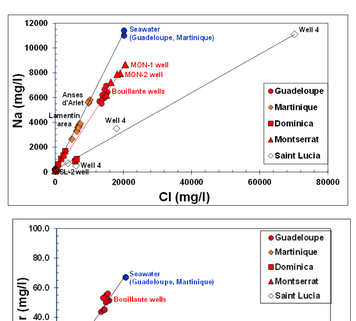
*Map of the different islands studied in this work, showing the location of these islands (left), and maps of: 1) **Saint Lucia,** with an outline of the Qualibou Depression and main vents of the Soufriere Volcanic Centre (from Joseph et al., 2013), 2) **Dominica**, with geothermal areas (springs, fumaroles, bubbling pools) (from Joseph et al., 2019), 3) **Montserrat**, with the geothermal wells MON-1 and MON-2 and the main thermal springs and fumaroles (from Brophy et al., 2014), 4) **Guadeloupe**, with the main geothermal areas and hot springs (from Bourdon et al., 2009), and 5) **Martinique**, with the main geothermal areas and hot springs (from Lopoukhine and Mouret, 1977).*

***Saint Lucia:** 7 deep wells (1975-1976) and 2 (1987-1988), in the Qualibou geothermal area (220-290°C).*
***Dominica:** 5 deep wells (2012-2014), in the Wotten Waven geothermal area (250°C).*
***Montserrat:** 2 deep wells (2013), in the St George's and Garibaldi geothermal areas (230-260°C).*
***Guadeloupe:** 4 deep wells (1970-1977) and 3 (2001), in the Bouillante geothermal area (260°C).*
***Martinique:** 1 deep well (1969) and 3 (2001), in the Lamentin plain area (90-100°C).*

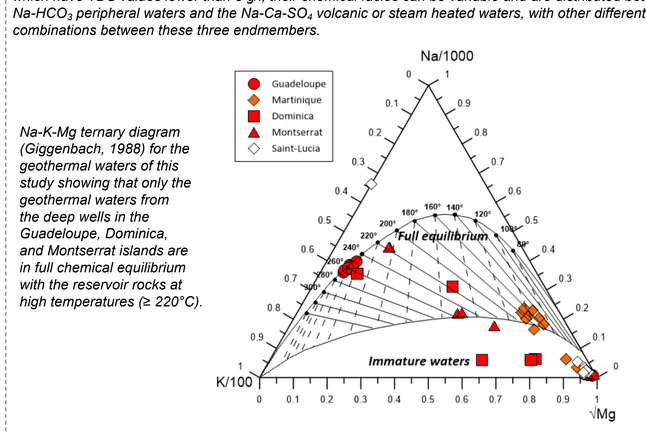
As for the Bouillante field, the deep geothermal waters from the other islands are NaCl neutral pH seawater derived fluids mixed with meteoric fresh waters at different proportions, which interact with reservoir volcanic rocks at temperatures close to 100-110°C and 180°C, in Martinique, and 230-260°C, in Montserrat and Dominica. The presence of fluids with higher temperatures (≥ 280°C) and different chemical facies, in the proximity of the active volcanoes, is possible, but can cause problems of exploitation, as observed in the past, in Saint Lucia, due to the high salinity and acidity of these fluids, and the low reservoir permeability.



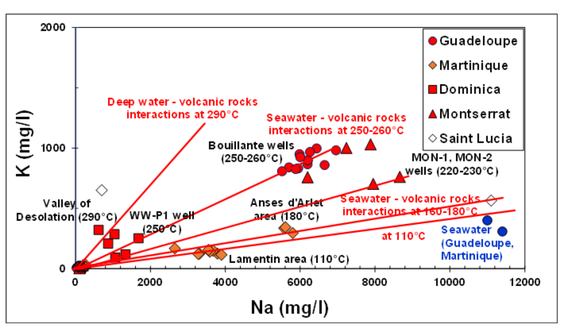
Piper diagram (left) and Cl-SO_4-HCO_3 ternary diagram (Giggenbach, 1988; right) for the geothermal waters of this study, showing that those discharged from the deep wells are mainly NaCl fluids. For the thermal waters, which have TDS values lower than 3 g/l, their chemical facies can be variable and are distributed between the Na-HCO_3 peripheral waters and the Na-Ca-SO_4 volcanic or steam heated waters, with other different possible combinations between these three endmembers.



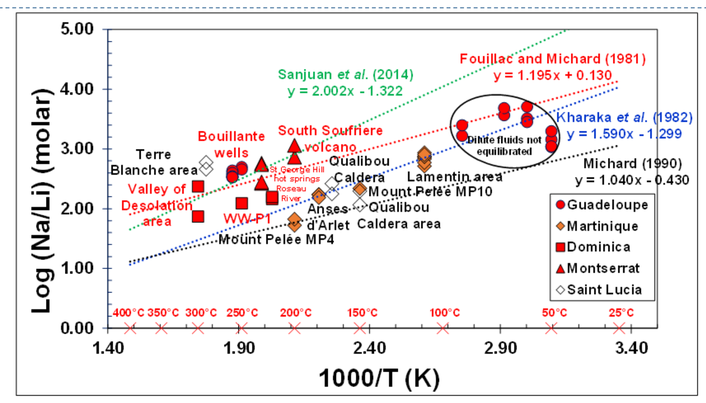
Na and Br versus Cl concentrations for the geothermal waters of this study, which indicate the strong influence of seawater in the chemical composition of most of the deep waters. Using the Cl and Br concentrations, the contributions of seawater can be estimated in these waters.



Na-K-Mg ternary diagram (Giggenbach, 1988) for the geothermal waters of this study showing that only the geothermal waters from the deep wells in the Guadeloupe, Dominica, and Montserrat islands are in full chemical equilibrium with the reservoir rocks at high temperatures (≥ 220°C).



K versus Na concentrations for the geothermal waters of this study showing K/Na increasing ratios with increasing reservoir temperatures.

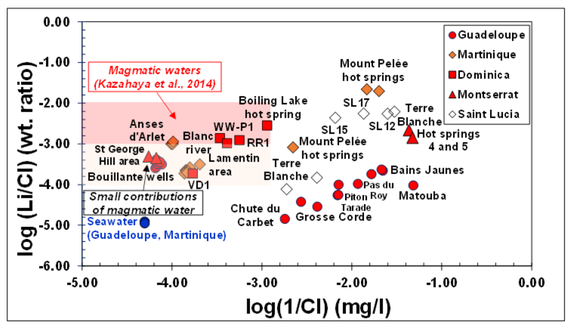


Logarithm of Na/Li (molar ratio) versus 1000/T (reservoir temperature in K). The data obtained in this study are compared to several Na-Li thermometric relationships existing in the literature. The Na-Li ratios seem to not only controlled by temperature, but also by other influent factors (nature of the rocks, fluid salinity, etc.).

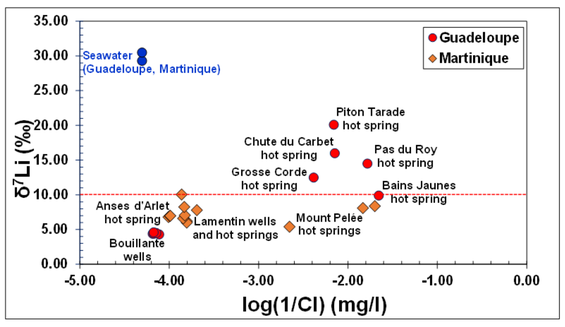
The Na-Li thermometric relationship defined by Sanjuan et al. (2014) for Icelandic HT geothermal waters is the most adapted for the deep HT geothermal waters from the Caribbean area.

For the volcano-sedimentary areas of the Lamentin plain and Anses d'Arlet in Martinique, and for some thermal springs of the Qualibou caldera in Saint-Lucia, the most adapted Na-Li thermometric relationship is that defined by Kharaka et al. (1982).

For the dilute thermal waters from the Mount Pelée in Martinique, the Na-Li thermometric relationship defined by Michard (1990) is the most adapted one.

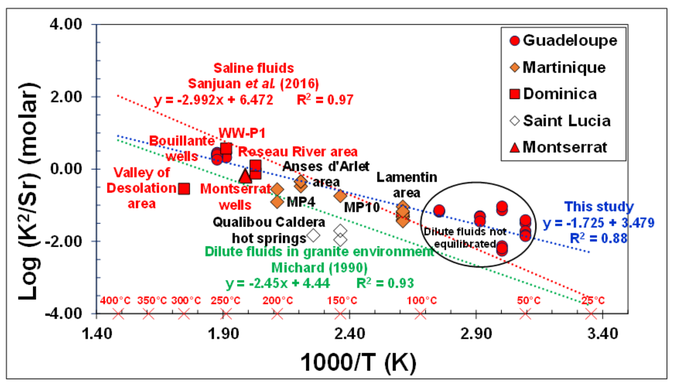


The Li concentrations associated with the Cl concentrations can be also used to highlight the geothermal waters with high contribution of magmatic waters (Kazahaya et al., 2014). The geothermal waters of this study, which seem to have the higher contributions of magmatic waters, come from Dominica (Wotten Waven, Blanc River and Boiling Lake areas) and from the Martinique Island (Anses d'Arlet area). The low δD isotope values observed for this area (Pedroni et al., 1999; Sanjuan et al., 2005) had already suggested a possible contribution of magmatic water.



Unlike the Na/Li ratios, it is difficult to use the isotope Li values as geothermometer. However, as already observed by Sanjuan et al. (2014) for geothermal fluids from Iceland and La Réunion, the hottest geothermal waters from Guadeloupe and Martinique have δ^7Li values lower than 10‰. The thermal waters from the Grande Soufriere area in Guadeloupe, considered as shallow waters heated by conduction, have relatively high δ^7Li values.

Among the auxiliary chemical geothermometers tested during this study, the Na-Li and K-Sr thermometric relationships were the most efficient tools to reduce the inaccuracy in the estimation of reservoir temperature, but with more available analytical data, other thermometric relationships like Na-Rb or Na-Cs could be probably used. It was also shown that the Li isotope values can be used to indicate if the waters are rather low- to medium-temperature (≤ 150°C), when most of the chemical geothermometers give discordant temperature estimations. In this case, the δ^7Li values are generally higher than 10‰.

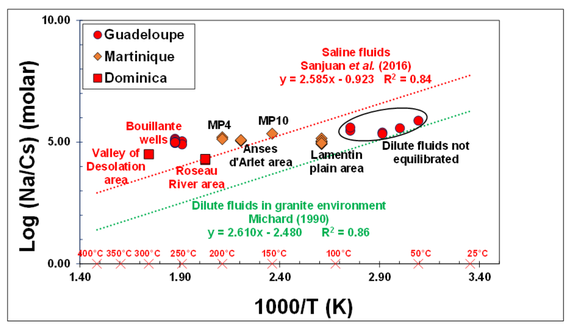


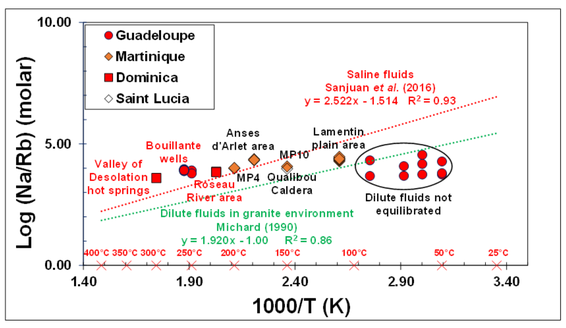
Logarithm of K^2/Sr (molar ratio) versus 1000/T (reservoir temperature in K). The data obtained in this study are compared to the two K-Sr thermometric relationships existing in the literature for dilute geothermal waters in granite environment (Michard, 1990) and for hot brines (Sanjuan et al., 2016).

As for the Na-Li geothermometer, the existence of different relationships for a given auxiliary geothermometer suggests that the latter depends not only on temperature, but also on other factors (nature of the reservoir rocks, fluid salinity, etc.).

In spite of the rare data relative to the trace elements, we can see that most of the geothermal and thermal waters of this study are located between the K-Sr thermometric relationship determined by Sanjuan et al. (2016) for the brines and that defined by Michard (1990) for dilute waters in granite environment, except for the water samples from three thermal springs located in Saint Lucia and from the VD1 hot spring in Dominica.

If we do not take into account these last thermal springs, we obtain a better and new K-Sr thermometric relationship for the other waters (in blue), with a relatively good regression coefficient R^2 of about 0.88.





In these two figures, despite the rare data, we can observe that the geothermal waters of this study, with reservoir temperature values higher than 150°C, fit relatively well the Na-Rb thermometric relationship defined by Sanjuan et al. (2016) for hot brines (left). For lower temperatures, the thermal waters rather fit more or less the Na-Rb thermometric relationship determined by Michard (1990) for dilute geothermal waters. We can observe similar trends for the Na-Cs thermometric relationships, but the correlations are poorer (right).

Conclusion

After an extensive literature review and a new data acquisition in Martinique and Guadeloupe, the fluid geochemical results as well as the geothermometric tests and validations are promising for further geothermal development in most of the Caribbean islands. The ambitious objectives of the energy transition in the world, the recent arrival of some industrials like Ormat, majority owner and operator of the Bouillante power plant since 2015, and new investors, who aim to develop and operate future geothermal fields in the Caribbean islands, encouraged by new types of funds, are an excellent message for the future. The Caribbean Centre of Excellence of Geothermal Energy, currently being created in Guadeloupe within the framework of the INTERREG V "Energy Transition in the Caribbean" Program (ETC), featuring a network of scientific research, formation and industrial activity, would have to allow promoting and developing this energy in this entire region. In this context, the success of the Bouillante story could become a stepping-stone for the geothermal development in the Caribbean area.

***Acknowledgments:** A major part of this work was carried out within the framework of **the WP-4 (Geothermal Energy) of the INTERREG V ETC Program** and was co-funded by the European Regional Development Fund (ERDF), the European Development Fund (EDF) and BRGM.*

*For more details and literature references, you can look at the **corresponding paper WGC2023 ID-1546 Sanjuan et al. (2023), and the technical report BRGM/RP-72352-FR, edited in 2023**.*