Stable isotope study of rainfall, river drainage and hot springs of the Kerguelen archipelago, SW Indian Ocean

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Abstract

This study is the first synthesis of chemical composition and stable isotopes values for the
Kerguelen archipelago waters. The stable isotope values for rainfall and river waters in the
Kerguelen archipelago allow a calculation of the Local Meteoric Water Line ($\delta D_{\text{rainfall}} = 8.43$

$\times \delta^{18}\text{O}_{\text{rainfall}} + 11$) and a summer runoff line ($\delta\text{D}_{\text{river drainage}} = 7.45 \times \delta^{18}\text{O}_{\text{river drainage}} + 6$).
 Surface waters with low- ion concentrations, chlorine facies and stable isotope values
 infiltrate through fractures and lava flows recharging deeper groundwaters. Thermal
 groundwater with low- (7 to 50 °C) and high- (50 to 100 °C) temperatures emerges in
 different localities in the volcanic archipelago. The low-temperature thermal waters might
 represent a mixture of high-temperature water with rainfall, thermal gradient changes or
 shallower infiltration compared to that for high-temperature thermal waters. The Rallier du
 Baty and Val Travers areas contain geothermal fluids with high-temperature springs,
 fumaroles and a large water flow. In the Rallier du Baty, the major ion chemistry and O, H, C
 and S stable isotope ratio of low (7 to 50 °C) temperature spring waters in Rallier du Baty
 area demonstrate a geothermal-system recharged by meteoric water ($\delta\text{D}_{\text{H}_2\text{O liquid}} = 7.0 \times \delta^{18}\text{O}_{\text{H}_2\text{O liquid}} + 0.5$) rather than sea water. The chemical and isotopic compositions of elevated
 temperature spring waters (50 to 100 °C) have a long and complex history of meteoric water
 interacting with cooling magmas ($\delta\text{D}_{\text{H}_2\text{O liquid}} = 1.78 \times \delta^{18}\text{O}_{\text{H}_2\text{O liquid}} - 23$). Surficial
 precipitation of aragonite, kaolinite, pyrite, native sulfur attest to a long lived geothermal
 system. A temperature of the geothermal reservoir has been estimated between 193 and 259
 °C by cation geothermometry. The combination of minerals observed, major ion composition
 of water with thermodynamic modeling and stable isotope data suggest a geothermal system
 with a series of water/rock interactions from 50 to 250 °C. The conductive cooling of rising of
 H₂O-CO₂-rich fluids have produced a H₂O-CO₂ phase separation with the precipitation of
 secondary minerals.

Keywords: Kerguelen archipelago, geothermal springs, stable isotope composition, water-
 rock interaction

46

47 1 Introduction

48

49 A prolonged record of continuous magmatic activity has been documented for the Kerguelen
50 archipelago (Fig 1A; Giret, 1990; Weis and Giret, 1994; Weis et al., 1998; Mathieu et al.,
51 2011), but little attention has been paid to the type of hydrothermal system responsible for the
52 generation of hot springs and fumarolic activity. The volcanic archipelago of Kerguelen hosts
53 several geothermal centers expressed by continuous fumaroles and thermal springs (Fig. 1B to
54 E). Local rainfall and geothermal waters collected over the years by the permanent scientific
55 base and episodic fieldwork (1981 to 1983 and 2002 to 2009) allow a survey of chemical and
56 stable isotope values.

57 This survey involves of rainfall and fumarolic fields associated with thermal springs at
58 temperatures below the boiling point of water. Heat and fluid flow in these areas have been
59 related to a magmatic source releasing CO₂ (e.g., Delorme et al., 1994) and periods of
60 volcanism throughout the Kerguelen archipelago. However, there is a lack of observational
61 data cataloguing recent volcanic eruptions due to the remoteness of the Kerguelen
62 archipelago. Various authors have interpreted local magmatic petrogenesis and temperature in
63 the Kerguelen archipelago (Giret, 1990; Luyendick and Rennick, 1977; Weis and Giret, 1994;
64 Weis et al., 1998; Mathieu et al., 2011). Fewer authors have focused on seawater and meteoric
65 water exchanged by hydrothermal water/rock interaction of geothermal systems associated
66 with magma (Ballestracci and Nougier, 1984; Delorme et al., 1994; Verdier, 1989) and almost
67 very few papers deal with present-day hydrology (Berthois and Le Provost, 1971),
68 hydrogeology or geothermal fluids ($\delta^{13}\text{C}_{\text{CO}_2}$: Javoy et al., 1982).

Our studies reported in this paper present the first chemical and isotopic database for rainfall, river drainage and thermal waters located in the Kerguelen archipelago. Stable isotope values and the chemical composition will be used to “fingerprint” surface and geothermal water, such as sources, recharge and transition processes taking place in underground aquifers such as rainfall or seawater recharge and temperature changes (c.f. Barbieri, 2019; Wang et al., 2018). We complemented the chemical composition and stable isotope values for fluids with stable isotope values for minerals (kaolinite, aragonite, pyrite and native sulfur) precipitated in thermal springs. Calculations based on stable isotope values for waters and minerals will be used to estimate long-term or short-term changes in the composition of geothermal fluids. Furthermore, magmatic and hydrothermal mineralogy combined with temperature estimates of water/rock interaction has been implemented in a thermodynamic model. These calculations have then been used for the Rallier du Baty area to schematize depth- mineral- and fluid transformations from the deep groundwater-geothermal reservoir to the shallow fumaroles and hot springs. The Kerguelen hydrothermal system provides a valuable dataset for further comparative studies with the geothermal systems of Kerguelen or Iceland, Guadeloupe, Hawaii and geothermal fields in the southern hemisphere.

Figure 1:

2 Regional setting

The Kerguelen archipelago is located in the southwestern Indian Ocean to the south of the 49th parallel. This archipelago plateau consists of successive submarine flows of tholeiite,

mildly alkaline basalts and trachyte associated with a silicic peralkaline volcanic activity (Bonin et al., 2004; Weis and Giret, 1994) dated from 115 Ma to 39 Ma ago (Duncan, 2002; Grégoire et al., 1997; Luyendick and Rennick, 1977). The emerged part of the archipelago rises to 1850 m above sea-level (Fig. 1A) is a series of younger basalt flows and intercalated ashes with ages ranging from 30 Ma to 0.13 Ma (Giret, 1990; Weis and Giret, 1994; Weis et al., 1993, 1998; Gagnevin et al., 2003).

The rugged geomorphology (Fig. 1A) of the Kerguelen archipelago induces large rainfall volumes in the west (estimated ca. 8000 mm/y) and drier conditions on the eastern side of the island (~ 800 mm/y). This eastward difference relates to the Cook Ice Cap and Mount Ross (Rallier du Baty area, RdB; Fig. 1B) with a permanent snow line at ca. 1200 m. This mountainous system produces a cold and desertic climate with peat formation on the archipelago. At the French weather station in Port aux Français (PaF: 49 ° 21'S; 70 ° 13'E; Fig. 1A) the average daily temperature is 4.6 °C ±0.4 with 760 mm/y of rain (1951 to 2008: data source Météo-France; cf. Lebouvier et al., 2011). Interpretation of satellite images taken recently (cf. Berthier et al., 2009; Frenot et al., 1993; Vallon, 1977) suggests a glacial retreat of 10 m/y. This ice retreat has been interpreted as related to current worldwide temperature changes (Bergstrom et al., 2006; Smith, 2002) which in Port aux Français records +0.2 °C/y and -10 mm/y of rain during the last twenty years. The large "Rivière du Chateau" watershed shows seasonal flow changes from 1 to 25 m³/s and low dissolved solids content of waters. The low dissolved solids content of the water is related to a significant proportion of melted snow and rainfall rather than a contribution from sea sprays (Berthois and Le Provost, 1971). The Scientific base of Port au Français (150 people during summer) uses drinkable water from a river in the Loranchet area, while the hydrology and hydrogeology of the Kerguelen (ca. 7215 km² with maximum 150 human being), is totally unknown.

The basaltic Kerguelen plateau hosts disseminated occurrences of altered tholeiitic lavas with clay minerals, sulfide, silica precipitation, zeolite and carbonates (Delorme et al., 1994; Renac et al., 2010; Verdier, 1989). The ‘Rallier du Baty’ (RdB) and ‘Presqu’îles de la Société de Géographie’ (PSG; Fig. 1A) locations represent visible, modern and large hydrothermal areas with a geothermal activity witnessed by fumarolic activity (Ballestracci and Nougier, 1984; Gagnevin et al., 2003). The largest fumarolic area is located at 49 ° 37’S, 68 ° 47’E (Fig. 1B; Ballestracci and Nougier, 1984); and the highest flow of thermal waters recognized in the Val Travers (49 ° 19’ 41S, 69 ° 24’10E; Fig. 1C, Berthois and Le Provost, 1971; Delorme et al., 1994).

3 Field measurements, water sampling, and chemical preparation

From 1981 to 1983 B. Blavoux and J. Nougier collected rainwaters (18 months) at the French meteorological station of PaF (Table 1, unpublished data provided by Bernard Blavoux). During summer camps (1981 to 1983) a series of river drainages and thermal springs throughout the whole archipelago were sampled (Fig. 1A; Tables 1, 2, 3). A digital elevation model and Qgis treatments associated these samplings (river drainage and springs) with tens of small catchment areas (<1 km²) and a larger watershed (<30 km², Fig. 1 B to E). These outlets are each other separated from 50 to 500 m (surface distance). Further scientific programs from 2002 to 2009 (Carbonatoker Dylioker and Hotvir IPEV program) allow summer sampling of river drainages, material from fumaroles, spring waters with low- to high-temperatures at Rallier du Baty, the Central-Plateau and Gallièni. Hot springs emerge in large ponds with thermal waters or as steam vents from fissures cutting lava flows or

pyroclastic rocks. Some outcrops and ponds are surrounded by centimeters to decimeters wide muddy fringes of gray to red altered volcanic rocks.

Field measurements of fluid parameters consisted of pH, temperature (°C), alkalinity (mg/L), and electrical conductivity measurements (μS/cm). For each water locality, four bottles of filtered water (250 cm³) plus several blanks of ultrapure Millipore water (Saint Etienne, δ²H= -60‰, δ¹⁸O= -8.5‰, δ¹³C and δ³⁴S= unmeasurable), with 1) Untreated waters for O, H isotopes, anions, and alkalinity analyses. 2) Samples with ~ 10 cm³ of 1% HNO₃) for cations and δ³⁴S_{SO4} analyses as BaSO₄ precipitates. 3) Water treated with 2 cm³ of 20N NaOH liquid (pH > 12) plus 5 cm³ of a BaCl₂ saturated solution added to the basic water to allow the precipitation of the dissolved species of carbon and sulfur as BaCO₃ and BaSO₄. Further, each precipitate was rinsed with deionized water and air-dried. The BaCO₃ and BaSO₄ were subsequently used to determine δ¹³C_{DIC} and δ³⁴S_{SO4} values. 4) We analyzed samples from two fumaroles at Rallier du Baty for δ¹³C_{CO2} values. Gases flowing through a quartz tube were cooled and bubbled into NaOH to remove H₂O vapor and CO₂. The CO₂ was precipitated as BaCO₃ and analyzed for δ¹³C_{CO2}. After tube purging and 30 min of steam flow, we collected anhydrous gas on outgassed charcoal in Pyrex tubes sealed for transport preservation and later analyzed for CO, N₂ and Ar proportions in the laboratories at the University of St Etienne. The mineralogy of red and gray precipitates surrounding mineral and thermal springs were characterized by X-ray diffraction (XRD; Brucker SIEMENS D5000 Model with 40 kV and 25 mA, at Ecole des Mines de Saint-Etienne). Further, we analyzed O, H (clays-minerals) and S (sulfide, native sulfur) stable isotopes of mono-mineral separates with procedures presented in Renac et al. (2010).

In the laboratory (field 1981-1983, Blavoux analyst; 2002-2009 Renac and Perrache analysts) analysis of cation-anion concentrations, O, H, C, and S stable isotope ratios were added to field measurements. Water samples and blank water were transported and stored in fridges and the following techniques of chemical analysis have been realized between 3 and 6 months after sample collection. For the first of the samples (1981 to 1983 mission) inductively coupled plasma atomic emission spectroscopy (ICP-AES) was used for cation and ion-specific electrodes for anion analysis for major element determinations at the Laboratoire d'Hydrologie d'Avignon and Thonon Les Bains (unpublished data communicated by B. Blavoux). While the ion composition of water samples, collected from 2002 and 2009, were determined by DIONEX ion chromatography (cations: Na, Ca, Mg, K, Sr, Li; anions: F, Cl, NO_3^- , SO_4^{2-} , Br, and PO_4^{3-} ; a detection limit 20 ppb and potential contamination related to the transport and storing of blank of <0.1 ppm). Stable isotope ratios of oxygen were determined using off-line extraction techniques with H_2O - CO_2 equilibration for oxygen isotopes (Majoube, 1971). The hydrogen isotope ratio was measured on H_2 after water reduction by hot depleted uranium (Bigeleisen et al., 1952). To obtain Carbon and sulfur stable isotopes dissolved in water BaCO_3 (5 mg) was reacted with H_3PO_4 , to liberate CO_2 then analyzed for carbon isotopes (McCrea, 1950). The S isotopes in dissolved sulfate were measured on SO_2 after combustion of BaCO_3 plus BaSO_4 precipitates (>350 μg) using a Vario Micro© elemental analyzer equipped with an IR detector (2002- 2009 samples). Quality control carried out on blank water indicate no $\delta^2\text{H}$, $\delta^{18}\text{O}$ and $\delta^{34}\text{S}$ changes, a small contamination by atmospheric CO_2 (0.05 mg/250 ml) was observed and related to sample preparation (opening addition of NaOH and BaCl_2 solutions) and transportation. This relatively low C

contamination, while water samples contain tens or hundreds milligram of carbonate species, has been neglected in further carbon isotope interpretation.

We measured $\delta^{18}\text{O}_{\text{H}_2\text{O}}$, $\delta\text{D}_{\text{H}_2\text{O}}$, $\delta^{13}\text{C}_{\text{DIC}}$, $\delta^{34}\text{S}_{\text{SO}_4}$ values by double (1981 to 1983 samples: VG602 E) and 2002 to 2009 samples on triple collectors (ISOPRIME) isotope ratio mass spectrometers equipped with a dual-inlet and a continuous flow system for $\delta^{34}\text{S}$ measurements. All stable isotope values are reported as per mil (‰) relative to V-SMOW for O and H in silicates and water (Coplen, 1988), $\delta^{34}\text{S}$ values relative to V-CDT and $\delta^{13}\text{C}$ values relative to V-PDB. Analytical error and reproducibility for standards (NBS 18, NBS 19, NBS 123, NBS 127) and replicates are ± 0.05 ‰ for the $\delta^{13}\text{C}_{\text{BaCO}_3}$ equivalent of $\delta^{13}\text{C}_{\text{DIC}} \pm 0.2$ ‰ for $\delta^{34}\text{S}_{\text{BaSO}_4}$ and ± 0.1 ‰ for $\delta^{18}\text{O}$ of water, and ± 1 ‰ for δD (2δ) of water

We quantified the anhydrous gases collected on charcoal (Ar, N₂) with an ISOPRIME dual inlet system. The mass calibration was realized on mass 36 for Ar mass 28 for N₂ and mass 44 for CO₂ and peak jumps. We measured the relative proportions of argon and nitrogen with a calibration curve obtained with mixtures anhydrous gas (Ar/N₂: 0.9/78; 2/ 98; 10/90; 20/ 80).

5 Results

5.1 Rainwater and river drainage at Kerguelen.

Rainwater volume and temperature measured from 1981 to 1983 are similar to the recent data obtained from the meteorological station at Port aux Français (PaF; Table 1). Meteoric waters at Port aux Français have low-concentrations with dominant Na and Cl contents with a 1:1 Na/Cl molar ratio for temperatures between 1 and 12 °C (Table 1; Fig. 2A). The $\delta^{18}\text{O}$ rainfall

and δD rainfall values vary from -4 to -12 ‰ and -22 to -91 ‰ respectively. The most negative O and H stable isotope values were associated with snow storms. These O and H stable isotope values define a local meteoric water line (LMWL, $\delta D_{\text{rainfall}} = 8.43 \times \delta^{18}O_{\text{rainfall}} + 11$, $R^2 = 0.975$; Σ rainfalls 1625 mm/ 18 months; Fig. 2B). The mean weighted $\delta^{18}O_{\text{rainfall}}$ value in 1982 was -6.8 ‰. River drainages dominantly in the southern part of the archipelago are Na and Cl dominant (Table 2; Fig. 2A) with Na concentrations higher than rainfalls. Moreover, the rivers are more Na- Cl-rich on the eastern side of the archipelago (Jeanne d'Arc, Ronarc'h and Loranchet areas, Fig. 1A) than the western Rallier du Baty area (Table 1). The Oxygen and hydrogen stable isotope values of river drainages form a trend line parallel to the local meteoric water line ($\delta D_{\text{river drainage}} = 7.45 \times \delta^{18}O_{\text{river drainage}} + 6$, $R^2 = 0.837$; Fig. 2B).

Figure 2 and Tables 1 to 3

5.2 Geothermal localities

Thermal waters (from 7 to 100 °C) usually appear as isolated ponds. The RdB area hosts many springs with a lower flow rate than in VT and Gallièni areas (Val Travers in the Plateau Central; Fig. 1C). In the RdB area, many small ponds can be found within a few square kilometers (Rallier du Baty; Fig. 3A). Thermal waters from rocks to ponds flow through channels stained by iron oxides, and along clay-rich horizons (Fig. 3B) intercalated in lava units associated with basaltic scoria (Fig. 3C). Some thermal outlets are surrounded by precipitation of kaolinite (XRD: 1Md polytype), goethite, pyrite, and native sulfur (RdB). The water temperature varies from an average surficial temperature of 6 to steam fumaroles at 100

°C. We arbitrarily define low-temperature springs as waters with temperatures higher than the average surficial temperature (6 °C) up to a maximum of ~50 °C. This range of temperature corresponds to a majority of thermal waters disseminated through the archipelago with variable flow rates with traces of mineral precipitation (Infernet valley, Fallot glacier, and Gallièni Massif; Table 3). The Val Travers area and the active fumaroles in the Rallier du Baty (RdB) area have both low- (7 to 50 °C, Fig. 3D and E) and high- temperature waters (50 to 100 °C; Figs. 1A and 3F).

In the RdB area, thermal springs (7 to 100 °C) are distributed from mean sea level to an altitude of 500 m above sea level (a.s.l.). Thermal water flow rates vary from 10s' L/ s (50 to 220 m) to low-flow rates represented by condensed H₂O liquid +H₂O vapor in a bubbling oxide-rich ponds (ca. 1 L/ hour) located above 220 m. springs. The low-temperature thermal waters occur from sea level to 220 m and high-temperature fluids (H₂O liquid + vapor and CO₂; 97 °C, Fig. 3F) between 220 m and 450 m above sea level.

5.3 Chemical and isotopic compositions of thermal fluids and hydrothermal precipitates

Low-temperature thermal waters, from sea level to 220 m, have dominant Ca, Mg, Na and HCO₃⁻ ion compositions (Table 3) with neutral pH and rare springs with a basic pH (Fig. 3B). The Na/Cl molar ratios are higher than those measured at rainfall river drainages (Fig. 4A). Some of the low-temperature thermal waters have high-Ca, K, Mg, NO₃⁻, SO₄²⁻ and Br ion contents with Na/Cl molar ratio < 1.9 below diluted seawater content and EC > 300 µS/cm (Fig. 4A). These waters have been further described as mineral waters. The high- temperature thermal waters (> 220 m above sea-level) have neutral to acid pH (~ 3), low EC and Total

257 Dissolved Solids (TDS; Table 3) with Na, Cl to Na, Cl, SO_4^{2-} ion concentrations and very
258 low-Na/Cl molar ratios.

259 Oxygen and hydrogen stable isotopic values of mineral and low- temperature thermal waters
260 (7 to 50 °C) plot on or beside the local meteoric water line and define a line ($\delta\text{D}_{\text{H}_2\text{O liquid}} = 7.0$
261 $\times \delta^{18}\text{O}_{\text{H}_2\text{O liquid}} + 0.5$; $R^2 = 0.904$) (LMWL). A large number of high- temperature thermal
262 waters (50 to 100 °C) are located on both sides of this LMWL. Nevertheless, some $\delta^{18}\text{O}$ and
263 δD values of high- temperature thermal waters form a trend line ($\delta\text{D}_{\text{H}_2\text{O liquid}} = 1.78 \times \delta^{18}\text{O}_{\text{H}_2\text{O liquid}} - 23$, $R^2 = 0.65$; Fig. 4B) from LMWL toward more positive values of $\delta^{18}\text{O}$ and δD
264 values.

266 In low- and high- temperature thermal waters dissolved carbon and sulfur species define a
267 wide range of stable isotopic values. The low-temperature thermal waters have $\delta^{13}\text{C}_{\text{DIC}}$ and
268 $\delta^{34}\text{S}_{\text{SO}_4}$ values ranging from -5.6 to -23 ‰, and of +5 to +12 ‰, respectively (Table 3). The
269 spring having high-Ca, K, Mg, NO_3^- , SO_4^{2-} , and Br ion contents has the highest $\delta^{34}\text{S}_{\text{SO}_4}$ value
270 (11.6 ‰) and the lowest $\delta^{13}\text{C}_{\text{DIC}}$ value (-23 ‰). High-temperature thermal springs, with
271 lower TDS contents than low- temperature springs (7 to 50 °C), have $\delta^{13}\text{C}_{\text{DIC}}$ and $\delta^{34}\text{S}_{\text{SO}_4}$
272 values ranging from -5 to -10 ‰ and +3 to +9 ‰, respectively (Table 3).

273 The two steamers associated with high-temperature waters consist of H_2O vapor dominant
274 (approximately 95 %) with CO_2 ($\delta^{13}\text{C}_{\text{CO}_2} = -5.1 \text{ ‰} \pm 0.2$), and S-rich gas attested by the odor
275 and native sulfur in muddy deposits. The measured anhydrous gases in vapor dominant steam
276 have a total pressure lower than atmospheric pressure (0.09 MPa) with dominant N_2 (98.7 %)
277 minor Ar (1.2 %) and traces of He and CO (close to detection limit= 1 ppmv).

278 The X-ray diffraction of mineral precipitates in the zone of low-temperature springs (0 to 220
279 m) identified precipitates of aragonite (Fig. 3D) or amorphous silica and goethite (Fig. 3E).

The aragonite precipitation has an average $\delta^{13}\text{C}_{\text{aragonite}}$ of $+2.1\text{‰} \pm 0.3$ (Table 3). In the upper zone with hot thermal water, a steam vent surrounded by mud consisted of dominant kaolinite, mixed with euhedral pyrite. These euhedral pyrites (py) in this kaolinite-rich mud have $\delta^{34}\text{S}_{\text{py}}$ between -2.3 and -1.5‰ ($n=5$ values) and a trace of native sulfur $+3.5\text{‰}$ ($\delta^{34}\text{S}_{\text{native sulfur}}$). The high-temperature thermal waters in ponds contain water mixed with goethite and a smaller proportion of amorphous silica with kaolinite (kln) (Fig. 3F). The O and H stable isotope values ($\delta^{18}\text{O}_{\text{kln}}$ and $\delta\text{D}_{\text{kln}}$) of kaolinite from the steam vent have of 20.8‰ and -91‰ respectively.

Figures 3 and 4

6 Discussion

6.1 Rainwater and river drainages

The Na-Cl composition for rainwater to surface water and river drainages covers a large range of salinity ($5 < \text{Na} < 27$ mg/l). We associated the highest salinity to rainfall more influenced by oceanic storms than the usual westward winds. These stormy conditions have mixed seawater spray with rainfall. The stable isotope values for rainfall in the eastern Kerguelen archipelago (PaF) draw the local meteoric water line (LMWL). However, the large topographical change from the western to the eastern side of the island does not allow extrapolation of these observations throughout the whole archipelago.

The river drainages during the summer are slightly more saline with O and H isotopes data forming a restricted domain of values as rainfalls (Table 1, Fig. 2A). The increasing salinities from West to East (Gallièni, Jeanne d'Arc, Ronarc'h and Loranchet plateau) suggest that runoff is Na-enriched either by leaching of a Na-rich surface of rocks or by storms in the eastern archipelago. We favor higher proportion of sea spray mixed with rainfall during storm events considering the low-altitude of the eastern part of the archipelago. Whereas, mountains on the western side of the archipelago reduce the inland incursion of storms as shown by the western-side watershed basins (Fig. 1A).

The O and H stable isotope values of river drainages aligned and centered with the LMWL confirm that they are meteoric water (rainfall and snowmelt: lowest $\delta^{18}\text{O}$ and δD) runoff and can percolate throughout the Kerguelen volcanic plateaus. The river drainages from the western side of the Archipelago (RdB) have the lowest Na-Cl concentrations, and similar to slightly higher O-H stable isotope values (Table 2, Fig. 2B). We interpreted this data as dominant meteoric waters with low salinity related to the dilution of sea spray by more rain (orographic effect: estimated around 8000 mm per year on the western coast and 800 mm per year on the Eastern side PaF).

6.2 Organic contamination of thermal water

Flowing thermal springs or larger geothermal areas in Rallier du Baty and Val Travers have different recharge areas (Fig. 1B and 1C) and geothermal reservoirs. Each of these geothermal areas may represent one or several sources of steam; high-temperature thermal water derived from condensed steam and mixtures with meteoric water (e.g., Giggenbach and Stewart, 1982; Marini, 2004). Moreover, thermal springs (the Infernet Valley, Fig. 1B) located on the

coastline represent a nesting area for different penguin communities. The proximity of animals at the low-altitude with low-temperature thermal springs of the Infernet Valley has changed the composition of water with high-Ca, K, Mg, Cl, SO_4^{2-} ($\delta^{34}\text{S}_{\text{SO}_4}$: 11.6 ‰), NO_3^- , Br and HCO_3^- ($\delta^{13}\text{C}_{\text{DIC}}$: -23 ‰) ion concentrations with O and H stable isotope values lying on the LMWL (PaF). These elementary constituents and stable isotope values show dominant meteoric water with S species related to seawater and C species derived from organic matter (Hoefs, 1980; Lowenstern et al., 1999). Consequently, we eliminated these springs from our further geothermal interpretation and focused on area multiple emergences of thermal water (Fig. 1A) in the Rallier du Baty and Val Travers areas. These areas host the highest temperatures water (RdB), with high flow rates (VT).

6.3 Origin of 7 to 50 °C waters

We tried to identify the recharge of this hydrothermal system with O, H, C and S stable isotope values of fluid and minerals. The 7 to 50 °C thermal springs are dominant in the Kerguelen. These waters have O and H stable isotopes that define a line ($\delta\text{D}_{\text{H}_2\text{O liquid}} = 7.0 \times \delta^{18}\text{O}_{\text{H}_2\text{O liquid}} + 0.5$; Fig. 4B) parallel to the river drainage (e.g., summer runoff: $\delta\text{D}_{\text{H}_2\text{O liquid}} = 7.45 \times \delta^{18}\text{O}_{\text{H}_2\text{O liquid}} + 6$) and LMWL (PaF). This parallel trend suggests a dominant proportion of meteoric water in the low-temperature springs (Rallier du Baty, Plateau Central; Gallièni) regardless of pH and chemical composition. Nevertheless, some of the $\delta^{18}\text{O}$ and $\delta\text{D}_{\text{H}_2\text{O liquid}}$ values do not fall on the line. Displacement of the $\delta^{18}\text{O}_{\text{H}_2\text{O liquid}}$ and the right side of the LMWL might be related to water/rock oxygen exchange or a mixture of high-temperature thermal water with a more positive $\delta^{18}\text{O}_{\text{H}_2\text{O liquid}}$ (see below) with rainfall or melted snow (part. 5.1), localities with a lower thermal gradient or a similar thermal gradient at a shallower

infiltration than the high-temperature waters. However, the lack of a time series of analysis did not permit the characterization of this phenomenon. In both cases, the meteoric recharge would be driven by the topography and infiltration through fractures, or along discontinuities between lava-flows and pyroclastic rocks (Fig. 3F). Their $\delta^{13}\text{C}_{\text{DIC}}$ and $\delta^{34}\text{S}_{\text{SO}_4}$ data (Table 3) confirm dominant sources of inorganic carbon (magmatic- mantle= $-6.0\text{‰} \pm 1$; e.g., Javoy et al., 1982) and sulfur (Hattori and Muehlenbachs, 1980; Watanabe and Sakai, 1983). Moreover, the substantial precipitation of aragonite observed (Fig. 3D) with $\delta^{13}\text{C}$ values recognized in hydrothermal systems (eg., Pichler and Veizer, 2004) suggests an even more important proportion of inorganic CO_2 in the past than the present-day.

6.4 Origin of 50 to 100 °C waters

The high-temperature thermal waters and fumaroles are the most representatives of a significant thermal flux or magma-derived fluids. The fluid flow of hot springs with thick kaolinite precipitates suggest a long-lived period of fluid circulation. The other thermal springs was not sufficient nor the composition stable enough for analysis. Therefore, the long-lived flow, temperature, and chemistry was not estimated for other localities. This kaolinite may have precipitated from fluids different from the present-day ones. Consequently, $\delta^{18}\text{O}_{\text{H}_2\text{O liquid}}$ (-5.1‰) and $\delta\text{D}_{\text{H}_2\text{O liquid}}$ (-39‰) in equilibrium with kaolinite were first calculated (Savin and Lee, 1988; Sheppard and Gilg, 1996) with the present-day temperature of steam ($T_{\text{measured}} = 97\text{ °C}$; Table 3). The calculated $\delta^{18}\text{O}_{\text{H}_2\text{O liquid}}$ and $\delta\text{D}_{\text{H}_2\text{O liquid}}$ are comparable to present-day O-H stable isotope values ($\delta^{18}\text{O}_{\text{H}_2\text{O liquid}}$ measured: -4‰ ; $\delta\text{D}_{\text{H}_2\text{O liquid}}$ measured: -32‰). Secondly, we used an equilibrium temperature of 105 °C ($T_{\text{measured}} = 97\text{ °C}$) with $\delta^{18}\text{O}_{\text{kln}}$ and $\delta\text{D}_{\text{kln}}$ of kaolinite (cf. paragraph 5.2) and its spring water ($\delta^{18}\text{O}_{\text{H}_2\text{O liquid}} = -4\text{‰}$;

374 $\delta D_{H_2O \text{ liquid}} = -32 \text{ ‰}$). Both calculations prove the precipitation of kaolinite with H_2O_{liquid} with
 375 $\delta^{18}O_{H_2O \text{ liquid}}$ and $\delta D_{H_2O \text{ liquid}}$ along the LMWL. The equilibrium of kaolinite with H_2O_{liquid}
 376 indicates a minor isotope exchange between H_2O_{liquid} and vapor phases and small
 377 temperature variations between past water, precipitating kaolinite, and present-day waters.

378 In the Val Travers area, the stable isotope ratios of the high-temperature thermal waters are
 379 more negative ($\delta^{18}O$: -9.4 to -8.1 ‰ and δD : -58 to -50 ‰) than those of the RdB (Table 3)
 380 and plot along the LMWL. The RdB high-temperature thermal waters have O, H stable
 381 isotope values below the LMWL (PaF) and form a trend line ($\delta D_{H_2O \text{ liquid}} = 1.78 \times \delta^{18}O_{H_2O}$
 382 $_{\text{liquid}} - 23$) with an intercept with the LMWL at $\delta^{18}O_{H_2O \text{ liquid}} \sim -5 \text{ ‰} \pm 1$ and $\delta D_{H_2O \text{ liquid}} \sim -35$
 383 ‰ and equivalent to a fluid in equilibrium with kaolinite. This intercept value is higher than
 384 those from river drainage or low-temperature thermal waters. In similar geothermal contexts,
 385 this intercept of thermal water lines and the LMWL represents the meteoric-water recharge of
 386 the geothermal field (cf. Clayton et al., 1968; Clayton and Steiner, 1975; Craig et al., 1956,
 387 Fritz and Fontes, 1986; Truesdell and Hulston, 1980).

388 Whatever the $\delta^{18}O$ and δD position on the LMWL, this meteoric recharge excludes the
 389 infiltration of seawater, located few kilometers away, in the geothermal reservoir. This
 390 meteoric recharge is in agreement with the low-salinity of all thermal springs in the Kerguelen
 391 archipelago. The meteoric recharge in the RdB area is delimited by a watershed in the
 392 surrounding volcanic plateaus with an average altitude of 700 m a.s.l. (Figs. 1B and 2) and the
 393 permanent snow line at a maximum altitude of ~1200 m (Table 2). Consequently, the higher
 394 $\delta^{18}O$ and δD values of the intercept suggests, a meteoric water recharge less influenced by
 395 melted snow than river drainage or a similar recharge affected by additional processes such as
 396 vapor-condensed liquid separation (Giggenbach and Stewart, 1982), H_2S - CO_2 - H_2O isotope
 397 exchange, and water-rock interaction (reference aforementioned). These processes are

evidenced by the composition of fumarole steam with anhydrous gas and an N₂/ Ar molar ratio of 80, similar to that of atmospheric air (84; cf. Fischer et al., 1998; Giggenbach, 1995; Shaw et al., 2003), as well as the inorganic carbon ($\delta^{13}\text{C}_{\text{CO}_2} = -5.1 \text{‰} \pm 0.2$) and the native sulfur ($\delta^{34}\text{S}_{\text{native sulfur}} = 3.5 \text{‰}$; Table 3; e.g., Craig, 1963; Javoy et al., 1982; Hoefs, 1980; Lowenstern et al., 1999). These additions of gas through hydration may contribute to an increase in the proportion of sulfuric and carbonic acids (Ohmoto and Rye, 1979) and kinetic water/rock interaction (Fritz and Fontes, 1986; Giggenbach, 1991; Liebscher and Heinrich, 2007).

6.5 Process changing stable isotope compositions of high-temperature of thermal waters

In the RdB hydrothermal systems, condensed fumarole steam (steamers: $\delta^{18}\text{O}_{\text{H}_2\text{O vapor}} = +3 \text{‰}$ and $\delta\text{D}_{\text{H}_2\text{O vapor}} = -20 \text{‰}$; Table 3) is O and D enriched compared to fluids from other high-temperature springs (Fig. 4B). The calculated $\delta^{18}\text{O}_{\text{H}_2\text{O liquid}} (2.24 \text{‰})$ and $\delta\text{D}_{\text{H}_2\text{O liquid}} (-7.8 \text{‰})$ values in equilibrium (oxygen and hydrogen fractionation factors; Majoube, 1971; Horita and Wesolowski, 1994; Table 2) with these vapors for a temperature of 100 °C are more positive than that of the estimated meteoric recharge ($\delta^{18}\text{O}_{\text{H}_2\text{O liquid}} \sim -5 \text{‰} \pm 1$ and $\delta\text{D}_{\text{H}_2\text{O liquid}} \sim -35 \text{‰}$; part. 6.4). This calculation suggests either a different recharge or a vapor-liquid separation associated with a stable isotopes kinetic-exchange.

This kinetic exchange can be estimated looking at the slope of $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ and $\delta\text{D}_{\text{H}_2\text{O}}$ values for high-temperature springs with a dominant H₂O- liquid in RdB. The trend line with $\delta\text{D}_{\text{H}_2\text{O liquid}} / \delta^{18}\text{O}_{\text{H}_2\text{O liquid}}$ with a slope of 1.78 then integrates buoyancy and changing vapor/liquid

ratios from depth to atmospheric pressure. The calculated $\delta D_{H_2O \text{ liquid}} / \delta^{18}O_{H_2O \text{ liquid}}$ ratio, equivalent to the $\delta D_{H_2O \text{ liquid-vapor}} / \delta^{18}O_{H_2O \text{ liquid-vapor}}$ ratio, is lower than the predicted ratio obtained by equilibrium or kinetic evaporation at $\leq 100^\circ C$ (below $100^\circ C$: equilibrium = 5.3, Majoube 1971 and kinetic evaporation = 2 to 5, Dansgaard 1964; Gonfiantini et al. 1973; Fig. 4B). This $\delta D_{H_2O \text{ liquid}} / \delta^{18}O_{H_2O \text{ liquid}}$ ratio below 2 excludes the equilibrium and kinetic process of liquid-vapor separation below $< 100^\circ C$. These O and H stable isotope changes may also relate to (i) isotopic fluid exchange (CO_2 , H_2S , and H_2O), (ii) fluid/rock interaction with O-H isotopic exchange (Craig et al. 1956), (iii) Mixing of meteoric water and magmatic-like water (cf. $\delta^{18}O = +9$ to $+10\text{‰}$ and $\delta D = -8$ to -18‰ ; Giggenbach, 1992b).

Firstly, we established a conceptual model that considers the lower part of the RdB reservoir as a rock-dominated system and the upper part of the reservoir with a steam dominated cell (Giggenbach, 1992b). We examined the CO_2 , H_2S and H_2O interactions able to produce dominant “horizontal” ^{18}O shifts (cf. Giggenbach, 1992a) related to a CO_2 - H_2O oxygen isotopic exchange (Majoube, 1971) and a H_2S - H_2O H isotopic exchange (cf. Galley et al., 1972). In both cases, the low- CO_2 (measured $CO_2 < 5 \text{ wt. \%}$) and estimated H_2S proportion (H_2S odor) and their C and S isotopic values would not produce an ^{18}O shift as observed (Table 3; Fig. 4B; cf. Chiodini et al., 1993; Giggenbach, 1987).

The second hypothesis (i), $\delta^{18}O$ and δD on both above and below of the LMWL may represent vapor and condensed liquid separation. The oxygen and hydrogen stable isotope values of condensed liquid on the LMWL and vapor above the LMWL (Fig. 4B) with a $\delta D_{H_2O \text{ liquid}} / \delta^{18}O_{H_2O \text{ liquid}}$ ratio of 1.78 would represent a high-temperature H_2O liquid-vapor system at $\sim 250^\circ C$ with a phase separation probably occurring in ascending fluids. Finally, hypotheses (ii) and (iii) are difficult to separate since water/rock interaction may produce large O isotope shifts driven by a thermal meteoric fluid/ magmatic rock interaction (Craig et al.,

1956). The stable isotope values tend toward this large domain so-called “magmatic-like water” (cf. Capasso et al., 1997; Chiodini et al., 2000; Giggenbach, 1992b). In this case, the hydrothermal alteration may shift the $\delta^{18}\text{O}_{\text{H}_2\text{O liquid}}$ and $\delta\text{D}_{\text{H}_2\text{O liquid}}$ toward the field of magmatic-like water. However, no high-temperature hydrothermal mineral (K-feldspar, epidote) has been observed in the RdB area.

We also calculated temperatures derived from different S isotopes in SO_4^{2-} -rich water and pyrite (S-isotopes fractionation factor: Ohmoto and Rye, 1979; Robinson, 1973). Assuming equilibrium, the calculation of $\delta^{34}\text{S}_{\text{SO}_4^{2-}} - \delta^{34}\text{S}_{\text{pyrite}}$ suggest a temperature varying from 240 to 300 °C. This calculation indicates either an inappropriate assumption of equilibrium or hot-springs with a fluctuation of temperature (dominant kaolinite ca. 100 °C, minor pyrite 240 to 300 °C). For a similar assumption of equilibrium, the C stable isotope values of CO_2 gas and CO_3^{2-} -rich water (C isotope fractionation factor: Mook et al., 1974). CO_2 and HCO_3^- equilibrium would be between 50 and 115 °C. The range of calculated temperatures indicate temperatures varying from 300 to 50 °C, with phase separation to water/rock interaction.

6.6 Ion concentration ternary diagrams and cation thermometers for water

The temperature range of the RdB geothermal reservoir was bracketed by the major element composition. The large surface of this geothermal area is attested by the volcanic context of the archipelago, and warm soils in the Infernet valley (Fig. 1B), where thousands of animals breed. This thermal flux could be regional or a local convective heat flux (Ballestracci and Nougier, 1984). The calculated critical points of water (NaCl between 0.001 and 0.1 weight %; CO_2 varying from 1 to 10 weight %; Table 2) between 340 and 370 °C for

468 22 MPa to 23 MPa (Duan and Sun, 2003) will limit the maximum temperature of the hydrous
469 geothermal reservoir.

470 The low- to high-temperature springs tend to have low- Na -Cl for acid and sulfate-rich
471 thermal waters. These chemical compositions may be the consequence of several processes
472 and the geometry of the geothermal reservoir. Processes can be due to hydrothermal cells with
473 steam or condensed steam (e.g., Giggenbach and Stewart, 1982; Marini, 2004), mixtures of
474 low-Na rainfall with a Na-precipitating phase, SO_4^{2-} enrichment for low Cl concentrations
475 with water-rock interaction (cf. Hedenquist et al., 1994; Sheppard, 1986; Taylor, 1979), and
476 up-flow circulation (Giggenbach, 1988).

477 We estimated the temperatures of the geothermal reservoir with a cation thermometer. The
478 calculated temperatures assume a chemical equilibrium between water and mineral in the
479 geothermal reservoir (e.g., Bowers and Taylor, 1985; Fournier and Potter, 1982; Pope et al.,
480 1987; Giggenbach, 1988; Fournier, 1991; Simsek and Gülec, 1994; White et al., 1971).

481 Thermal springs with steam loss with CO_2 , acid pH, or amorphous silica, kaolinite, and
482 aragonite indicate under-saturation or saturation of carbonates and silicates during conductive
483 undercooling or fluid transport. These conditions exclude the assumption of chemical
484 equilibrium for Si, Ca compounds and the use of Si-Ca geothermometry.

485 Consequently, a preliminary calculation of the temperature of the thermal reservoir used
486 information on conservative elements such as cationic diagram and thermometry (Fig. 5A;
487 Giggenbach, 1988). Nevertheless, the cation diagram shows that most low and high-
488 temperature spring waters are not classified as “fully equilibrated mineral waters” (Arnórsson,
489 2000; Arnórsson et al., 1983; Giggenbach, 1988). One acid and two basic thermal fluids plot
490 in the field of fully equilibrated water. A Cl^- , SO_4^{2-} and HCO_3^- diagram (Fig. 5B) and the
491 SO_4^{2-} -rich water suggest of volcanic origin; whereas the HCO_3^- -rich waters are reported in
492 the literature as related to peripheral waters or mature fluids.

Consequently, several cation thermometers have been used to estimate the temperature at different stages of fluid/rock interaction. The calculation of Na- K cation thermometer temperature is based on the water/feldspar interaction (Fournier and Truesdell, 1974). This cation thermometer indicates that the two fully equilibrated waters considered in this study would range from 270 to 290 °C (Fig. 5A). This range of temperature is similar to the one obtained with high -temperature liquid-vapor ($\delta D_{H_2O \text{ liquid}} / \delta^{18}O_{H_2O \text{ liquid}}$ ratio= 1.78), sulfate-pyrite equilibrium (240 to 300 °C).

6.7 Thermodynamic modeling of water/rock interaction in Rallier du Baty

Whole fluid-rock interaction and associated chemical changes have been reconstructed with the thermodynamic model (PhREEQC 3.3 software, with the Lawrence Livermore National Laboratory thermodynamic database: LLNL database, July 2017; Parkhurst and Appelo 1999). We selected chemical compositions of the thermal spring waters in the fully equilibrated field (Fig. 5A) with an estimated temperature of the geothermal reservoir between 200 and 300 °C (Table 2). This model uses the influx of meteoric water with a chemical composition of river drainage in RdB (Cap Bourbon) representing the meteoric and hydraulic recharge of the geothermal reservoir (Table 1). This meteoric recharge can interact with the anorthite, albite, olivine, Ca-pyroxene, pyrite, and quartz for volcanic glass, considered a primary mineral of the surrounding rocks (Beaux, 1986; Moine et al., 2004), and produce secondary minerals observed in the RdB area (goethite, amorphous silica, aragonite, kaolinite, and pyrite) or found in the Kerguelen archipelago (analcime, clinoptilolite, stilbite, illite, smectite, quartz, K-feldspar (adularia) and carbonates; cf. Renac et al., 2010; Verdier, 1989).

This modeling assumes a first stage with the injection of meteoric water into a geothermal reservoir where reactions reach equilibrium. The second stage will examine chemical changes in fluids produced from the geothermal reservoir toward the surface. Temperature and pressure in the first stage vary from 6 °C to a maximum temperature of 306 °C and from atmospheric pressure to 24 MPa. In order to follow chemical changes 6 cells with a dT/dP gradient of +50 °C/ +4 MPa were separated. In summary, a calculation with increasing temperature and pressure predicts the dissolution of ferromagnesian minerals, feldspars in trachyte and the production of a Na, Ca, H₂S and SO₄²⁻ acid brine (pH~ 4.5) well known to exist in oceanic hydrothermal areas (Brombach et al., 2000; D'Amore and Panichi, 1980; Pope et al., 2009). Such fluids in RdB and VT would represent the most thermal and pristine geothermal fluids. Nevertheless, acid thermal waters represent a small number of recognized hot springs in the Kerguelen archipelago (Table 3). The results of these calculations combined with stable isotope values indicate that the analyzed geothermal waters have evolved chemically. Consequently, the high -temperature H₂O liquid-vapor or CO₂ -HCO₃⁻ represent a phase change and a separation during fluid ascent from the geothermal reservoir to the surface (adiabatic cooling). This modeling predicts the formation of secondary minerals (smectite, smectite-illite below 200 °C, quartz and K-feldspar (adularia) from 150 to 306 °C) that haven't been recognized in the RdB or VT areas but described by Verdier (1989) in highly altered rocks.

The second stage of this thermodynamic model deal with ascending fluids and mineral changes from the geothermal reservoir (306 °C) through conductively cooling trachyte (50 to 100 °C). As observed, the calculation predicted the alteration of a primary mineral and the precipitation of kaolinite (stable isotopes ca. 100 °C) and amorphous silica (Fournier and Rowe, 1966) with pyrite at temperature starting at 150 °C. These secondary minerals equilibrate with acid pH, a low-Si concentration with high-Na-Ca and SO₄²⁻ concentrations.

542 The low-Na concentration of the thermal waters suggests the precipitation of Na-rich
543 secondary minerals (zeolite or smectite).

544 The differences between the analyzed composition of the thermal waters and the calculated
545 composition combined with the interpretation of $\delta^{18}\text{O}$, δD , $\delta^{13}\text{C}$ and $\delta^{34}\text{S}$ values suggest that
546 the RdB area consists either of several hydrothermal cells (heated groundwater) and/or a
547 progressive separation of fluids (H_2O liquid-vapor, cation-anion changes, CO_2 dissolved -gas)
548 takes place. The $\delta^{18}\text{O}$ and δD hypothesis of an ‘incomplete water-rock interaction’ would be
549 derived from several hydrothermal cells with different liquid-vapor separation as suggested by
550 a SO_4^{2-} -rich water related to volcanic-sourced steam (part 6.3).

551 We combined these different hypotheses in a schematic cross-section in the RdB (Fig. 6).

552 This cartoon indicates a high-temperature geothermal reservoir with acid brine and water-rock
553 interaction between 250 and 300 °C. The final stage is represented by a $\text{CO}_2_{\text{gas}}\text{-HCO}_3^-$ phase
554 separation (50 °C) associated with an N_2/Ar ratio similar to the atmospheric ratio. Between
555 these two stages, conductive cooling of rising fluids has produced carbonates, amorphous
556 silica, and kaolinite (~ 100 °C). The depth of the RdB geothermal reservoir is difficult to
557 determine because of the unknown geothermal gradient. Therefore, the meteoric origin of the
558 water recharging the RdB hydrothermal system (surrounding plateau: 700 to 1200 m, Fig. 1)
559 promotes a maximum hydraulic pressure of 7 to 12 MPa. Assuming a maximum pressure of
560 about 23 MPa (critical point of liquid water) then their differences would represent the
561 hydrostatic pressure below sea level. The difference ranges between 16 (23-7 MPa) and 11
562 (23-12) MPa equivalent to a depth of 1.6 km to 1.1 km or 0.4 to 0.6 km under hydrostatic or
563 lithostatic pressure. In such a context, the RdB geothermal gradient (300 °C/ 0.4 km or 300
564 °C/0.6 km or 300 °C/ 1.1 km or 300 °C/1.6 km) is equivalent to the Iceland or Guadeloupe
565 active geothermal fields (Pope et al., 2009; Brombach et al., 2000).

566

567 Figures 5 and 6

568

569 7 Summary and conclusions

570

571 The results of the comparison of chemical composition and stable isotope values for
572 rainwater, river drainage, minerals, and thermal spring waters supports the concept of
573 meteoric recharge and geothermal activity. The large volcanic plateau with issuing low- to
574 high- thermal waters in the different areas of the Kerguelen suggest that heated groundwater
575 might represent shallow and deep fluids and thermal water diluted with meteoric recharge.
576 Nevertheless, the fumarole field of Rallier du Baty and other geothermal locations in the
577 Kerguelen archipelago represent the surficial expression of meteoric-water hydrothermal
578 systems. In the Rallier du Baty, meteoric thermal waters are chemically modified by boiling
579 and gas-water-rock interaction. Meteoric recharge and thermal fluids such as acid brines have
580 interacted with anhydrous gas from magma to alter igneous rocks and to precipitate kaolinite
581 (ca; 100 °C), amorphous silica, carbonate on the surface and presumably adularia and zeolite
582 at depth.

583 The O, H and S stable isotope ratios confirmed a high-enthalpy hydrothermal system with
584 temperatures between 250 to 300 °C and HCO_3^- separation to CO_2 between 50 and 115 °C
585 associated with an N_2/Ar - like atmospheric ratio gas and the precipitation of kaolinite. The
586 depth of 400 to 1600 m below sea level of the geothermal reservoir was calculated using
587 values for lithostatic and hydrostatic pressure.

588 The stable isotope and chemical data presented in this paper could encourage further
589 comparisons to be made with infrared thermography, and fluid-inclusion microthermometry

to obtain a realistic interpretation of earlier magmatic activity in the simulation of active geothermal systems throughout the Kerguelen archipelago.

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Figure and Table captions

Figure 1: A) Kerguelen Archipelago with locations of present-day hot springs (red dots: Rallier du Baty, Plateau Central, Gallieni) and sampled river drainage (blue dots) associated with a large watershed basin identified by a digital elevation model (SRTM 1arc second) and QGIS software associated with flow accumulation, successive flow routing and catchment area algorithms to delimit watersheds (Saga algorithms). B) a simplified geological map of Rallier du Baty area, associated with a digital elevation model. C) A digital elevation model of the Plateau Central area with Val Travers, Lili, Bossière thermal springs and watershed; D) digital elevation model of the Jeanne d'Arc area with locations of sampled rivers and their

watersheds; E) digital elevation model of the Gallièni area with sampling locations of river and thermal springs and watershed associated.

Figure 2: A) Na vs. Cl concentration (mg/l) of rainfall (red circle) and watershed waters (blue circle) B) δD vs. $\delta^{18}O$ diagram, showing the isotope composition of rainwater from Port aux Français and river drainage composition from all over the archipelago. Also, shown in A) Na/Cl molar ratio distribution and composition of water mixed with seawater (diluted seawater) as well as a Na vs. Cl regression line. In B) the worldwide and local meteoric water lines are presented (Global meteoric water line: GMWL; Craig, 1961), the composition of seawater and “andesite type magmatic waters” (Giggenbach, 1992a) regression line for the local meteoric water line (LMWL) and river drainage regression line.

Figure 3: A) Fumarole field of Rallier du Baty (420 m a.s.l.), B) Thermal water iron oxides and silica particles in the Upper Infernet valley, C) Steam and thermal water emergence in an altered pumice level at the Infernet valley in the Rallier du Baty area, D) aragonite crust encountered nearby low-temperature thermal springs in Plage du Feu de Joie E) modern opal precipitates on Plage du Feu de Joie, F) Steamer sampled at Mount des fumarole for fluids (H_2O and CO_2 , anhydrous gas) and alteration phases (kaolinite and pyrite).

Figure 4: A) Na vs. Cl concentration (mg/l) of mineral and thermal spring waters of Kerguelen (7 to 50 °C: blue circle; 50 to 100 °C red circle); B) δD vs. $\delta^{18}O$ diagram, showing the isotope composition 7 to 50 °C (blue circle) and 50 to 100 °C (red circle) of mineral and thermal spring waters of the Kerguelen archipelago. Springs with carbonate, opal, kaolinite precipitates are marked. Also shown are the GMWL (dashed line), the composition of

‘andesite type magmatic waters’ (Giggenbach, 1992) and Na, Cl and O-H stable isotope composition of RdB watershed water A trend line for O- H stable isotope values is shown for 50 to 100 °C spring waters from the RdB (plain line).

Figure 5: Mineral and thermal water composition of Kerguelen (blue circle: 7 to 50 °C waters; red circles: 50 to 100 °C waters and composition fields for rainwater and watershed waters) in A) Na–K–Mg^{1/2} triangular diagram, and B) SO₄²⁻–HCO₃⁻–Cl (%) triangular diagram and fields of immature and fully equilibrated waters as well as some calculated temperatures using Na-K and Mg-K geothermometers (after Giggenbach 1988).

Figure 6: Schematic model of the Rallier du Baty geothermal field based on interpretations of the water chemistry and stable isotope values. The model presents infiltration of meteoric water into the geothermal reservoir followed by the upflow conductive cooling and a liquid-vapor separation.

Table 1: Sampling of rainwater (month), average temperature, amount of rainfall (mm), , electrical conductivities (μS/cm), pH, total dissolved species (mg/l), chemical composition (concentrations in mg/l), calculated amount of HCO₃⁻ (mg/l), and stable isotope values (δD and δ¹⁸O) of rainwater in Port aux français (n.d. not detected; n.a. not analyzed)

Table 2: Location, GPS position and altitude of sampled river drainage in the Kerguelen archipelago (Rallier du Baty, Val Travers, Galliéni, Ronarc’h...) with temperatures (°C),

660 electrical conductivities ($\mu\text{m}/\text{cm}$), pH, cation and anion concentrations (mg/L) and $\delta^{18}\text{O}$ - δD
661 stable isotope values.

662

663 Table 3: Location, GPS position and altitude of thermal and mineral springs in the Kerguelen
664 archipelago (Rallier du Baty, Val Travers, Galliéni, Ronarc'h...) with temperatures, pH,
665 alkalinities, electrical conductivities, cation and anion concentrations (mg/L), $\delta^{18}\text{O}$, δD ,
666 $\delta^{13}\text{C}_{\text{DIC}}$ or CO_2 and $\delta^{34}\text{S}_{\text{SO}_4}$ values (n.a. stands for not analyzed). The Na-K thermometer was
667 used to calculate the equilibrium temperature of water at the following conditions:
668 temperature above 50 °C, pH= 6.9 to 7.5; Ca/ Na molar ratio<1 and $\text{pCO}_2 < 10^{-4}$ atm

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46.6532 S; 46.11983 W

61.7821 S; 46.11983W

Figure 2

Figure 4

Figure 5

Figure 6

Months	temperature	rainfall	c25°C	pH	TDS	Ca	Mg	Na	K	Cl	SO ₄	NO ₃	calculated	δ ¹⁸ O	δD
	(°C)	(mm)	µS/cm		mg/l	mg/l	"	"	"	"	"	"	HCO ₃	‰	‰
May 1981	3.7	79	66	n.d.	25	0.28	0.22	7.20	0.25	14.72	2.19	0.03	0	-6.9	-42
June- July	2.5	120	47	"	18	0.16	0.26	5.20	0.18	9.33	2.58	0.04	0	-5.7	-35
Aug-October	n.d.	135	81	"	35	0.60	1.07	10.20	0.42	19.97	2.39	0.04	0	-5.9	-33
Nov-Dec	4.7	105	53	"	21	0.35	0.74	6.24	0.18	9.65	2.19	0.03	2	-10.9	-79
January 1982	7.3	n.d.	38	"	15	0.20	0.42	4.62	0.11	6.38	2.19	0.03	1	n.d.	n.d.
Jan to Feb	7.5	53	83	"	32	0.46	1.46	8.80	0.43	17.84	2.80	0.01	0	-6.9	"
Feb	8.5	45	45	"	32	6.56	0.24	1.80	0.16	2.72	1.80	0.03	19	-8.2	-64
March	7.4	60	75	"	48	7.80	0.72	4.65	0.23	7.08	3.10	0.04	24	-6.7	n.d.
April	5.9	69	230	"	101	8.08	0.78	26.40	1.80	48.20	8.00	0.07	8	-7.2	-51
May	3.9	81	80	"	29	1.82	0.93	7.00	0.48	13.36	2.80	0.02	3	-4.5	-33
June	3.0	70	105	"	37	1.15	1.60	9.60	0.56	19.68	-	0.01	4	-6.4	n.d.
July	2.3	76	64	"	23	1.00	0.87	5.90	0.31	11.44	2.10	0.03	1	-7.0	"
Aug	1.9	70	120	"	40	1.20	1.60	10.60	0.61	22.80	3.60	-	0	-5.6	"
Sept	2.4	72	52	"	17	0.63	0.63	4.70	0.21	8.48	1.80	-	1	-9.0	-67
Oct	3.9	62	80	"	29	0.70	1.27	7.50	0.48	13.84	3.00	0.02	2	-8.4	n.d.
Nov	5.2	61	41	"	15	1.25	0.30	2.90	0.20	4.48	-	-	6	-6.9	"
Dec	6.5	64	49	"	15	0.61	0.60	3.85	0.17	7.92	1.80	-	0	-5.7	"
January 1983	7.8	55	49	"	18	0.55	0.63	4.50	0.24	7.28	2.30	0.01	2	-6.8	n.d.
Feb	8.2	46	120	"	46	1.01	2.07	12.80	0.54	25.92	4.00	0.01	0	-4.1	-22
March	7.2	61	55	"	19	0.49	0.80	5.30	0.23	9.68	1.80	-	1	-3.9	-23
April	6.0	68	116	"	48	0.81	1.87	13.80	0.56	24.64	4.00	-	2	-5.5	n.d.
May	3.2	79	70	"	24	0.45	0.87	7.10	0.43	12.32	2.10	-	1	-12.2	-91
June	2.7	71	68	"	23	0.53	0.93	6.60	0.35	12.24	2.30	0.03	0	-8.7	n.d.
July	2.2	73	42	"	13	0.33	0.48	3.55	0.16	7.06	1.30	-	0	-8.8	"

	Longitude	Latitude	altitude (m)	Temperature (°C)	pH	EC (µS/cm)	Ca mg/l	Mg "	Na "	K "	HCO ₃ "	Cl "	SO ₄ "	NO ₃ "	SiO ₂ "	δ ¹⁸ O ‰	δD ‰
Rallier du Baty																	
Glacier de Plan praz (Riv)	49° 27' 14.73" S	69° 00' 24.89"	41	5	7.10	34	5.00	1.00	6.20	1.13	18.90	5.20	5.40	0.11	4.80	-7.59	-47
Glacier Arago (Riv)	49° 34' 57.31" S	69° 02' 20.35"	7		7.00	31	1.67	0.68	5.20	0.65	8.50	8.20	2.39	0.19	6.80	-6.79	-43
Les 2 frères (Riv)	49° 38' 39.49" S	69° 00' 56.21"	32	16	6.70	47	2.26	0.77	9.20	0.88	8.50	13.60	3.17	0.07	9.40	-6.61	-
Vallée de la Mouche (Riv)	49° 36' 56.82" S	69° 04' 13.61"	23		6.70	51	5.49	1.28	4.90	0.57	9.20	8.70	15.60	0.06	4.40	-6.48	-44
Le portillon (Mt Erebus: Riv)	49° 38' 35.11" S	68° 58' 09.75"	41	7	7.00	26	2.20	0.56	4.40	0.76	6.10	8.70	2.19	0.03	7.60	-6.77	-44
Plateau Central																	
Riv des Tourmentes	49° 18' 41.37" S	69° 25' 13.96"	17	11	7.40	46	4.86	1.35	9.90	0.27	17.70	13.50	4.54	0.06	7.40	-8.89	-54
Tristan lake (end of H. Bossière Fjord)	?	?		18	7.20	57	2.88	0.87	10.00	0.55	9.20	13.70	3.37	0.05	5.80	-7.11	-48
Gallieni Massif																	
Plaine de Dante (Riv)	49° 33' 32.15" S	69° 21' 54.34"	62	9	7.30	54	2.67	1.32	14.40	0.82	18.30	15.00	3.17	0.10	6.10	-8.54	-55
Riv au glacier blanc (snow melted)	49° 35' 55.43" S	69° 23' 37.13"	21	2	7.30	45	8.00	1.54	7.70	1.19	18.90	10.30	22.40	0.14	7.30	-8.28	-58
Diane's Lake	?	?		11	7.80	90	5.25	4.34	14.00	1.70	37.20	18.00	5.72	0.07	18.10	-5.73	-32
Val des Skuas (Riv)	49° 36' 16.31" S	69° 35' 49.74"	263	7	7.50	63	4.62	1.09	8.20	1.94	22.60	15.00	3.90	0.07	9.10	-5.81	-32
Val des Skuas (Riv)	49° 36' 21.57" S	69° 36' 02.40"	263	5	6.80	71	4.51	2.34	9.80	3.90	32.90	16.00	4.30	0.04	20.20	-8.97	-59
Table du Cratère 'snow melted'	49° 35' 34.03" S	69° 36' 27.29"	228	2	6.60	49	1.69	1.45	15.00	2.13	23.80	13.70	3.37	0.08	14.80		
Courbet Peninsula																	
Port aux Français (water supply: 12/1981)	49° 20' 47.79" S	70° 13' 25.81"	32	6	7.00	94	7.34	4.60	17.50	1.24	32.30	30.00	9.50	0.04	17.50	-7.51	-49
Port aux Français (water supply: 04/1981)	"	"		5	7.30	47	5.46	1.28	12.00	0.52	11.00	22.00	3.95	0.04	5.90	-6.54	-45
Riv du Château (04/1981)	49° 16' 42.14" S	70° 08' 03.88"	111	17	6.70	38	1.16	0.70	5.50	0.66	5.50	9.50	2.18	0.08	1.10	-7.34	-50
Presqu'îles Jeanne d'Arc																	
Riv des Charbons	49° 33' 27.25" S	69° 48' 48.71"	102	8	7.70	80	4.51	2.34	19.20	0.83	18.30	26.50	5.13	0.06	6.20	-7.27	-50
Pte de la Géodésie (Peatbog)	49° 33' 45.29" S	69° 50' 14.36"	56	8	7.70	155	11.90	6.68	27.60	0.93	56.10	46.00	7.88	0.08	12.70	-7.60	-54
Vallée des Neiges (Riv)	49° 35' 23.87" S	69° 52' 46.32"	144	7	7.40	84	5.12	2.94	18.80	0.89	23.20	28.00	4.35	0.13	7.40	-7.25	-50
Vallée de l'Acœna (Riv)	49° 36' 04.16" S	69° 56' 26.09"	5	15	7.40	120	6.21	3.56	20.50	1.04	29.30	30.00	4.54	0.15	11.70	-7.44	-54
Vallée de la Planchette (Riv)	49° 36' 24.32" S	70° 00' 25.58"	17	15	7.60	117	6.49	4.12	17.80	0.92	30.50	29.00	7.49	0.07	12.60	-7.40	-
Vall Levant (Riv)	49° 39' 44.97" S	70° 02' 32.40"	65	14	7.20	120	3.36	2.74	21.00	0.93	16.50	35.00	6.50	0.07	8.60	-	-
Presqu'îles Ronarc'h																	
Riv des Macaronis	49° 34' 54.61" S	70° 15' 25.15"	126	11	7.10	80	2.35	2.10	17.10	2.10	17.10	25.00	5.13	0.07	9.90	-8.36	-56
Nord de la Coupole (Peat bog)	49° 35' 21.56" S	70° 14' 36.38"	193	6	7.10	128	5.22	4.54	25.40	2.05	35.40	35.50	9.25	0.21	13.60	-7.66	-52
Loranchet Peninsula																	
Les Nuageuses (Riv Ile de Croÿ: 04/1981)	48° 38' 34.41" S	68° 39' 25.07"	23	13	7.30	152	7.31	3.76	29.60	0.71	15.90	52.50	13.57	0.03	0.30	-5.92	-

Location sampling year	sample name and field observation	GPS location	altitude (m)	Temperature (°C)	pH	EC µS/cm	Ca mg/l	Mg "	Na "	K "	Li "	NH ₄ "	HCO ₃ "	CO ₃ "	Cl "	SO ₄ "	PO ₄ "	NO ₃ "	F "	Br "	SiO ₂ "	δ ¹⁸ O ‰	δD ‰	δ ¹³ C _{DIC} ‰	δ ³⁴ S _{SO4} ‰	Na-K geothermometer °C		
RdB (Cap Bourbon; 1982)			25	88	6.1	217	12.82	2.26	21.20	14.08	15.00		47.00		19.50	32.23		0.08				122.1	-7.1	-44				
1982				92	3.5	406	5.84	4.00	29.60	14.92	30.00		0.00		16.00	285.00		0.14				137.3	-3.8	-32				
Vallée du Glacier Fallot (2009)		49° 39'22"S; 68°53'10"E		57	7.3	1578	85.50	54.29	191.80	33.26			1066.00		44.12				3.84					-9.3	-63	-6.3		278
Rallier du Baty																												
2009	Carbonate precipitate; mineral spring	49°40'37"S; 68°54'02"E		15	7.2	1351	34.86	56.76	177.56	34.09			859.00		29.14	0.40			1.99				-8.7	-65	-6.5		292	
RdB (Infernet Valley; 2009)		49° 38'02"S; 68° 48'09"E	30	60	7.3	1872	68.83	8.77	294.97	41.41			412.00		310.06	77.75		1.40	17.26	0.25			-6.8	-49	-22.9		249	
"		49° 38'04"S; 68°48'04"E	ca. 50	68	6.5	1993	86.18	19.02	294.54	38.15			602.00		256.96	55.75			4.81				-7.6	-54	-7.3			
"		49° 38'08"S; 68°47'40"E	60	68	7.4	340	4.01	0.42	59.38	15.43			152.00		15.74	8.57			1.75						-8.4			
RdB (Feu de Jole beach; 2009)		49° 38'25"S; 68°47'36"E	18	87	3.6	423	12.56	3.94	40.98	10.94					43.85	122.72							-4.4	-28				
"	H ₂ S odour	49° 38'06"S; 68°47'10"E		90	7.5	925	47.30	17.03	115.75	12.30			233.00		140.25	58.49		5.52	0.55				-5.6	-30	-14.3	11.6	216	
"		49° 38'08"S; 68°47'08"E		85	3.2	336	10.70	4.01	37.28	10.57					23.23	98.00							-5.6	-41	-8.4			
"		49° 38'29"S; 68°47'19"E		69	7.5	1102	72.38	10.33	138.25	13.99			369.00		132.22	43.44			2.14	3.24			-8.3	-61	-7.0		211	
"		49° 38'38"S; 68°47'13"E		93	6.8	393	24.33	11.61	29.47	4.79			98.00		42.04	37.56							-6.9	-47	-6.5			
RdB (Mont des Fumeroles; 1981)	condensed vapor	49°37'54" S; 68° 47'94" E	ca. 425	72	4.5	361	0.51	1.42	30.30	23.80	0.01				41.00	118.00		0.09				195.3	2.2	-21				
2007	RB1	49°37'54" S; 68° 47'94" E		82	3.5	380	1.15	2.04	30.26	22.80	0.01	0.82			1.77	110.08			0.07									
2007	RB2		ca. 425	100	7.3	83	0.13	0.58	11.67	4.23		n.d.	6.00		5.70	19.13			0.09				2.7	-16				
2007	Condensed vapor (RB 3)		"	97	7.6	88.5	1.06	2.68	10.85	1.21		0.14	12.00		16.34	5.73			0.09				-5.2	-42				
	Condensed vapor (RB 4)		"	87	4	110	0.20	1.34	6.74	5.39		1.26			3.26	43.81			0.02				-5.9	-41	-10.9			
1981	Steamer (native sulfur)		"	95	6.6	153	0.49	1.40	21.60	5.52	<5		3.70		36.20	27.60		0.07				50.7	-2.4	-31	-10.2			
2007	RB5		"	85	7.2	146.8	1.92	5.41	19.90	6.37		0.17	41.00		16.87	19.88			0.20				-2.8	-30			260	
2007	Opale precipitate		203	62	10.4	3400	13.50	1.56	673.72	147.96	1.22	8.62	150.00	800.00	183.48	40.34			23.78	0.38	<200		-5.5	-49			"270"	
"	Opale precipitate				10.3	3510	3.83	0.46	711.89	156.21	1.29	0.00	150.00	800.00	184.42	39.59			24.06	0.61			-5.7	-52			"290"	
2007	Soc Pl 335		300	50	6.4	965	5.05	1.12	20.85	5.68		0.12	48.00		14.42	10.40			0.38				-5.7	-26				
"	Soc Pl 334			50	7.4	681	178.77	12.95	21.99	1.87	0.01	0.00	650.00		4.96	3.04			0.33				-5.6	-37			193	
"	RB5			57	4.5	109	0.67	0.76	9.73	5.21		0.72			7.16	24.44			0.03				3.1	-16				
2007	RB7			70	2.7	341	11.83	5.57	11.94	9.77		4.83			2.82	140.19			0.10				-8.2	-37				
2009					5.1	117	2.29	1.34	9.36	5.78					5.43	37.85							-6.7	-35				
1981	Vapor, H ₂ S odour minor amount of pyrite (RB 5)		ca. 330	95	8.5	123	3.19	0.52	19.80	7.50			38.50	trace	14.70	15.76		0.06				77.8	-6.0	-35				
2007	RB10			82	7.8	168	4.23	0.50	19.71	6.77	0.01	0.00	58.00		5.15	9.03			0.28				-6.3	-29	-5.1			
2009	"			91	7.2	156	4.18	0.47	20.10	7.27			38.00		14.19	12.63			0.47				-6.5	-30		5.5		
1981	-28		ca. 300	61	6.3	123	0.57	0.74	16.80	6.00	<5		9.80		19.50	31.45		0.16				68.1	-2.3	-28				
2007	RB13			73	7.6	145	2.80	0.79	19.80	7.55		0.26	31.00		15.19	16.35			0.26				-2.6	-33				
2009	"				7.5	298	3.24	0.36	55.85	8.44			133.00		13.76	8.24			1.77					-30				
2007	kaolinite, pyrite and vapor (RB 14)	49°37'54"S; 68°48'48"E	430	98	8.5	147	4.08	0.51	19.96	6.71	0.01	0.00	50.00	4.00	3.98	11.27		0.24	0.24				-4.0	-32	-5.05 to -5.2 (CO ₂)	3.5 (native S)		
2007	RB15			73	8.3	164	2.96	0.28	58.86	8.54	0.03	0.00	132.00	5.00	15.91	8.02			1.53				-4.6	-35		5.5		
2009	"				7.5	298	3.24	0.36	55.85	8.44			133.00		13.76	8.24			1.77				-6.8	-32			259	
2007	thermal and watershed (RB18)			65	7.4	83	2.62	1.39	10.14	0.97		0.16	10.00		16.35	3.94	0.14		0.04				-5.2	-30				
2009	"				6.3	68	2.38	1.08	9.13	1.95			12.00		17.10	2.81			0.01				-7.8	-35				
2007	RB21	49°37'36"S; 68° 47'54"E		79	6.9	192	4.01	1.93	24.08	8.80			45.00		10.36	28.69	0.18		0.18				-3.7	-28		9.0		
2009				91	7	133	1.67	0.45	17.47	7.39			20.00		13.00	16.10			0.65			7.3	-4.9					
2010					7.1	120	1.19	0.49	17.42	5.89			31.00		8.11	12.42			0.29				-4.6	-23				
2007	RB32			90	6.7	91	0.77	0.80	10.02	4.71		0.59	2.00		8.17	20.26			0.05				-1.4	-22				
2009	"				6.4	103	2.18	1.32	10.29	5.59					8.24	22.15							-3.2	-22			242	
2007	RB35				4.1	103	1.57	0.99	11.30	5.42					8.25	24.23							0.2	-20				
2007	condensed vapor (RB 39)			60	3.5	390	2.01	0.90	29.47	23.43	0.01	1.31			7.36	108.62			0.22				3.4	-17				
2009	"				4	276	2.27	1.03	28.25	22.37					8.87	94.79			0.28				1.4	-26				
Plateau Central (Thermal springs)																												
Val Travers (1981)	1	49° 18' 31" S; 69°25'47"E	11	61	9.3	250	1.37	0.15	49.80	0.68	<10		30.50	19.80	30.00	15.60		0.04				82.6	8.8	56				
	2	49° 18' 31" S; 69°25'45"E	11	62	9.4	250	1.38	0.16	48.80	0.62	<10		30.50	19.20	31.50	16.20		0.04				82.2	-8.9	-56				
	3	49° 18' 31" S; 69°25'45"E	11	60	9.4	241	1.35	0.16	47.30	0.67	<10		29.30	17.40	30.00	16.30		0.04				86.4	-8.8	-56				
2007	1	"		61	9.5	237	0.79	0.27	49.33	0.68		0.44	72.00		24.42	16.58			0.16									
"	2	"		61	9.4	222	0.85	0.34	50.09	0.66		0.53	80.00		23.48	14.02			0.14				-8.1	-54	-9.4			
"	3	"		60	8.1	182.6	0.83	0.55	49.51	0.68		1.02	75.00		25.13	15.45			0.11				-8.1	-50				
2010	1	"			8.6	235	2.97	0.53	42.09	0.64			60.00		26.38	14.22			0.20				-8.4	-54	-9.5			
"	2	"			8.1	252	3.13	0.04	46.54	0.65			70.00		25.67	15.26			0.21				-9.5	-58	-9.4			
"	3	"			7.4	248	3.38	0.09	45.81	0.63			70.00		24.26	16.26			0.24				-8.1	-55				
Source Lili (1981)		49° 23' 35" S; 69°32'51"E	122	48	9.6	244	1.08	0.20	49.50	0.61	<10		29.30	18.00	33.00	13.10		0.04				86.4	-8.4	-55				
Source Lili (2009)	PC09-04	49° 21'58"S; 69°31'53"E	100	47	8.9	253	2.74	0.13	48.53	0.55			57.00	16.00	21.88	13.60			0.14						-15.5			
Plateau Central																												
Bossiere (2009)	mineral spring	49°23'19"S; 69°36'23"E		18	8.1	177	4.65	0.18	27.36	0.07			28.00		30.36	5.85			0.06				-8.1	-55	-3.7			

Months	temperature (°C)	rainfall (mm)	c25°C µS/cm	pH	TDS mg/l	Ca mg/l	Mg "	Na "	K "	Cl "	SO ₄ "	NO ₃ "	calculated HCO ₃	δ ¹⁸ O ‰	δD ‰
May 1981	3.7	79	66	n.d.	25	0.28	0.22	7.20	0.25	14.72	2.19	0.03	0	-6.9	-42
June- July	2.5	120	47	"	18	0.16	0.26	5.20	0.18	9.33	2.58	0.04	0	-5.7	-35
Aug-October	n.d.	135	81	"	35	0.60	1.07	10.20	0.42	19.97	2.39	0.04	0	-5.9	-33
Nov-Dec	4.7	105	53	"	21	0.35	0.74	6.24	0.18	9.65	2.19	0.03	2	-10.9	-79
January 1982	7.3	n.d.	38	"	15	0.20	0.42	4.62	0.11	6.38	2.19	0.03	1	n.d.	n.d.
Jan to Feb	7.5	53	83	"	32	0.46	1.46	8.80	0.43	17.84	2.80	0.01	0	-6.9	"
Feb	8.5	45	45	"	32	6.56	0.24	1.80	0.16	2.72	1.80	0.03	19	-8.2	-64
March	7.4	60	75	"	48	7.80	0.72	4.65	0.23	7.08	3.10	0.04	24	-6.7	n.d.
April	5.9	69	230	"	101	8.08	0.78	26.40	1.80	48.20	8.00	0.07	8	-7.2	-51
May	3.9	81	80	"	29	1.82	0.93	7.00	0.48	13.36	2.80	0.02	3	-4.5	-33
June	3.0	70	105	"	37	1.15	1.60	9.60	0.56	19.68	-	0.01	4	-6.4	n.d.
July	2.3	76	64	"	23	1.00	0.87	5.90	0.31	11.44	2.10	0.03	1	-7.0	"
Aug	1.9	70	120	"	40	1.20	1.60	10.60	0.61	22.80	3.60	-	0	-5.6	"
Sept	2.4	72	52	"	17	0.63	0.63	4.70	0.21	8.48	1.80	-	1	-9.0	-67
Oct	3.9	62	80	"	29	0.70	1.27	7.50	0.48	13.84	3.00	0.02	2	-8.4	n.d.
Nov	5.2	61	41	"	15	1.25	0.30	2.90	0.20	4.48	-	-	6	-6.9	"
Dec	6.5	64	49	"	15	0.61	0.60	3.85	0.17	7.92	1.80	-	0	-5.7	"
January 1983	7.8	55	49	"	18	0.55	0.63	4.50	0.24	7.28	2.30	0.01	2	-6.8	n.d.
Feb	8.2	46	120	"	46	1.01	2.07	12.80	0.54	25.92	4.00	0.01	0	-4.1	-22
March	7.2	61	55	"	19	0.49	0.80	5.30	0.23	9.68	1.80	-	1	-3.9	-23
April	6.0	68	116	"	48	0.81	1.87	13.80	0.56	24.64	4.00	-	2	-5.5	n.d.
May	3.2	79	70	"	24	0.45	0.87	7.10	0.43	12.32	2.10	-	1	-12.2	-91
June	2.7	71	68	"	23	0.53	0.93	6.60	0.35	12.24	2.30	0.03	0	-8.7	n.d.
July	2.2	73	42	"	13	0.33	0.48	3.55	0.16	7.06	1.30	-	0	-8.8	"

	Longitude	Latitude	altitude (m)	Temperature (°C)	pH	EC (μS/cm)	Ca mg/l	Mg "	Na "	K "	HCO ₃ "	Cl "	SO ₄ "	NO ₃ "	SiO ₂ "	δ ¹⁸ O ‰	δD ‰
Rallier du Baty																	
Glacier de Plan praz (Riv)	49° 27' 14.73" S	69° 00' 24.89"	41	5	7.1	34	5.00	1.00	6.20	1.13	18.90	5.20	5.40	0.11	4.80	-7.59	-47
Glacier Arago (Riv)	49° 34' 57.31" S	69° 02' 20.35"	7		7.0	31	1.67	0.68	5.20	0.65	8.50	8.20	2.39	0.19	6.80	-6.79	-43
Les 2 frères (Riv)	49° 38' 39.49" S	69° 00' 56.21"	32	16	6.7	47	2.26	0.77	9.20	0.88	8.50	13.60	3.17	0.07	9.40	-6.61	-
Vallée de la Mouche (Riv)	49° 36' 56.82" S	69° 04' 13.61"	23		6.7	51	5.49	1.28	4.90	0.57	9.20	8.70	15.60	0.06	4.40	-6.48	-44
Le portillon (Mt Erebus; Riv)	49° 38' 35.11" S	68° 58' 09.75"	41	7	7.0	26	2.20	0.56	4.40	0.76	6.10	8.70	2.19	0.03	7.60	-6.77	-44
Plateau Central																	
Riv des Tourmentes	49° 18' 41.37" S	69° 25' 13.96"	17	11	7.4	46	4.86	1.35	9.90	0.27	17.70	13.50	4.54	0.06	7.40	-8.89	-54
Tristan lake (end of H. Bossière Fjord)	?	?		18	7.2	57	2.88	0.87	10.00	0.55	9.20	13.70	3.37	0.05	5.80	-7.11	-48
Galliéni Massif																	
Plaine de Dante (Riv)	49° 33' 32.15" S	69° 21' 54.34"	62	9	7.3	54	2.67	1.32	14.40	0.82	18.30	15.00	3.17	0.10	6.10	-8.54	-55
Riv au glacier blanc (snow melted)	49° 35' 55.43" S	69° 23' 37.13"	21	2	7.3	45	8.00	1.54	7.70	1.19	18.90	10.30	22.40	0.14	7.30	-8.28	-58
Diane's Lake	?	?		11	7.8	90	5.25	4.34	14.00	1.70	37.20	18.00	5.72	0.07	18.10	-5.73	-32
Val des Skuas (Riv)	49° 36' 16.31" S	69° 35' 49.74"	263	7	7.5	63	4.62	1.09	8.20	1.94	22.60	15.00	3.90	0.07	9.10	-5.81	-32
Val des Skuas (Riv)	49° 36' 21.57" S	69° 36' 02.40"	263	5	6.8	71	4.51	2.34	9.80	3.90	32.90	16.00	4.30	0.04	20.20	-8.97	-59
Table du Cratère 'snow melted'	49° 35' 34.03" S	69° 36' 27.29"	228	2	6.6	49	1.69	1.45	15.00	2.13	23.80	13.70	3.37	0.08	14.80		
Courbet Peninsula																	
Port aux Français (water supply. 12/1981)	49° 20' 47.79" S	70° 13' 25.81"	32	6	7.0	94	7.34	4.60	17.50	1.24	32.30	30.00	9.50	0.04	17.50	-7.51	-49
Port aux Français (water supply; 04/1981)	"	"		5	7.3	47	5.46	1.28	12.00	0.52	11.00	22.00	3.95	0.04	5.90	-6.54	-45
Riv du Château (04/1981)	49° 16' 42.14" S	70° 08' 03.88"	111	17	6.7	38	1.16	0.70	5.50	0.66	5.50	9.50	2.18	0.08	1.10	-7.34	-50
Presqu'îles Jeanne d'Arc																	
Riv des charbons	49° 33' 27.25" S	69° 48' 48.71"	102	8	7.7	80	4.51	2.34	19.20	0.83	18.30	26.50	5.13	0.06	6.20	-7.27	-50
Pte de la Géodésie (Peatbog)	49° 33' 45.29" S	69° 50' 14.36"	56	8	7.7	155	11.90	6.68	27.60	0.93	56.10	46.00	7.88	0.08	12.70	-7.60	-54
Vallée des Neiges (Riv)	49° 35' 23.87" S	69° 52' 46.32"	144	7	7.4	84	5.12	2.94	18.80	0.89	23.20	28.00	4.35	0.13	7.40	-7.25	-50
Vallée de l'Acoena (Riv)	49° 36' 04.16" S	69° 56' 26.09"	5	15	7.4	120	6.21	3.56	20.50	1.04	29.30	30.00	4.54	0.15	11.70	-7.44	-54
Vallée de la Planchette (Riv)	49° 36' 24.32" S	70° 00' 25.58"	17	15	7.6	117	6.49	4.12	17.80	0.92	30.50	29.00	7.49	0.07	12.60	-7.40	-
Val Levant (Riv)	49° 39' 44.97" S	70° 02' 32.40"	65	14	7.2	120	3.36	2.74	21.00	0.93	16.50	35.00	6.50	0.07	8.60	-	-
Presqu'îles Ronarc'h																	
<i>Riv des Macaronis</i>	<i>49° 34' 54.61" S</i>	<i>70° 15' 25.15"</i>	126	11	7.1	80	2.35	2.10	17.10	2.10	17.10	25.00	5.13	0.07	9.90	-8.36	-56
<i>Nord de la Coupole (Peat bog)</i>	<i>49° 35' 21.56" S</i>	<i>70° 14' 36.38"</i>	193	6	7.1	128	5.22	4.54	25.40	2.05	35.40	35.50	9.25	0.21	13.60	-7.66	-52
Loranchet Peninsula																	
Les Nuageuses (Riv Ile de Croy; 04/1981)	48° 38' 34.41" S	68° 39' 25.07"	23	13	7.3	152	7.31	3.76	29.60	0.71	15.90	52.50	13.57	0.03	0.30	-5.92	-

Location sampling year	sample name and field observation	GPS location	altitude (m)	Temperature (°C)	pH	EC μS/cm	Ca mg/l	Mg "	Na "	K "	Li "	NH ₄ "	HCO ₃ "	CO ₃ "	Cl "	SO ₄ "	PO ₄ "	NO ₃ "	F "	Br "	SiO ₂ "	δ ¹⁸ O ‰	δD ‰	δ ¹³ C _{DIC} ‰	δ ³⁴ S _{SO4} ‰	Na-K geothermometer °C	
RdB (Cap Bourbon; 1982)			25	88	6.1	217	12.82	2.26	21.20	14.08	15.00		47		19.50	32.23		0.08			122.1	-7.1	-44				
1982				92	3.5	406	5.84	4.00	29.60	14.92	30.00		0		16.00	285.00		0.14			137.3	-3.8	-32				
Vallée du Glacier Fallot (2009)		49° 39'22"S; 68°53'10"E		57	7.3	1578	85.50	54.29	191.80	33.26			1006		44.12				3.84				-9.3	-63	-6.3		278
Rallier du Baty																											
2009	bonate precipitate; mineral sp	49°40'37"S; 68°54'02"E		15	7.2	1351	34.86	56.76	177.56	34.09			859		29.14	0.40			1.99				-8.7	-65	-6.5		292
RdB (Infernet Valley; 2009)		49° 38'02"S; 68° 48'09"E	30	60	7.3	1872	68.83	8.77	294.97	41.41			412		310.06	77.75		1.40	17.26	0.25			-6.8	-49	-22.9		249
"		49° 38'04"S; 68°48'04"E	ca. 50	68	6.5	1993	86.18	19.02	294.54	38.15			602		296.96	55.75			4.81				-7.6	-54	-7.3		
"		49° 38'08"S; 68°47'40"E	60	68	7.4	340	4.01	0.42	59.38	15.43			152		15.74	8.57			1.75					-8.4			
RdB (Feu de Joie beach; 2009)		49° 38'25"S; 68°47'36"E	18	87	3.6	423	12.56	3.94	40.98	10.94					43.85	122.72							-4.4	-28			
"	H ₂ S odor	49° 38'06"S; 68°47'10"E		90	7.5	975	47.32	17.03	115.75	12.30			233		140.25	58.49		5.52	0.55				-5.6	-32	-14.3	11.6	216
"		49° 38'08"S; 68°47'08"E		85	3.2	336	10.70	4.01	37.28	10.57					23.23	98.00							-5.6	-41	-8.4		
"		49° 38'29"S; 68°47'19"E		69	7.5	1102	72.38	10.33	138.25	13.99			369		132.22	43.44			2.14	3.24			-8.3	-61	-7.0		211
"		49° 38'38"S; 68°47'13"E		93	6.8	393	24.33	11.61	29.47	4.79			98		42.04	37.56							-6.9	-47	-6.5		
RdB (Mont des Fumeroles; 1981)	condensed vapor	49°37'54" S; 68° 47'94" E	ca. 425	72	4.5	361	0.51	1.42	30.30	23.80	0.01				41.00	118.00		0.09			195.3	2.2	-21				
2007	RB1	49°37'54" S; 68° 47'94" E		82	3.5	380	1.15	2.04	30.26	22.80	0.01	0.82			1.77	110.08			0.07				2.7	-16			
2007	RB2		ca. 425	100	7.3	83	0.13	0.58	11.67	4.23		n.d.	6		5.70	19.13			0.09								
2007	Condensed vapor (RB 3)		"	97	7.6	88.5	1.06	2.68	10.85	1.21		0.14	12		16.34	5.73			0.09				-5.2	-42			
	Condensed vapor (RB 4)		"	87	4	110	0.20	1.34	6.74	5.39		1.26			3.26	43.81			0.02				-5.9	-41	-10.9		
1981	Steamer (native sulfur)		"	95	6.6	153	0.49	1.40	21.60	5.52	<5		4		36.20	27.60		0.07			50.7	-2.4	-31	-10.2			
2007	RB5		"	85	7.2	146.8	1.92	5.41	19.90	6.37		0.17	41		16.87	19.88			0.20				-2.8	-30			260
2007	Opale precipitate		203	62	10.4	3400	13.50	1.56	673.72	147.96	1.22	8.62	150	800	183.48	40.34			23.78	0.38	<200	-5.5	-49			"270"	
"	Opale precipitate				10.3	3510	3.83	0.46	711.89	156.21	1.29	0.00	150	800	184.42	39.59			24.06	0.61			-5.7	-52			"290"
2007	Sce Pt 335		300	50	6.4	965	5.05	1.12	20.85	5.68		0.12	48		14.42	10.40			0.38				-5.7	-26			
"	Sce Pt 334			50	7.4	681	178.77	12.95	21.99	1.87	0.01	0.00	650		4.96	3.04			0.33				-5.6	-37			193
"	R35			57	4.5	109	0.67	0.76	9.73	5.21		0.72			7.16	24.44			0.03				3.1	-16			
2007	RB7			70	2.7	341	11.83	5.57	11.94	9.77		4.83			2.82	140.19			0.10				-8.2	-37			
2009					5.1	117	2.29	1.34	9.36	5.78					5.43	37.85							-6.7	-35			
1981	Vapor, H ₂ S odour minor amount of pyrite (RB 5)		ca. 330	95	8.5	123	3.19	0.52	19.80	7.50			39	trace	14.70	15.76		0.06			77.8	-6.0	-35				
2007	RB10			82	7.8	168	4.23	0.50	19.71	6.77	0.01	0.00	58		5.15	9.03			0.28				-6.3	-29	-5.1		
2009	"			91	7.2	156	4.18	0.47	20.10	7.27			38		14.19	12.63			0.47				-6.5	-30		5.5	
1981	-28		ca. 300	61	6.3	123	0.57	0.74	16.80	6.00	<5		10		19.50	31.45		0.16			68.1	-2.3	-28				
2007	RB13			73	7.6	145	2.80	0.79	19.80	7.55		0.26	31		15.19	16.35			0.26				-2.6	-33			
2009	"				7.5	298	3.24	0.36	55.85	8.44			133		13.76	8.24			1.77					-30			
2007	kaolinite, pyrite and vapor (R	49°37'54"S; 68°48'48"E	430	98	8.5	147	4.08	0.51	19.96	6.71	0.01	0.00	50	4	3.98	11.27		0.24	0.24				-4.0	-32	5 to -5.2	5 (native S)	
2007	RB15			73	8.3	164	2.96	0.28	58.86	8.54	0.03	0.00	132	5	15.91	8.02			1.53				-4.6	-35		5.5	
2009	"				7.5	298	3.24	0.36	55.85	8.44			133		13.76	8.24			1.77				-6.8	-32			259
2007	thermal and watershed (RB18)			65	7.4	83	2.62	1.39	10.14	0.97		0.16	10		16.35	3.94	0.14		0.04				-5.2	-30			
2009	"				6.3	68	2.38	1.08	9.13	1.95			12		17.10	2.81			0.01				-7.8	-35			
2007	RB21	49°37'36"S; 68° 47'54"E		79	6.9	192	4.01	1.93	24.08	8.80			45		10.36	28.69	0.18		0.18				-3.7	-28		9.0	
2009				91	7	133	1.67	0.45	17.47	7.39			20		13.00	16.10			0.65		7.3		-4.9				
2010					7.1	120	1.19	0.49	17.42	5.89			31		8.11	12.42			0.29				-4.6	-23			
2007	RB32			90	6.7	91	0.77	0.80	10.02	4.71		0.59	2		8.17	20.26			0.05				-1.4	-22			
2009	"				6.4	103	2.18	1.32	10.29	5.59					9.24	22.15							-3.2	-22			242
2007	RB35				4.1	103	1.57	0.99	11.30	5.42					8.25	24.23							0.2	-20			
2007	condensed vapor (RB 39)			60	3.5	390	2.01	0.90	29.47	23.43	0.01	1.31			7.36	108.62			0.22				3.4	-17			
2009	"				4	276	2.27	1.03	28.25	22.37					8.87	94.79			0.28				1.4	-26			
Plateau Central (Thermal springs)																											
Val Travers (1981)	1	49° 18' 31" S; 69°25'47"E	11	61	9.3	250	1.37	0.15	49.80	0.68	<10		31	20	30.00	15.60		0.04			82.6	-8.8	-56				
	2	49° 18' 31" S; 69°25'45"E	11	62	9.4	250	1.38	0.16	48.80	0.62	<10		31	19	31.50	16.20		0.04			82.2	-8.9	-56				
	3	49° 18' 31" S; 69°25'45"E	11	60	9.4	241	1.35	0.16	47.30	0.67	<10		29	17	30.00	16.30		0.04			86.4	-8.8	-56				
2007	1	"		61	9.5	237	0.79	0.27	49.33	0.68		0.44	72		24.42	16.58			0.16								
"	2	"		61	9.4	222	0.85	0.34	50.09	0.66		0.53	80		23.48	14.02			0.14				-8.1	-54	-9.4		
"	3	"		60	8.1	182.6	0.83	0.55	49.51	0.68		1.02	75		25.13	15.45			0.11				-8.1	-50			
2010	1	"			8.6	235	2.97	0.53	42.09	0.64			60		26.38	14.22			0.20				-8.4	-54	-9.5		
"	2	"			8.1	252	3.13	0.04	46.54	0.65			70		25.67	15.26		0.52	0.21				-9.5	-58	-9.4		
"	3	"			7.4	248	3.38	0.09	45.81	0.63			70		24.26	16.26			0.24				-8.1	-55			
Source Lili (1981)		49° 23' 35" S; 69°32'51"E	122	48	9.6	244	1.08	0.20	49.50	0.61	<10		29	18	33.00	13.10		0.04			86.4	-8.4	-55				
Source Lili (2009)	PC09 -04	49° 21'58"S; 69°31'53"E	100	47	8.9	253	2.74	0.13	48.53	0.55			57	16	21.88	13.60			0.14						-15.5		
Plateau Central																											
Bossiere (2009)	mineral spring	49°23'19"S; 69°36'23"E		18	8.1	177	4.65	0.18	27.36	0.07			28		30.36	5.85			0.06				-8.1	-55	-3.7		
"	mineral spring	49° 22'19"S; 69°32'59"E		27	8.7	198	5.38	0.12	31.92	0.14			42		27.38	9.52			0.05	0.23			-9.2	-60			
"	mineral spring	49°21'58"S; 69°31'53"E																									

Geochemical exploration of *geothermal* activity in the Kerguelen archipelago, SW Indian Ocean

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This paper described the geothermal water of Kerguelen and its active geothermal system. We reconstruct the meteoric origin, and the hydrothermal processes from chemical and isotopic data of rain water and thermal water. Interpretations indicate series of reactions from 6 up to 260°C and few hundred meters below the surface.