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Mean recharge times and chemical modelling transfers from shallow groundwater to mineralized thermal waters at Montrond-les-Bains, Eastern Massif Central, France

C. Renac[a,*], Fr. Gal[a,1], R.-P. Ménot[a], P. Squarcioni[b], Ch. Perrache[a]

[a] Laboratoire Magmas et Volcans, UMR CNRS 6524, Université Jean Monnet, 23, rue du Dr P. Michelon, St. Etienne 42023 Cedex 2, France
[b] Société HydroInvest Siège social, 60 rue d'Agris, Champnier 16430, Angoulême, France

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SUMMARY

A re-appraisal of interactions between basinal waters and hydrothermal fluids within the silici-clastic series of the intracontinental Cenozoic Forez Basin is proposed using major element and isotope geochemistry together with thermodynamic models. Recharge processes and shallow sedimentary units in the Forez Basin were compared using major elements and isotopic data ($^{87}Sr/^{86}Sr$, $\delta^{18}O$, $\delta^{2}H$, $\delta^{13}C$, Tritium and ^{14}C) for waters, sedimentary carbonates and Hercynian basement rocks. Waters derived from Late Pleistocene to Early Holocene surface recharge followed by mixing and chemical evolution through percolation into deep groundwater horizons are investigated. Isotopic ratios and chemical speciation computed for deeper waters from 0 to 200 m depth indicate that mineralised waters were produced by initial surficial dissolution of calcite in calcareous-mudstone providing its Sr isotopic signature. At about 200 m depth, $Na–H_3O^+$ cation-exchange with clayey-sand rich levels provides additional Ca, Na, and OH contents, for carbonate-saturated water. $Na–H_3O^+$ cation exchange can not contribute large $Na–HCO_3$ concentrations. Geochemical changes such as increasing $\delta^{13}C_{DIC}$ values observed from 200 to 500 m depth were modelled by addition of thermal water and geogenic CO_2 in increasing proportions with depth (500 mbs). Thermodynamic calculations of mineral proportions indicate water–rock interactions with primary minerals in the metamorphic basement and secondary minerals observed in the basin. Water temperature and its meteoric origin suggest a basin-wide recharge system with water–rock interaction driven by heat flow rather than through deep crustal fractures.

Introduction

Most of the Cenozoic Basins of Western Europe are associated with mineral and thermal waters; which exist in massive limestones formations. Very specifically, the intra continental Forez Basin, located in the Eastern French Massif Central, represents one of the rare Cenozoic Basins which developed 600 m thick detritic sequences involving dominant clayey-sands and subordinate calcareous-mudstone intercalations (Fig. 1). Rare conglomerates consist of cobbles of gneiss or granite similar to the surrounding Hercynian basement. The Forez Basin displays similarities with the larger Limagne Basin, located 50 km further to the North-West. Both basins are surrounded by Hercynian horsts draining rainfall of mainly Atlantic origin (Négrel and Roy, 1998; Gal, 2005). The two sedimentary basins are characterized by mineralized thermal waters with prominent $Na–Ca–Mg–HCO_3$ content (Genter et al., 2003; Serra et al., 2003; Millot et al., 2007; Millot and Négrel, 2007). These waters are largely used for thermal cures, and bottled water (e.g. Badoit). In the Forez Basin, 30 mineral-rich thermal waters (Canard, 1983) are known flowing through fractured Hercynian basement or sand-rich reservoirs. Nevertheless, the Forez groundwater system is still one the least studied in the French Massif Central (e.g. Serra et al., 2003), and very little is known about the space and time evolution of the water chemistry. New studies on water–rock interaction and fluid-migration associated with the Limagne graben and Forez Basin could provide valuable information for future water prospection. This paper deals with geochemical data of waters arising from new boreholes located at Montrond-les-Bains close to the centre of the Forez Basin. Drillings by HydroInvest Society were performed from 2003 to 2006 to different depths and referenced as Mon 1 (0–200 mbs), Mon 2 (0–200 mbs) and Mon 3 (0–300 mbs). Collected waters and sediments offer the opportunity to compare the Limagne and the Forez groundwaters produced in similar tectonic settings. Our geochemical studies of water samples use thermodynamic and isotopic models to evaluate processes involved in water–rock interaction

* Corresponding author. Tel.: +33 04 77 48 1563; fax: +33 04 77 48 5108.
E-mail address: renac@univ-st-etienne.fr (C. Renac).
[1] Present address: BRGM, 3 avenue Claude Guillemin, 45060 Orléans, France.

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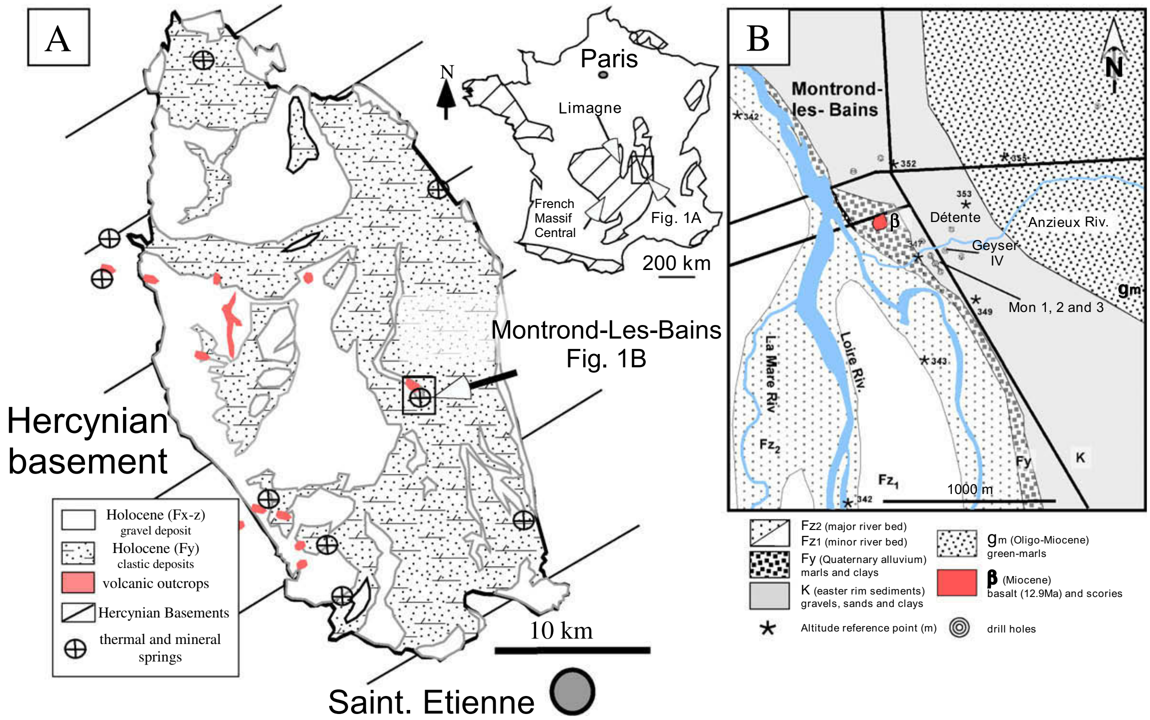

Fig. 1. (A) Schematic map of France showing the location of the French Massif Central; Limagne Basin and Forez Basin. An enlargement of the Forez Basin with main sedimentary and volcanic units recognized in outcrop. In the Forez Basin, crossed circle represent known locations of thermal and mineral springs. (B) Geological map of Montrond-les Bains with drill holes locations (Mon 1–3, Geyser IV, and Détente...).

within the silici-clastic sedimentological reservoirs of the Forez Basin.

Geological setting and seasonal variations of surficial waters

Metamorphic and magmatic rocks in the Hercynian basement of the Forez Basin consist of dominant Neoproterozoic gneiss and Carboniferous granites dated from 330 and 305 Ma. Western border faults of the Forez Basin around Montrond-les-Bains host small volcanic intrusions related to West European rifting during Oligocene to Miocene times. Tectonic movements, weathering, hydrothermal alteration of surrounding Hercynian basement associated with sedimentary processes produced the alluvial system of the Forez Basin. Alluvium transport, deposited mineral particles and chemical compounds were responsible for the formation of clayey-sands and subordinate calcareous-mudstones intercalations.

Sparkling artesian waters for commercial bottling and thermal waters for bathing occur within the Forez Basin and along its border faults (Fig. 1A). One of the latter, used for thermal cures at the Montrond-les-Bains resort (Fig. 1B) is known as Geyser IV (drilled from 1880 to 1881) and represents now a two components mixture of shallow low mineralised waters, sparkling artesian Na–HCO_3 –rich water, and thermal water. Such a mixing occurs from 10 m below surface (mbs) to about 495 mbs below the bubbling point along the old borehole casing (Fig. 2; Lamotte and Vigouroux, 2003). Historic reports of drilling logs (Geyser IV, Laur, 1881) indicate detailed changes in sediment texture, colour, chemical composition (Fig. 2) and temperature of intersected groundwaters. The deepest groundwater located at ca. 400 mbs produced a geyser of water and gas flowing for weeks with temperatures ranging from 38 to 43 °C. A more recent and deeper borehole (Détente: 560 mbs; Barat and Iundt, 1988) discharges the deepest (460 and 500 mbs) and most mineralised thermal water in 2006 (16.56 mS/cm and 38 °C) known in the Forez Basin. At surface, the Détente water undergoes strong degassing (P_{CO2} up to several atmospheres) with dominant CO_2 and traces of H_2S. During exploitation of the Détente borehole, some significant physical and chemical changes occurred in waters of Geyser IV at a distance of 100 m (Lamotte and Vigouroux, 2003; Gal, 2005). Chemical and flow changes in Geyser IV related to Détente pumping (460–500 mbs) are evidence of a lateral connection at 400 mbs between both boreholes with inflow of shallow groundwaters. Moreover, the variability of chemical composition during exploitation lead to the drilling of three new boreholes (Mon 1 and Mon 2: 0–198 mbs and Mon 3: 0–300 mbs) located in a perimeter between 3 m from each other and 200 m far from Geyser IV (Figs. 1 and 2).

Run-off watershed and river drainage suffer seasonal changes in the Forez Basin. Seasonal changes are associated with spring and autumn rains, as well as melted snowfalls during wintertime. Seasonal rainfalls contribute approximately 800 mm/y with temperatures ranging from −5 to 35 °C at a mean air temperature of 12 °C. In consequence, surficial waters and ephemeral springs suffer temperature and flow regime changes. In general, temperature and flow of thermal springs and minerals springs do not vary with present-day weather variations. Small physical and chemical changes (e.g. pH, T, and conductivity) are probably related to longer periods of water–rock interaction, and additional parameters. This paper will present "in situ" sampling of twenty three water levels encountered during the drilling phase as well as selected groundwaters for drinking and thermal spa water for medicinal purposes.

Methodology

Water sampling

During drilling, all individual groundwater levels were sampled. After drilling, each new drill hole was devoted to pumping a