

Investigating Flow in a Complex Aquifer Using Isotopic Geochemistry: the Example of the Geothermal Reservoir of Hainaut (Belgium, NW Europe)

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ABSTRACT

The geothermal reservoir of Hainaut is a complex aquifer in terms of lithology, tectonic history and hydrogeological behavior. It is composed by Mississippian carbonates, with thick layers of massive anhydrite laterally replaced by collapse breccias. The opening of the aquifer to meteoric water is supposed to have taken place during Cretaceous extensional phase, inducing carbonate karstification and anhydrite leaching. The heterogeneous removal of anhydrites had several influences, first on reservoir permeability (i.e. local increase), and second on subsidence rate during post-Palaeozoic times.

In spite of more than twenty years exploitation experience, the hydrogeological behavior of the aquifer is still obscure. Recharge zone is thought to extend over outcropping reservoir rocks, a few km North from the exploited geothermal wells. The only supposed natural exurgences are a few springs, located in the same area, that show anomalies in temperature and/or in chemical composition. Isotopic analyses have been carried out on spring and geothermal waters. δD and $\delta^{18}O$ data are consistent with meteoric origin. Deep waters depleting in heavy H and O isotopes confirms ^{14}C dating of 15000 years of average residence time, and infiltration under glacial climate. Deep reservoir waters are at isotopic equilibrium with carbonate matrix following $\delta^{13}C$ results, whereas shallow waters are mainly influenced by atmospheric CO_2 . Sulfate isotopic ratios confirm mixing of deep and shallow waters and allow the differentiation between anhydrite dissolution and sulfide oxidation origin. The mixing rate can be estimated, and natural recharge flow of the deep reservoir can further be assessed.

1. INTRODUCTION

The geothermal aquifer of the Mississippian Limestones of Hainaut has been discovered in 1976 thanks to Saint-Ghislain geological exploration borehole, which became later the first well to exploit the regional reservoir. It encountered thick and massive anhydrite layers in the Upper and Middle Viséan, at about 2500 m deep. At the bottom of those layers, more than two hundred meters of karstic breccias gave hot artesian waters, which occurrence changed this exploration borehole into a geothermal well.

Reservoir exploitation began ten years after the drilling itself, and two other wells were drilled, a few kilometers North-East from the first one. These two wells didn't encounter anhydrite, but only partly cemented residual breccias, where they reached hot waters in karstified fissures.

The hydrogeological behavior of the aquifer is poorly known. Pressures and temperatures remain stables without any reinjection, which supposes a huge reservoir capacity.

The resource quantification is difficult however, particularly because of geological singularities such as the suspected influence of tectonic on structure and permeability at a local scale. In addition, if the recharge zone of the aquifer can be supposed to be the Northern outcrop, there is no confirmed natural exurgence, except a few springs located at the margin of the same area. These springs show anomalies in temperature and/or chemical composition, particularly the sulfate content. Confirmation of the origin of these sulfates is thus of great interest for interpretation of flows and exchanges between shallow and deep aquifer.

2. GEOLOGICAL CONTEXT

2.1 Localization

The geothermal reservoir of Hainaut is located in Southern Belgium (Figure 1). The three existing wells are set between Mons and the French border, in Saint-Ghislain (S), Douvrain (D) and Ghlin (G).

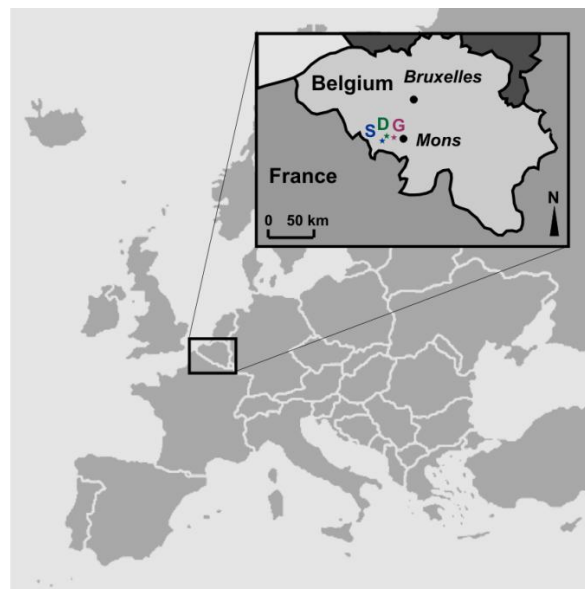


Figure 1: Localization of the three geothermal wells.

2.2 Reservoir Lithology

The rocks composing the geothermal aquifer are mainly Mississippian carbonates. These rocks outcrop at the North of the geothermal district, and Mississippian succession is thus quite well known. Figure 2 gives a schematic lithostratigraphic log as it has been described at the outcrop in Hennebert (1999) and Doremus and Hennebert (1995).

The Saint-Ghislain well revealed thick anhydrite layers in Middle and Late Viséan series (see Figure 3), as detailed in Groessens *et al.* (1979). These anhydrites seem to correspond to breccias that appear at the outcrop and in other geothermal wells. Anhydrite and gypsum pseudomorphs were found in most of these breccias, and confirm the

contribution of anhydrite removal to their origin, though they may not be pure collapse breccias and be the result of several phenomena (De Putter *et al.*, 1994; Rouchy *et al.*, 1993).

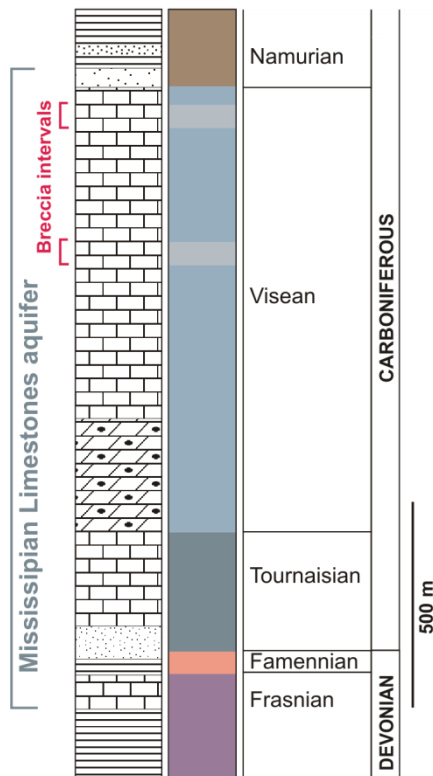


Figure 2: Reservoir lithostratigraphy (Northern outcrop).

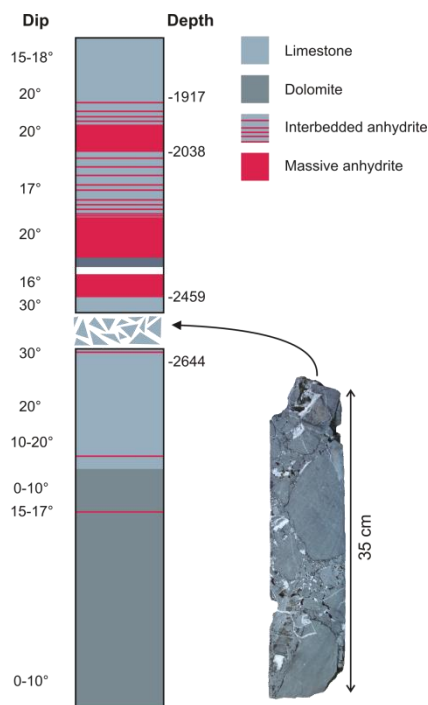


Figure 3: Visean series in the Saint-Ghislain well (anhydrites represented in red).

2.3 Structural Context

Mississippian series have been shaped by Hercynian tectonic which intensity culminated in Late Carboniferous. Result of

Hercynian tectonic is schematized at Figure 4: an allochton massif, coming from South, overlays the parautochton unit. The two units are separated by several thrust sheets that can be overturned (Figure 4).

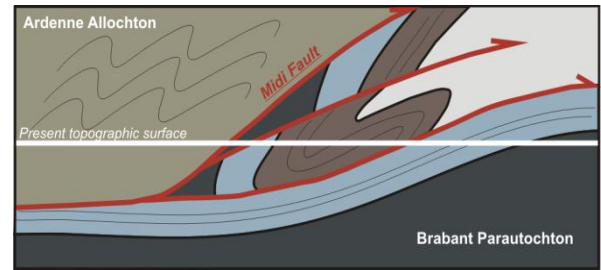


Figure 4: Schematic N-S cross section in the Palaeozoic bedrock of the Mons region (from Lacquement, 2001).

The geothermal reservoir is part of the parautochton unit. It shows a gentle South dip, and few faults and folds, contrary to allochton massif, heavily folded and faulted.

The opening of the reservoir to meteoric waters is supposed to have taken place in Late Jurassic/Early Cretaceous times, after erosion and fracturation of the parautochton carbonates under extensional tectonic regime. Penetration of fresh waters in the deep massif has induced anhydrite dissolution, which is part of the origin of the basin-shaped top Palaeozoic surface, where Cretaceous sediments have been conserved in the present Mons Basin (Quinif *et al.*, 1997).

Figure 5 shows the present geological situation. Mississippian rocks crop out at the North of the three geothermal wells. A thin strip of Pennsylvanian formations appears between the Mississippian strata and the Cretaceous overburden that took place in the basin shape of the Palaeozoic bedrock. South from the Cretaceous Mons Basin, the upper major thrust-fault called Midi Fault appears, separating the allochton unit from the thrust sheets.



Figure 5: Geological map of the Mons region.

3. RESERVOIR GEOCHEMISTRY

Available data on Mississippian formations waters come from two main origins: on one hand, shallow waters from springs, water catchment and quarries pumping, and on the other hand, deep waters from the three geothermal wells.

3.1 Shallow Waters

Data have been collected from water catchment companies, limestone quarries, and several sampling campaigns.

These waters show a high HCO₃⁻ and Ca²⁺ content, inherited from the aquifer nature. The sulfate content is very fluctuant,

but most of the waters show a concentration of 70 to 90 mg/l (see Figure 6).

3.2 Deep Waters

Among the three wells, only two are under continuous exploitation. Chemical data series exist since 1986. The third well has been recently opened, and several samples have been taken.

The geothermal waters have a moderate ionic content, between 1 and 2 g/l, and are strongly influenced by anhydrite leaching (see Figure 6), as indicated by the sulfate content, that exceeds 1g/l.

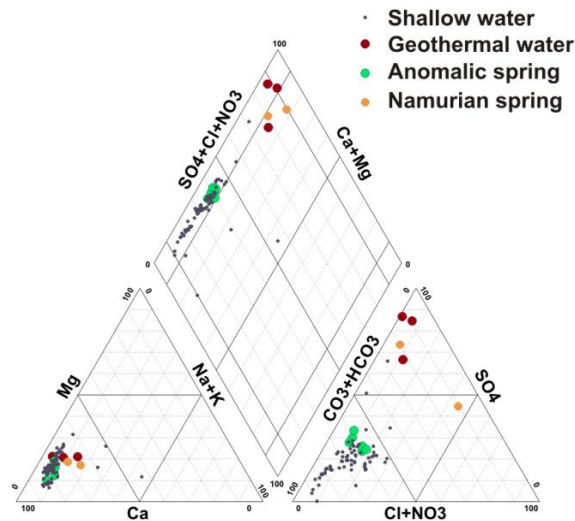


Figure 6: Waters from the Mississippian aquifer: Piper diagram.

3.3 Anomalic Springs

Among spring of the Mississippian outcrop, several waters show anomalies in temperature, and/or in chemical composition. Sulfate content is high, compared with the average content in the shallow aquifer. Sulfate origin can be found in pyrite oxidation, deep anhydrite dissolution, and/or in human activities.

Anomalic springs are illustrated on Figure 7 map. Most of them are located at the Southern margin of the limestones outcrop, near the top of the reservoir.

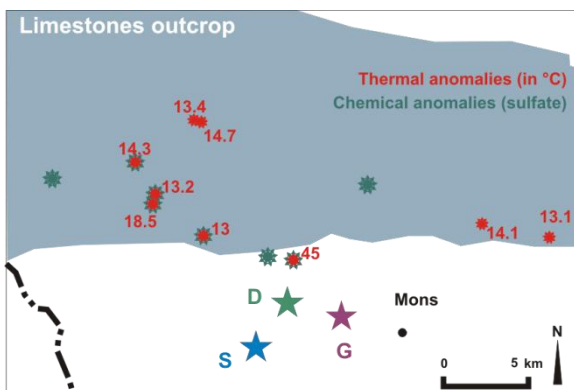


Figure 7: Anomalic springs localization.

Some of these springs appear in the Namurian shales. They have been selected because of their sulfate and temperature anomalies.

Chemical content is illustrated on Figure 6. It shows the stronger concentration of springs in sulfate that tend to appear on the border of the shallow waters group. Waters coming from Namurian shales clearly appear on the diagram, with lower calcium and carbonate content.

4. STABLE ISOTOPE COMPOSITION

4.1 Sampling Sites

Three main groups of sampling sites were selected: the two active geothermal wells, anomalic springs, and water catchment wells as a reference for shallow aquifer waters. The sampling sites are located on the Figure 8 map.

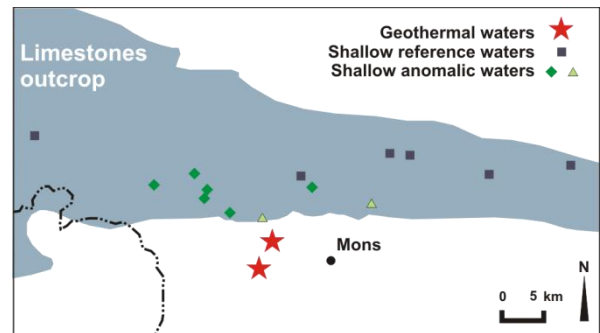


Figure 8: Localization of the sampling sites for isotopic composition analyses.

4.2 δD and δ¹⁸O of Water

Results for δD and δ¹⁸O are given in Figure 9. It shows the repartition of the samples around the global Meteoric Water Line (Craig, 1961).

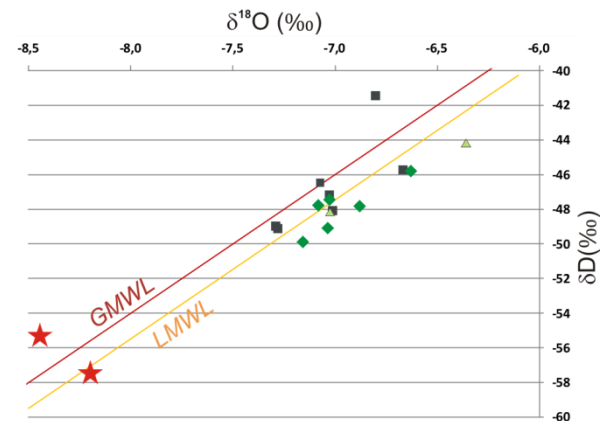


Figure 9: δD and δ¹⁸O vs SMOW of samples and GMWL.

The line that fits best with experimental points repartition (Local Meteoric Water Line or LMWL) show a deuterium excess value around 8.5. This value is consistent with IAEA-WMO GNIP data, which give a d value around 9 in Belgium region (IAEA, 2001).

The geothermal waters are strongly depleted in heavy isotopes. This result shows coherence with waters infiltrated under cold and dry climatic conditions.

4.3 δ¹³C and ¹⁴C in Bicarbonates

δ¹³C from HCO₃⁻ is represented at Figure 10, compared to bicarbonate concentration.

Geothermal waters show ratios indicating isotopic equilibrium with carbonated matrix. Shallow waters ratios (except the Namurian spring) range from -14 to -10‰,

revealing the mixed influence of aquifer matrix and atmospheric CO₂ (Mook, 2000).

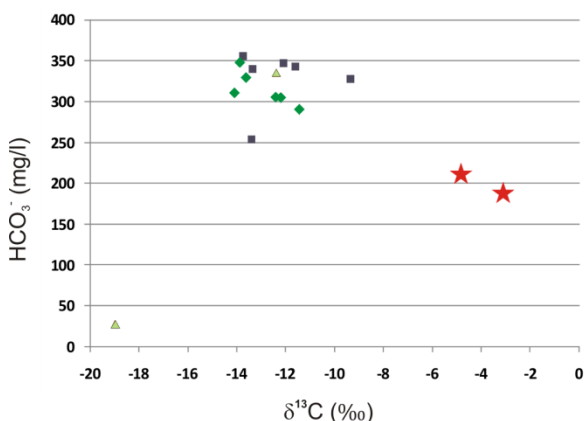


Figure 10: HCO₃⁻ concentrations and δ¹³C vs PDB.

¹⁴C content has been analyzed for geothermal waters. Residence times estimated from different interpretations range from 35 to 21 ky for Saint-Ghislain water (more distant from the outcrops), and from 8 to 20 ky for Douvrain water (Vogels, 1970; Tamers, 1975; Ingerson and Pearson, 1964). These residence times are consistent with geothermal waters depletion in heavy oxygen and hydrogen isotopes, as they date infiltration back to the last ice age.

4.4 δ³⁴S and δ¹⁸O in Sulfates

Figure 11 shows measured isotopic ratios of sulfates. Geothermal waters are represented on the top right of the graph, and their isotopic ratios reflect those of solid anhydrite that have been measured on Saint-Ghislain cores (Pierre, 1986; Langguth and Nielsen, 1980). In the opposite corner, one of the quarries pumping waters has typical values of δ³⁴S issued from sulfide oxidation (Krouse, 1980). Between these two poles, points representing shallow waters are spread. A few springs escape from the group, however, and tend to join the anhydrite influenced geothermal waters.

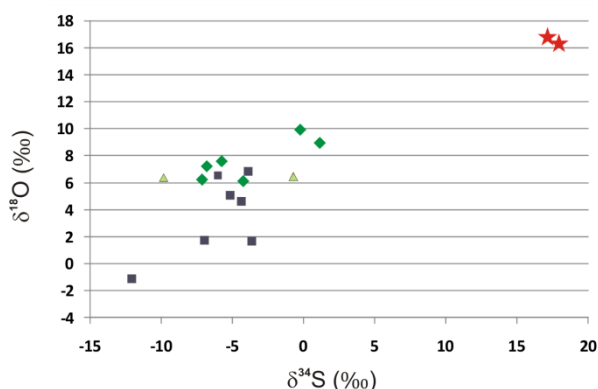


Figure 11: δ³⁴S vs CDT and δ¹⁸O vs SMOW.

Using possible origins and mass balance of sulfates, relative influences of each sulfate source can be determined (André et al., 2002). Anhydrite dissolution, sulfide oxidation and meteoric sulfate content are the three main origins of sulfates in Mississippian reservoir waters. After calculation, it appears that meteoric sulfates are quite a small part of the whole content. Figure 12 gives the balance between the two remaining sources of sulfates

Several springs seem to get their sulfate content from deep anhydrite for more than 50%. These springs were those

which separated from the main group of points on Figure 11, showing a greater deep water influence than others.

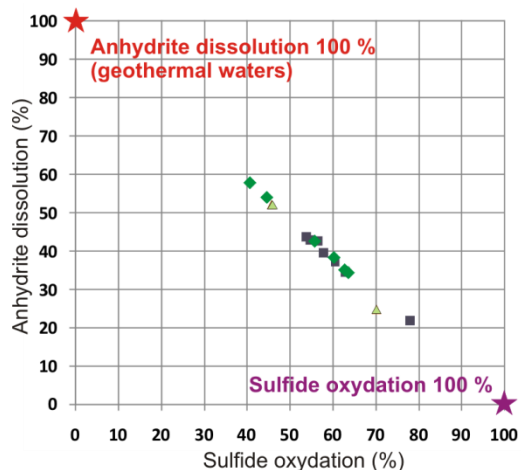


Figure 12: Relative contribution of anhydrites and sulfides oxydation to sulfate content in Mississippian reservoir waters.

Other waters show a lighter contribution from deep reservoir, but this influence is sensible however.

This allows to fix a mixing rate for the sampled springs, and, using gauging, estimation of present outflow of the deep reservoir through these exsurgences becomes possible.

5. CONCLUSIONS

Geothermal waters of the Hainaut reservoir have been characterized in terms of isotopic geochemistry. Water stable isotopes confirm meteoric origin, and DIC shows isotopic equilibrium between deep waters and carbonated matrix. ¹⁴C have been used to estimate residence times, and dates back infiltration of the deeper exploited water to more than 20000 years, during the last ice age, which looks consistent with depletion in heavy isotopes of hydrogen and oxygen in water.

Anomalous springs at the Northern outcrop of the geothermal reservoir have been sampled and analyzed with the intention, among others, of confirming the deep waters influence on their temperature and chemical content. Sulfur and oxygen isotopes in sulfates confirm mixed influence between shallow and deep waters in these springs, with a mixing rate exceeding 50% of deep water in several cases. Further use of these results with gauging of the springs flow will give estimation of deep reservoir exsurgence flow.

REFERENCES

André, L., Franceschi, M., Pouchan, P. and Atteia, O.: Origine et évolution du soufre au sein de l'aquifère des Sables infra-molassiques du Bassin Aquitain, C. R. Geosciences, 334, (2002), 749-756

Craig, H.: Isotopic variation in meteoric waters, Science, 133, (1961), 1702-1703

De Putter, T., Rouchy, J.-M., Herbosch, A., Keppens, E., Pierre, C. and Groessens, E.: Sedimentology and palaeoenvironment of the Upper Viséan anhydrite of the Franco-Belgian Carboniferous Basin (Saint-Ghislain Borehole, Southern Belgium), Sedimentary Geology, 90, (1994), 77-93

Doremus, P., and Hennebert, M.: Carte géologique de Wallonie, 38/5-6, Blicquy-Ath, notice explicative, MRW-DGRNE (1995)

- Groessens, E., Conil, R. and Hennebert, M.: Le Dinantien du sondage de Saint-Ghislain, Stratigraphie et paleontology, Mem. Expl. Cartes Géol. Min. Belg., 22, (1979), 137
- Hennebert, M.: Carte géologie de Wallonie, 44/3-4, Laplaigne-Péruwelz, notice explicative, MRW-DGRNE (1999).
- IAEA (2001). GNIP Maps and Animations, International Atomic Energy Agency, Vienna. Accessible at <http://isohis.iaea.org>
- Ingerson, E. and Pearson, F.J.: Estimation of age and rate of motion of groundwater by the ^{14}C method, Recent Researches in the Field of Hydrosphere, Atmosphere and nuclear chemistry. Maruzen Co, Tokyo, (1964), 263-283
- Krouse, H.: Sulphur isotopes in our environment, Handbook of Environmental Isotopes, Geochemistry, (1980), 435-471
- Lacquement, F.: L'Ardenne Varisque. Déformation progressive d'un prisme sédimentaire pré-structuré, de l'affleurement au modèle de chaîne, Soc. Géol. Nord, 29, (2001), 284
- Langguth, H.R. and Nielsen, H.: Sulphur isotopes in thermal waters and anhydrites of the Dinantian at the Southern margin of the Brabant Massif: preliminary note, Meded. Rijks Geol. Dienst, 32-13, (1980), 101-105
- Mook, W.G.: Environmental isotopes in the hydrological cycle, IHP-V Technical Documents in Hydrology, 39, (2000), 280
- Pierre, C.: Données de géochimie isotopique sur les anhydrites (^{18}O , ^{34}S) et les carbonates (^{18}O , ^{13}C) des évaporites givésiennes et viséennes du Nord de la France et de la Belgique, Bull. Soc. Belg. Géol., 95, (1986), 129-137
- Quinif, Y., Vandycke, S. and Vergari, A.: Chronologie et causalité entre tectonique et karstification. L'exemple des paléokarst crétacés du Hainaut (Belgique), Bull. Soc. Belg. Géol., 168, (1997), 463-472
- Rouchy, J.M., Groessens, E. and Laumondais, A.: Dislocation des formations évaporitiques par la tectonique et la dissolution: le modèle des évaporites dinantiennes du domaine varisque franco-belge, Bull. Soc. Belg. Géol., 164, (1993), 39-50
- Tamers, M.A.: Validity of radiocarbonates on groundwater, Geophysical Survey, 2, (1975), 217-239
- Vogels, J.C.: Carbon 14 dating of groundwater, Isotope Hydrology IAEA, 225, 239