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Understanding the Thermal-induced Flow in the Carbonate and Sulphate Karstic Reservoir of Hainaut (South Belgium)

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ABSTRACT

The geothermal reservoir of Hainaut, South Belgium, has been producing geothermal energy for district heating for more than 25 years. Two wells give a 100 m³/h artesian flow rate of hot water at 70°C. Exploitation of a third well will start in the next future for a similar use. The reservoir is a fissured and karstic aquifer composed of thick Lower Carboniferous limestone and dolostone formations. In one of the wells, anhydrite was discovered in the Upper and Middle Visean carbonate, overlying a thick karstified and/or brecciated permeable horizon. The near outcrop show collapse breccias in coeval formations probably resulting from the entire anhydrite/carbonate sequence karstification. In the other geothermal wells, permeability was met in these breccia layers, highlighting their importance for the reservoir productivity.

Karst development in the deep Lower Carboniferous strata of Hainaut can be related to past tectonic activity, identified using several tectonic, karstic and sedimentological arguments, that caused the increase of permeability and the onset of thermal-induced convective flow in the aquifer. Anomalies in temperature and/or chemical and isotopic signatures of spring water from the outcrop attest moderate uprising flow of geothermal water, and show that convection is still occurring nowadays.

Understanding the deep water flow at regional and local scale is crucial for the exploitation development of the Hainaut reservoir, as the thermal, lithological and hydrogeological heterogeneities of the aquifer are demonstrated. Failures due to lack of knowledge can be avoided by careful exploration in the future.

1. INTRODUCTION

The exploration borehole of Saint-Ghislain, drilled in 1975 in the Hainaut region (South Belgium) revealed the existence of a geothermal resource at 2.500 m deep (Delmer, 1977). Converted into a geothermal well, it offers 73°C hot water at a 100 m³/h natural artesian flow rate. Two other wells were drilled a few years later in Douvrain and Ghlin (Leclercq, 1977; Delmer *et al*., 1982; Delmer *et al*., 1996), a few km North and North-East from the first one (see Figure 1). They met the same reservoir at lower depths (respectively 1.350 m and 1.575 m), and can produce water at similar temperature (67°C and 71°C) and flow rate. The Saint-Ghislain and Douvrain wells are used since 1986 mainly for district heating applications. The Saint-Ghislain water is exploited through a cascade system. After the heating plant, it is used for greenhouses heating and then for biogas production stimulation. The Douvrain well, dedicated since the beginning of its production to the heating of sanitary water for a nearby hospital, has recently been connected to new customers. The third well of Ghlin will soon start production for similar purpose. The drilling of a fourth well is planned in the next few months.

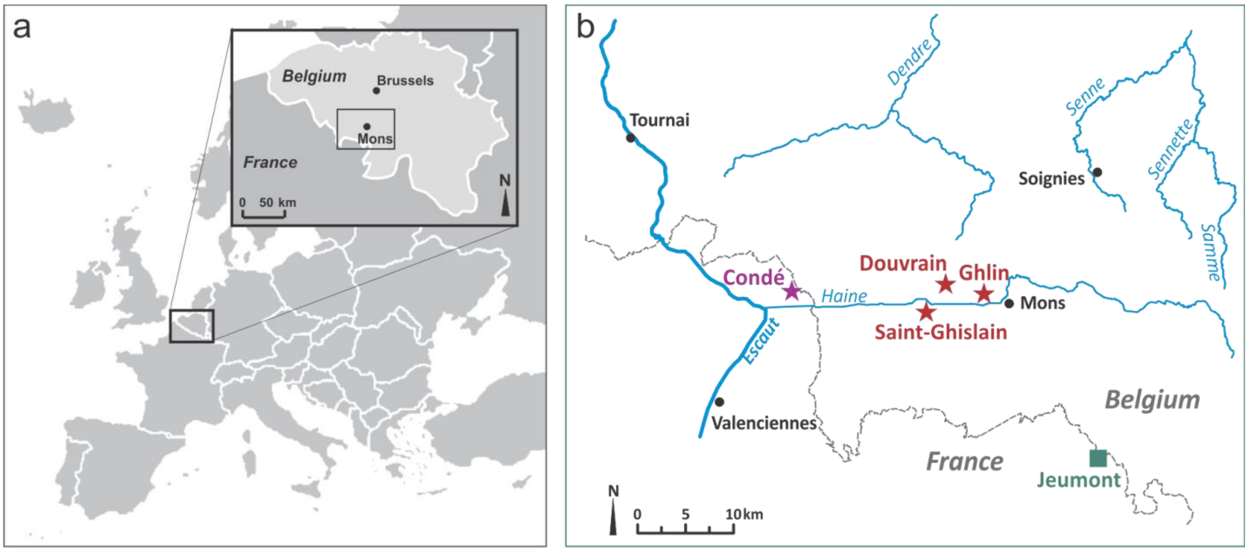

Figure 1: Localization of the geothermal exploitation area of Hainaut. a: The Mons region and the geothermal exploited area. b: Localization of the Saint-Ghislain, Douvrain, Ghlin and Condé wells and Jeumont deep borehole. The Wépion borehole doesn't appear on this map, and is located 60 km East from Mons. Geothermal wells are represented by stars, deep borehole is represented by a square.

A few km West from the Hainaut exploited area, over the French border, the Condé well (CFG, 1988, unpublished), drilled soon after the three Hainaut wells, met waters that did not reach 30°C, at similar depths and in the same geological formations. This demonstration of the heterogeneity of the temperature distribution in the reservoir shows the necessity of a careful exploration to characterize the nature and extension of the favorable conditions of the Saint-Ghislain area. Recent work (Licour, 2012) synthesizes and gives consistent and global interpretations of decades of geological, hydrogeological and chemical studies. This paper summarizes some of the main results of this work. It presents hypotheses regarding the karstification processes in relation with the permeability, and gives insights for a conceptual model of flow and heat transfer in the geothermal reservoir.

2. GEOLOGICAL SETTING

The geothermal reservoir of Hainaut is located in the Paleozoic bedrock of the Hainaut region, in Lower Carboniferous (Mississippian, previously Dinantian) carbonated strata. It lies under coal measures of Upper Carboniferous, and under thin Meso-Cenozoic cover locally known as Mons Basin deposits (see Figure 2). The Dinantian aquifer outcrops a few kilometers north from the exploited area.

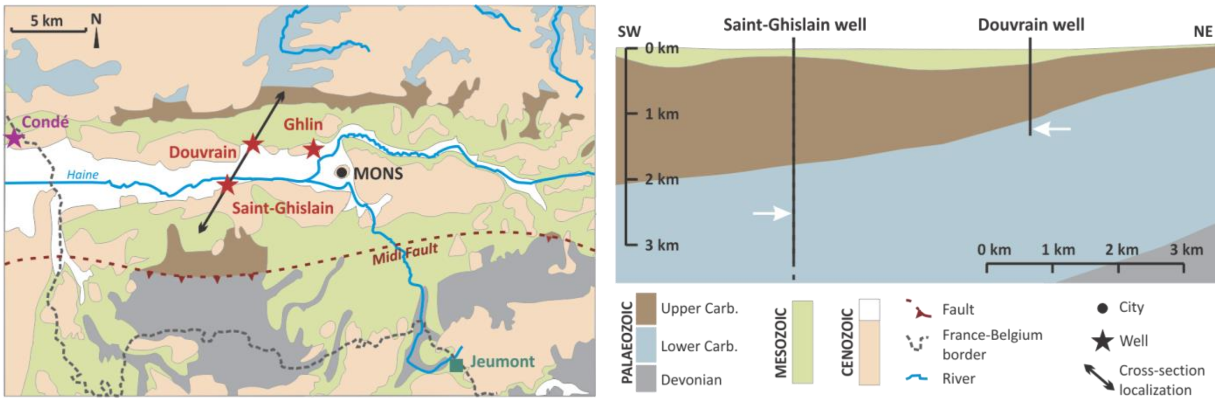

Figure 2: Simplified geological map (left) and cross section (right) of the Mons Basin and the exploited geothermal area. The white arrows represent productive layers in the Saint-Ghislain and Douvrain wells.

2.1 Structural Context

The Mons Basin Paleozoic bedrock has been shaped by several successive tectonic phases. First the deep bedrock, made of Cambrian to Silurian rocks, has been heavily folded and faulted during Caledonian orogeny (Legrand, 1968; Verniers *et al*., 2001). The resulting London-Brabant Massif has then been eroded during deposition of Devono-Carboniferous sediments (Meilliez, 1989; Mansy et Meilliez, 1993; Vanbrabant *et al*., 2002; Mansy and Lacquement, 2006). The Hercynian orogeny then made three main structural units out of those Paleozoic rocks (Mansy *et al*., 1999; Lacquement *et al*., 1999; Lacquement *et al*., 2005): the Brabant Parautochton and Brabant Massif, that remained approximately still and show few folds and faults, the strongly deformed and faulted Ardennes Allochton, thrusted over the former unit, and the Overturned Thrust-Sheets (OTS), that form the intermediate unit and are composed of numerous thrust-sheets and overturned massifs (see Figure 3). The Midi Fault is the uppermost thrust-fault of this ensemble, and is usually given as the limit between the Allochton and the underlying units.

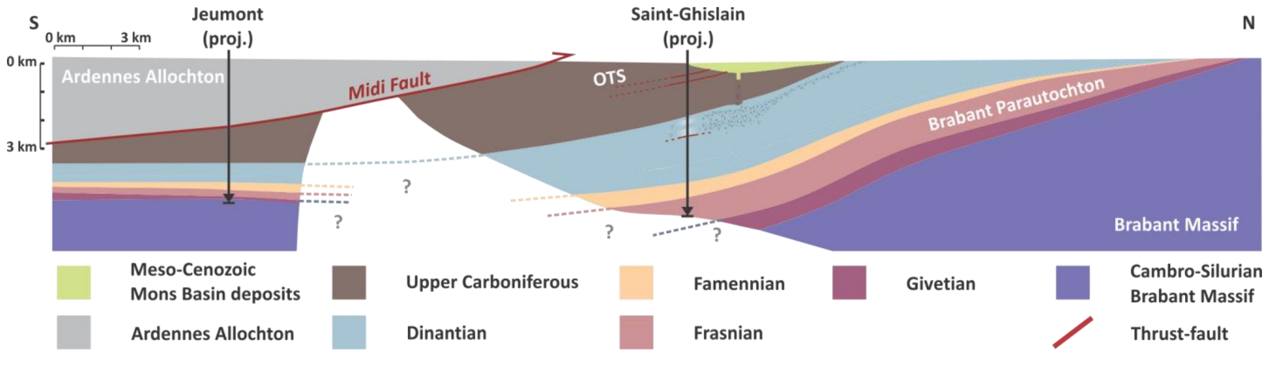

Figure 3: Schematic structural N-S cross section of the Hainaut region. Projected section of the Saint-Ghislain and Jeumont boreholes are represented. Ardennes Allochton Paleozoic strata are not differentiated on this figure.

Later Meso-Cenozoic tectonic effects are mostly fault creation and reactivation under extensive stress (Colbeaux *et al*., 1977; Vergari and Quinif, 1997; Quinif *et al*., 1997, Vandycke, 2002). Despite the apparently moderate impact of this tectonic phase in the region, the opening of permeable fractures in the Paleozoic bedrock had strong consequences on the future geothermal reservoir.

Thus, the geothermal reservoir is located in the Lower Carboniferous strata of the Brabant Parautochton. It shows few faults and deformation. It appears as a several hundreds of meters thick set of strata with a global E-W direction and a moderate dip of a few degrees toward South.

2.2 Lithology of the Lower Carboniferous of Hainaut

The Dinantian formations of Hainaut (Doremus and Hennebert, 1995; Poty *et al*., 2001; Hennebert and Eggermont, 2002; Delcambre and Pingot, 2008) are mainly composed of limestone and dolostone, with more detritic series in their upper and lower parts (see Figure 4). They are overlaid by Upper Carboniferous coal measures, consisting essentially of shales and sandstones (Delmer *et al*., 2001). Below the permeable Famennian and Upper Frasnian limestones, sandstones and dolomites, still considered as part of the Dinantian aquifer, the shaly Frasnian strata form the impervious bottom of the reservoir (Bultynck and Dejonghe, 2001). At the outcrop, the thickness of the Dinantian series varies from more than 1.5 km in the western part to less than 800 m in the East (Doremus and Hennebert, 1995; Delcambre and Pingot, 2008). In the Saint-Ghislain borehole, the Dinantian is particularly thick and exceeds 2.5 km (Groessens *et al*., 1979).

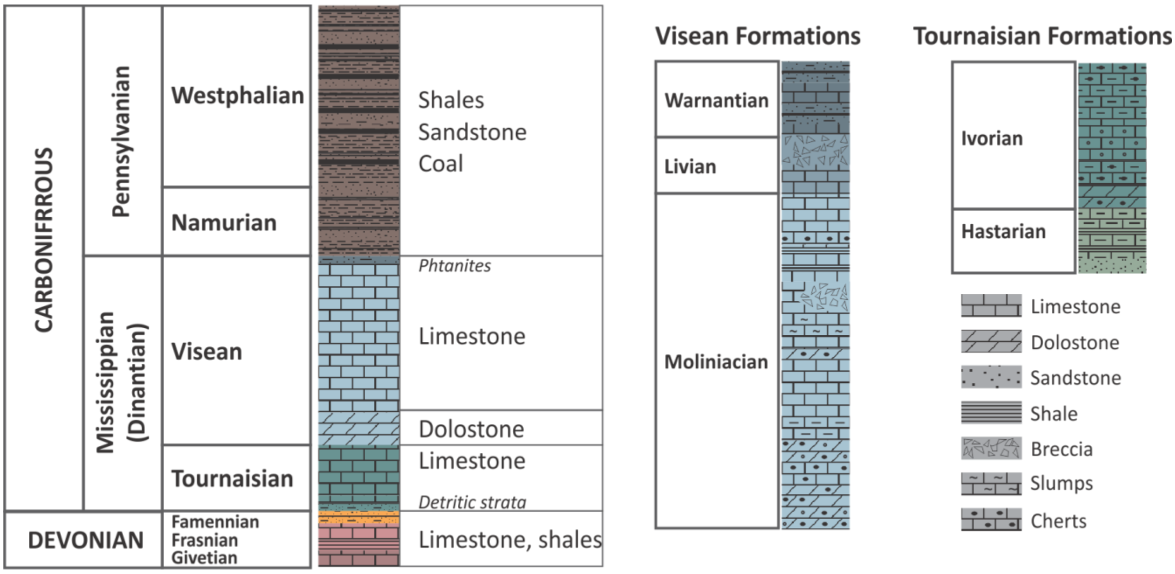

Figure 4: Synthetic lithostratigraphic logs of the Paleozoic of Hainaut (from Doremus and Hennebert, 1995; Hennebert, 1999; Hennebert and Eggermont, 2002; Delcambre and Pingot, 2008). These logs show the formations described at the outcrop (left), with more detail (right) on the Visean and Tournaisian series.

3. REGIONAL SUBSIDENCE, KARSTIC FEATURES AND COLLAPSE BRECCIAS

The Saint-Ghislain borehole revealed massive anhydrite strata that had never been observed before in the Upper and Middle Visean series neither in boreholes nor at the outcrops (Groessens *et al*., 1979; De Putter et al., 1991; De Putter, 1995). Permeability was met at the bottom of this several hundred of meters thick evaporitic formation, in karstic breccia (Delmer, 1977). The Douvrain and Ghlin wells productive layers are located in a permeable breccia as well (Leclercq, 1980; Delmer *et al.*, 1982; Delmer *et al*., 1996). The relation between permeability and breccia layers is then obvious in the Hainaut reservoir (see Figure 5).

3.1 Shallow karst features

The shallow part of the Dinantian reservoir is well known geologically and hydrogeologically because of the extensive observations that can be made in the numerous limestone quarries, and through its exploitation for drinking water distribution. Karst features have been studied for years (Quinif, 1989; Vergari and Quinif, 1997; Quinif *et al*., 1997, Kaufmann, 2000; Quinif *et al*., 2006) and conclude to a strong relation between karst and regional extensive tectonic context during Late Jurassic / Early Cretaceous times, resulting in preferential karst directions. Several types of karst features have been identified and related to former paleogeographic context and hydraulic regime (Vergari and Quinif, 1997; Quinif *et al*., 1997), some of them corresponding to very low hydraulic potential has been described in the quarries of the Tournai and Soignies regions (see Figure 1 for localization).

3.2 Breccia layers

The discovery of evaporites in the Saint-Ghislain borehole in 1975 (Dejonghe *et al*., 1976; Delmer, 1977; Rouchy *et al*., 1984; De Putter *et al*., 1994) and breccias met soon after in Douvrain and Ghlin wells (Leclercq, 1980; Delmer *et al*., 1982) led to new investigations about the outcropping Dinantian formations. Stratiform breccia layers were then more closely examined and the observation of anhydrite pseudomorphs in some of them indicated their probable origin as collapse breccias caused by the dissolution of evaporites (de Magnée *et al*., 1986; Mamet *et al*., 1986; Rouchy *et al*., 1986; Rouchy *et al*., 1993; De Putter, 1995).

Breccia layers were investigated throughout the whole region and it appears that the evaporitic conditions caused extensive deposits in the Visean times which traces remain in Parautochton as well as in Allochton strata (Hance and Hennebert, 1980; Rouchy *et al*., 1984; Rouchy *et al*., 1986; De Putter *et al*., 1994; De Putter, 1995). ‘

3.3 Breccia pipes and regional subsidence

The Hainaut region has a long mining history and geological information about coal bearing Upper Carboniferous strata is plentiful. Among other, the depth at which the Paleozoic bedrock is met under the Meso-Cenozoic sediments of the Mons Basin has been carefully mapped (Stevens and Marlière, 1944; Cordonnier, 1984; de Magnée *et al*., 1986). Figure 6 illustrates the irregular shape of the Mons Basin, an E-W 30 km long structure of a few hundreds of meter deep in the lowest parts. The mining activities also revealed the existence of numerous karstic pipes across the whole Upper Carboniferous series (Delmer and Van Wichelen, 1980). These pipes are represented on Figure 6 as well.

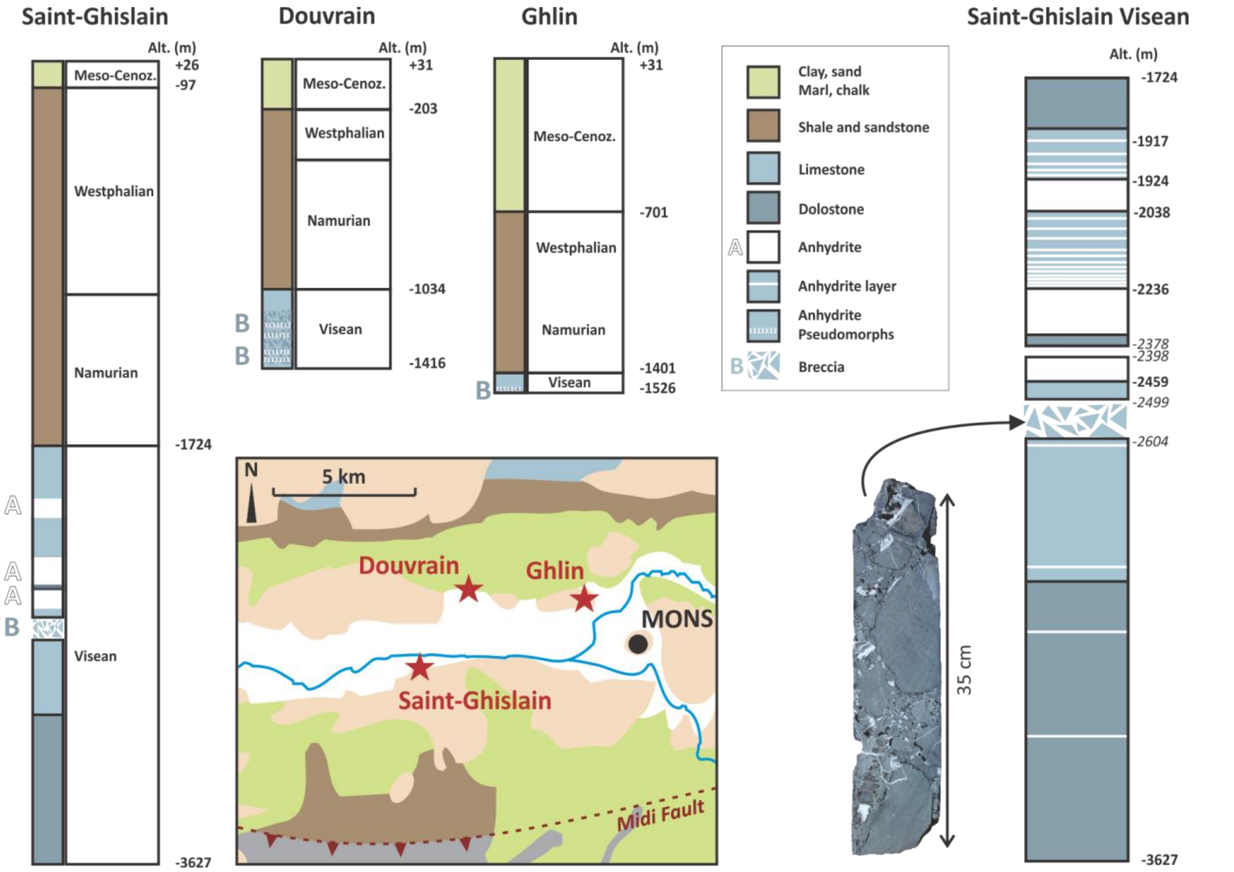

Figure 5: Simplified logs of the Visean and overlying rocks in the 3 geothermal wells of Hainaut.

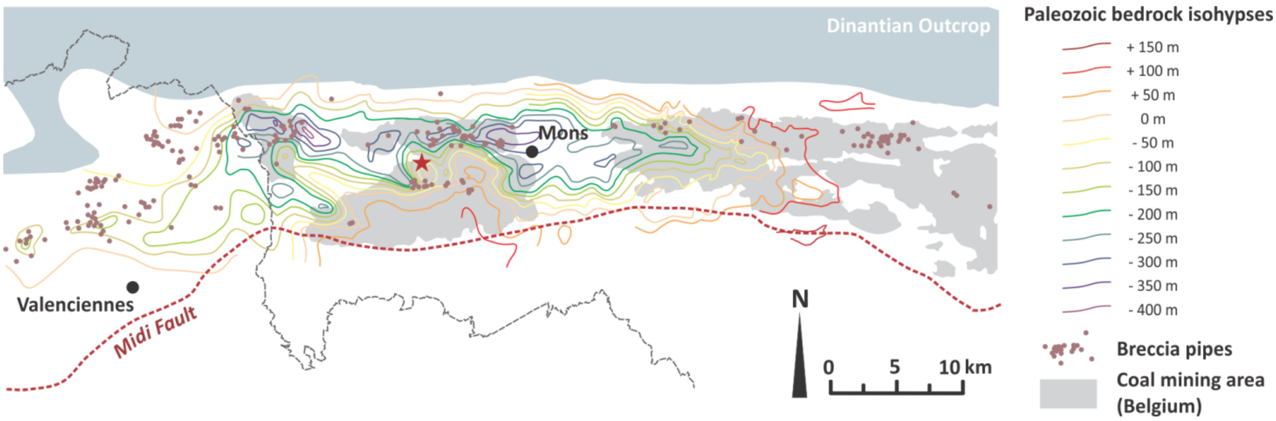

Figure 6: Isohyps map of the top of the Paleozoic bedrock in Hainaut (from Stevens and Marlière, 1944) and localization of the karstic pipes (from Delmer and Van Wichelen, 1980). Grey areas show the extension of coal mining exploitations. The red star localizes the Saint-Ghislain well.

3.3.1 Karstic Pipes Description and Repartition

The karstic pipes (Delmer and Van Wichelen, 1980; Spagna, 2010; Quinif and Licour, 2012) are roughly vertical and cylindrical features, from a few meters to several tens of meters wide. Their vertical extension can reach more than a kilometer. They are mainly filled with Upper Carboniferous shales and sandstones breccia, but in a few occurrences, more recent filling has been observed. Trapped sediments from the contemporary surface can allow an estimation of the period when the pipes were forming. The age of these sediments ranges from Barremian to Turonian (Delmer and Van Wichelen, 1980). One of them is famous for the Iguanodons skeletons that were discovered in the Lower Cretaceous sediments trapped within the coal measures (Yans *et al*., 2005; Baele *et al*., 2012).

The spatial repartition of the karstic pipes fits the shape of the Paleozoic bedrock surface (see Figure 6). They are abundant in the subsided regions, and rarer in the higher parts. Note that they have only been observed in coal mined areas.

3.3.2 Regional Subsidence: the Mons Basin

The Cretaceous and Cenozoic deposits of the Mons Basin show thickness variations that indicate the displacement of the subsidence maxima throughout time (de Magnée *et al*., 1986; Dupuis and Vandycke, 1989; Quinif *et al*., 1997; Spagna, 2010). The earlier deposits are located on a flank of the structure, and their recent study (Spagna, 2010) confirms the evolution of a subsidence front towards south during Cretaceous period.

3.4 Hypotheses on Deep Dissolution

Closer observation of the Saint-Ghislain area (see Figure 6) allows noticing the absence of karstic pipes along with the high position of the Paleozoic surface (Licour, 2009; Licour, 2012). Saint-Ghislain is also the only location in the Hainaut region where anhydrite can still be observed in the Dinantian strata. Based on a simple model (Friedman, 1997) of a thick soluble and ductile layer between less soluble fragile layers (see Figure 7), the hypothesis can be made that the remaining high regions without karstic pipes are the result of the anhydrite mechanical behavior that prevents the initiation of breccia pipes by slowly adapting to the voids created by removed material (Licour, 2009; Licour, 2012).

The subsidence, karstic pipes and breccia layer phenomena can be related to each other using this schematic model. The initiation of karstic pipes is due to more intense local dissolution caused by water fluxes through joints and fractures. The dissolution then spreads laterally and provokes the formation of a collapse breccia layer and the regional subsidence of the contemporary surface.

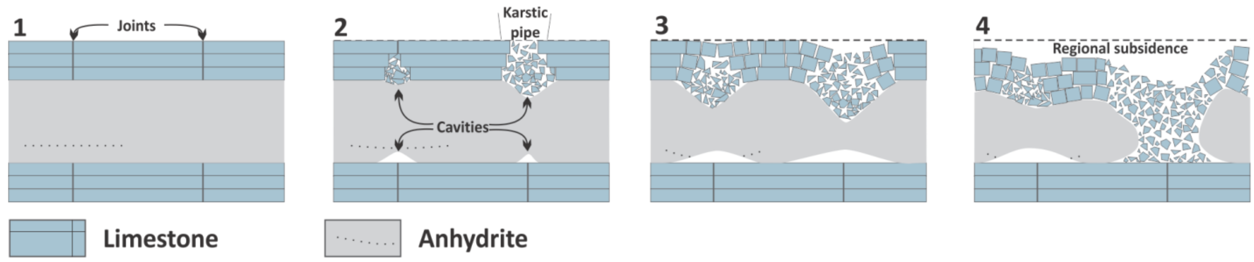

Figure 7: Schematic model of dissolution of a thick ductile stratum (e. g. anhydrite) between more fragile strata (e. g. limestone) (Licour, 2012, from Friedman, 1997, modified).

4. CONVECTIVE FLOW IN THE LOWER CARBONIFEROUS RESERVOIR

4.1 Thermal indications

The first and more obvious indication of fluid convection in the Dinantian reservoir is the geothermal fluids temperature itself (Delmer, 1977; Leclercq, 1980; Delmer *et al*., 1982; Delmer *et al*, 1996, Licour, 2012). Saint-Ghislain produces 73°C water from 2.500 m deep. The two other wells give respectively 67°C from 1.350 m and 71 °C from 1.575 m. Temperature/depth ratio in Saint-Ghislain only is 29 °C/km, in Douvrain it reaches 49 °C/km and 45 °C/km in Ghlin.

4.1.1 Well temperature logging

Temperature logging in Saint-Ghislain (see Figure 8) shows an alteration of the temperature profile at the very depths of the Dinantian formations. Bottom hole temperature measurements taken during the drilling operations confirm this logging, and give additional and deeper information (Legrand, 1978). It seems that when the impervious bottom of the reservoir is touched, temperatures increase strongly.

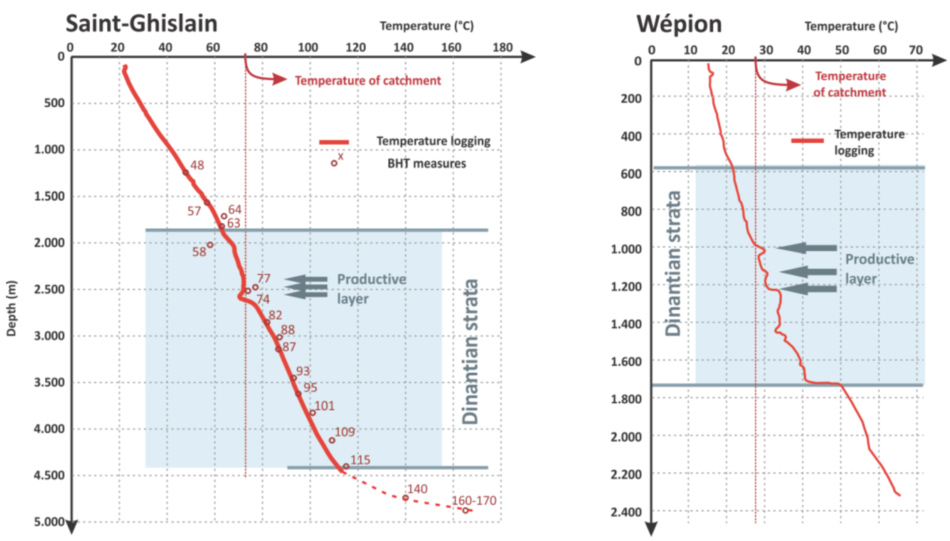

Figure 8: Temperature logs and bottom hole temperature (BHT) measures in Saint-Ghislain and Wépion boreholes.

The Wépion borehole is located East from the Saint-Ghislain area, and crosses the same formations (Graulich, 1961; Coen-Aubert, 1988). The temperature log (Graulich, 1960) shows similar shape (see Figure 8), suggesting the influence of fluid flow in the permeable strata, that does not affect the impervious over- and underlying strata.

4.1.2 Temperature mapping in the shallow reservoir and thermal gradient in overlying strata

All the available temperature data have been collected and/or measured in the shallow part of the aquifer (Licour, 2012), allowing a rough temperature mapping (see Figure 9). Strong anomalies appear north-west from the geothermal exploitations, in the region where a warm spring named "Fontaine bouillante" gives 18°C sulfated water.

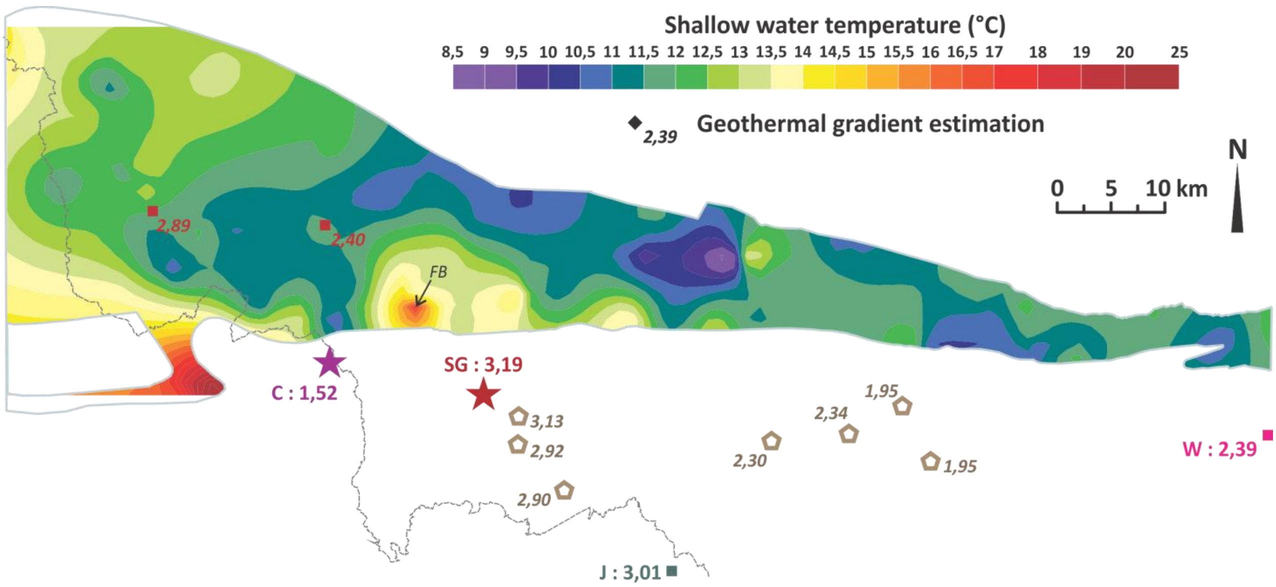

Figure 9: Temperature map of the shallow Dinantian aquifer. Geothermal gradients are estimated using the deepest available temperature information. Boreholes are represented by squares (J for Jeumont, W for Wépion). The Condé and Saint-Ghislain wells are symbolized by stars (SG for Saint-Ghislain, C for Condé). The grey pentagons represent data coming from coal mining operations, and then concern Upper Carboniferous strata overlying the geothermal reservoir. The "Fontaine Bouillante" (FB) warm spring is located.

The temperature map, associated with thermal gradient evaluation in boreholes and mining shafts that concern Upper Carboniferous formations, suggest a convective flow scheme in the deep reservoir. Cool water from the outcrop could flow down towards the deep part of the reservoir, along the bottom of the permeable Dinantian aquifer. That downflow could be more important in the East part of the area, where the water table is about 100 m higher than the West part, with the "cool" gradient measured in overlying strata as a consequence (Licour, 2012; Licour, 2014).

The heated fluid then reaches the top of reservoir and follows it towards surface, provoking Douvrain and Ghlin positive thermal anomalies and moderate warming of shallow waters, with local remarkable exsurgence such as the "Fontaine Bouillante".

A cold zone appears west from the Fontaine Bouillante region. It is located close to the Condé well and the existence of NE-SW faults in this area can explain the very low temperature measured in this well by cool water fluxes enhanced by fracture permeability.

The West part of the reservoir, beyond the French border, appears to be warmer. This is due to regular geothermal gradient and gradual burrying of the Dinantian strata under thicker cover in that region (Licour, 2012).

4.2 Chemical tracing of deep water exsurgence

Water upflow from the deep reservoir towards surface can be confirmed by chemical data. Sulfate resulting from anhydrite dissolution can be considered as a signature of deep waters. Springs, water catchment wells and quarries pumping were investigated for temperature and chemical content measurements (Bosch *et al*., 1981; Delmer *et al*., 1982; Blommaert *et al*., 1983; Licour, 2012). Two diagrams (see Figure 10a) that illustrate the chemical signature of regular shallow groundwater, deep groundwater from the geothermal wells and several warm springs, located on the map of Figure 10b. Sulfate content is high in these springs, but not very different from the sulfates resulting of sulfide oxidation and often present in regular shallow water.

Figure 10c shows the results of isotopic characterization of sulfates in deep and shallow groundwater and in warm springs of the outcropping reservoir (Licour, 2012; Licour, 2014). The differentiation can clearly be made (Krouse, 1980; Pearson and Rightmire, 1980; Mook, 2000) between oxidized sulfide with very low $\delta^{34}S$ and $\delta^{18}O$ (water issuing from a pyrite-rich alterite) and dissolved anhydrite sulfate with very positive $\delta^{34}S$ and $\delta\ ^{18}O$ (geothermal waters). Sampled shallow groundwaters range between the two extremes of the scheme and can thus be considered of mixed origin. Some of them tend to show a bigger contribution of deep water in their sulfate content, as the "Fontaine Bouillante".

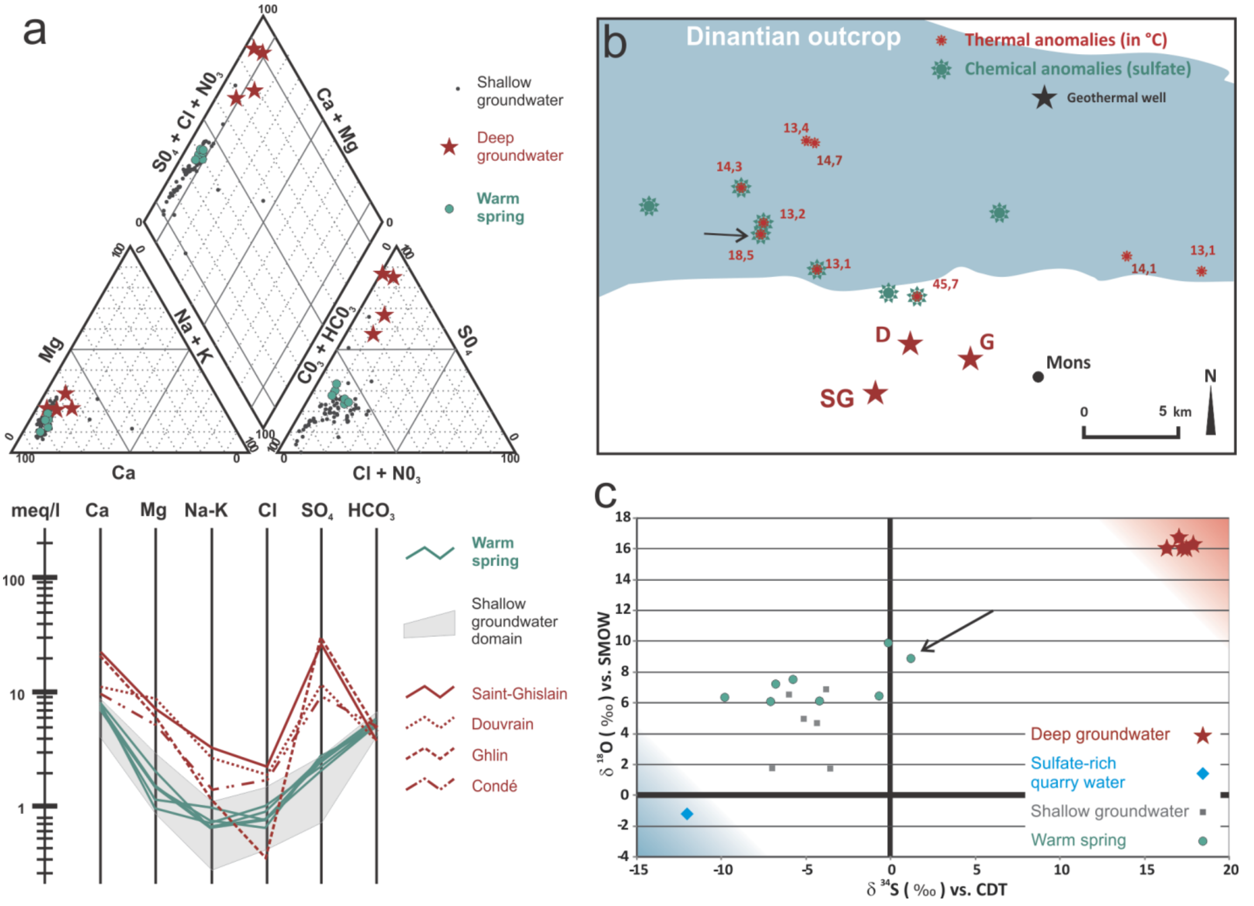

Figure 10 : Chemical content of shallow and deep groundwaters from the Dinantian reservoir. a: Piper (above) and Schoeller-Berkaloff (below) diagrams giving the chemical composition of deep groundwater, shallow groundwater and warm springs from the Dinantian outcrop. b: Localization of several warm and/or sulfated springs of the outcropping Dinantian aquifer. The geothermal wells are symbolized by stars. The black arrow points to the "Fontaine Bouillante" spring. c: Isotopic ratios of sulfur and oxygen in the sulfate ion in shallow and deep groundwater. The black arrow points to the "Fontaine Bouillante" marker.

5. SYNTHESIS AND DISCUSSION

5.1 Breccias and Reservoir Permeability

As said before, evaporites deposited during Visean times probably covered a great domain, and at least the whole area concerned by the present paper. Those deposits were deeply buried under the Ardennes Allochton at the end of Paleozoic. Erosion occurring during Mesozoic times brought Dinantian rocks to the outcrop, but the karstification of the present days outcropping carbonates only started thanks to the increase of permeability caused by Cretaceous extensive stress.

Evaporites dissolution probably started at the same period, and propagated towards South, deeper in the reservoir. It first provoked local instabilities, initiating karstic pipes that trapped contemporary sediments when reaching the surface, at least between Barremian and Turonian. Second, the lateral spreading of dissolution led to regional subsidence, and conservation of Cretaceous sediment in the Mons Basin, with evidences of the displacement of subsidence maxima towards South as a consequence of the progression of the dissolution front at depths. The evaporites dissolution left collapse breccia layers that can be observed at the outcrops and in the Douvrain and Ghlin geothermal wells. In Saint-Ghislain, thick anhydrite strata remain, overlying a karstic permeable breccia layer. In this region, ductile anhydrite has preserved the integrity of the overlying strata, preventing the formation of karstic pipes.

Permeability in the exploited reservoir can be related to two main situations. First, in the Douvrain and Ghlin configuration, the productive layers are met in the upper part of the reservoir, in a collapse breccia where anhydrite seems to have totally disappeared. Second, in the Saint-Ghislain situation, a very high permeability karstic breccia layer lies under thick anhydrite strata.

The existence of the Saint-Ghislain conditions can be assumed in the zones where karstic pipes are rare or absent and where the Paleozoic surface remained relatively high (see Figure 11). The Douvrain and Ghlin configuration can be supposed present in the rest of the area, based on the hypothesis of the extension of the evaporitic conditions to the whole region during Visean times (Licour, 2012).

5.2 Convective Flow

Thermal and chemical data indicate the possibility of fluid convection between the outcrop and the depths of the Dinantian aquifer. First, the temperature logging in several wells and boreholes looks affected by fluid circulation, cooler at the bottom and warmer at the top of the reservoir. The positive thermal anomaly at the top of the reservoir is well illustrated by the high temperatures measured at Douvrain and Ghlin wells.

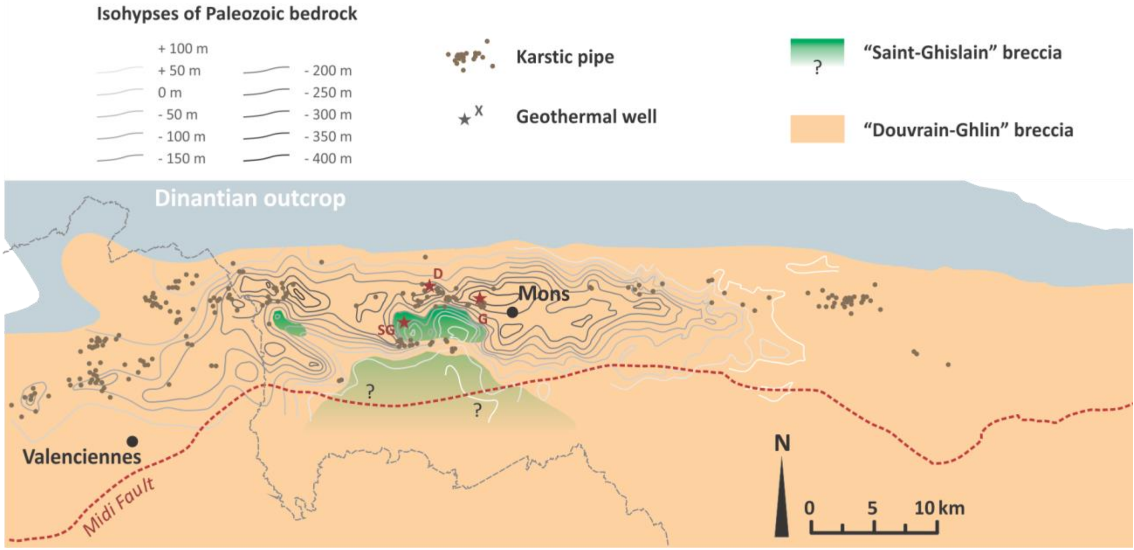

Figure 11: Hypothetic localization of the Visean breccia layers. The "Saint-Ghislain" case is likely to happen in regoins where no karstic pipes are present and Paleozoic bedrock surface remained relatively high. The "Douvrain-Ghlin" configuration is potentially present in the whole area.

Thermal convection can occur in a porous medium if the following condition is verified (Combarnous and Bories, 1975) :

$$Ra \cdot \cos \gamma \geq 4\pi^2 \qquad (1)$$

where Ra is the Rayleigh number dependant on the fluid characteristics, the permeability of the porous medium, its thickness and the temperature gradient. γ is the dip of the porous stratum. The thickness and permeability of the Dinantian strata are sufficient to allow convection. Schematic simulation of a 2D cross section in a thick permeable layer (se Figure 12) has been realized as a test (Licour, 2012), using SHEMAT (Clauser *et al*., 2003), a finite elements code specifically designed for hydrothermal reservoirs. That simplified model represents a 13° dipping 2 km thick layer, which is very near from real geometry. Homogeneous permeability of $k=10^{-13}$ m² was used, which is very low compared to the productive layers permeability, but may be closer to an average value for the whole reservoir. Despite the simplicity of the model, the resulting velocities (0,2 to 1 m/yr) and temperature fields are consistent with temperature data and ^{14}C–estimated residence times (from 22 to 30.10^3 yrs for Saint-Ghislain water) (Licour, 2012). The large convection loops scheme then looks confirmed.

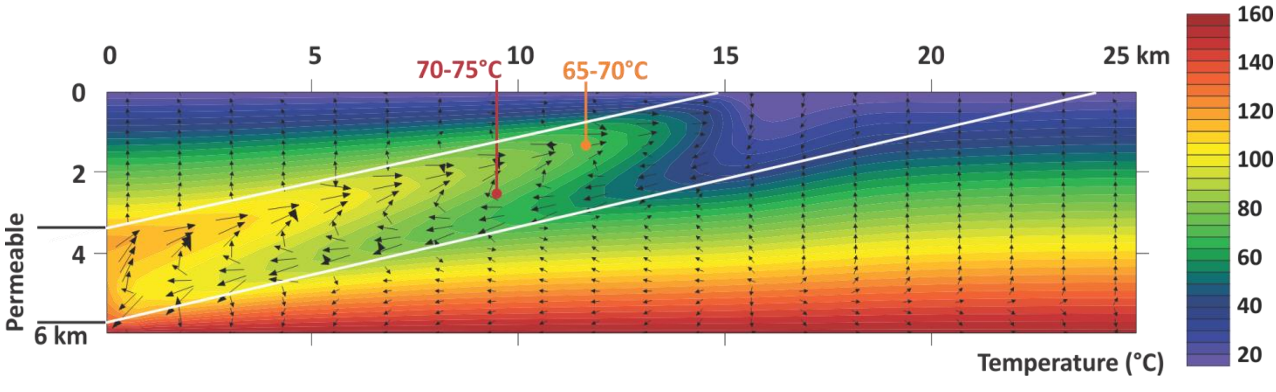

Figure 12: Simplified model 2D of flow and heat transfer in the Dinantian reservoir. The permeable layer is represented between white lines. The markers represent the Saint-Ghislain (red) and Douvrain (orange) catchment depth and at projected distance from the outcrop. Despite the simplicity of the model, the simulated temperatures match the real measured temperatures in the geothermal fluids.

5.3 Convection Initiation and Reservoir Formation

The understanding of the formation of the Hainaut reservoir and the spreading of dissolution at depths involves the existence of fluid flow, as solvent fluid has to be renewed and solutions evacuated. The outcropping part of the Hainaut reservoir has to be considered as both the recharge and discharge area, with low hydraulic gradients. Thermal convection is then needed to induce and sustain flow between the shallow and the deep parts of the Dinantian reservoir.

The convection condition previously given (1) can be used to estimate permeability threshold that could allow convection to start in an unconfined aquifer, under regular thermal gradient conditions. Using a 300 m thickness, the permeability needed is about 10^{-11} m², which is an average value in the present shallow reservoir (Licour, 2012). Thermal convection is then likely to be part of the original processes that started the propagation of karst toward depths in sulfated strata, and have most probably played a role in the karstification of carbonates in the shallow parts of the reservoir (Licour, 2012; Licour, 2014).

6. CONCLUSION

The geothermal reservoir of Hainaut is a karstic carbonated and sulfated aquifer showing locally strong permeability related to the existence of collapse and karstic breccia layers. The collapse breccias are the result of the removal of evaporitic strata, which remains are still present in some parts of the reservoir. These breccias can be considered as present over the whole area, but the greatest permeabilities are met in the regions where some anhydrite strata are still observed. Hypotheses are produced for the localization of such regions, based on the presence/absence of karstic features in overlying strata.

A conceptual model is presented about the flow patterns between the deep part of the reservoir and its outcropping part, which is both its recharge and discharge area, and where moderate warm sulfated water exsurgence is confirmed. This paper discusses the formation of the reservoir as well as the initiation and contribution of thermal convection to the karst development in the shallow and deep regions of the aquifer.

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