

Hydrogeophysical characterization of the porous and fractured media (chalk aquifer in the Beauvais, France)

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Abstract This study is aimed to investigate the principal aquifer in the northern part of Paris (Beauvais region) which is materialized by the Senonian chalk deposits. This aquifer supplies water to the principal region in the north and in particular the Picardie and Artois region. In order to characterize the chalk aquifer of this area, a wide pluridisciplinary research program based on the well logging and near surface geophysics surveys (seismic refraction and electrical resistivity tomography) is in progress. These surveys were carried out within the experimental site of the LaSalle Beauvais Polytechnic Institute and its hydrogeological boreholes. The heterogeneous distribution of the seismic velocities in the complex aquifer and of the physico-chemical properties (conductivity, temperature and gamma-ray) of the chalk aquifer were revealed by the analysis and the interpretation of the seismic lines and data logging, which are linked to changes in lithology and water properties at the place of the hydrogeological wells. The fracturation investigation identified during this work makes it possible to consider the relationship between the degree of the fracturation and the variation of the hydrogeological parameters (hydraulic conductivity, porosity) and physico-chemical parameters (electrical conductivity and temperature). The interface between vadose and saturated zones was assessed by the measurement of the water conductivity, the variation of the average temperature and by the cuttings analysis in particular at the level of the capillary fringe of the chalk aquifer. The presence of the saturated depth is confirmed by the piezometric investigation. The interpretation of the well logging by using gamma-ray is consistent

with the seismic and electrical analysis: the three principal layers are composed of silt and clay with cherts, soft chalk, as well as hard chalk.

Keywords Chalk aquifer · Seismic and electrical sections · Well logging · Conductivity · Temperature · Gamma-ray · Experimental site · Beauvais · France

Introduction

Hydrological wells which constitute an important potential of drinking water of Beauvais city are rather scarce and relatively deep. At the same time, the Beauvais region (northern part of the Paris Basin) has an intense agricultural activity as well as food industry activity. In this context, an accurate quantitative description of the geometry of the Turonian chalk aquifer is essential for the management of the water resources. Additionally, the characterization of the Turonian chalk aquifer is important in terms of groundwater flow and spatial repartition of the physical and structural characteristics taking into account that the Turonian chalk groundwater is the greatest drinking water resource in the Picardie region (Antonellini and Aydin 1994; Bloomfield 1999; Hanich et al. 2011; Muldoon et al. 2001; Zouhri 2002).

In order to characterize the Turonian chalk aquifer, there were two coupled approaches used in hydrogeological and geophysical investigations (well logging, seismic and electrical methods). The studies conducted in the experimental site of the Institut Polytechnique LaSalle Beauvais have the originality of hydrogeophysical approaches such as the deep hydrogeological wells (100 m) and the interest that the site is located near the Therrain River, which implies that the alluvial system may constitute an additional feature in the hydrogeological characterization of the Picardie region. A

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new and modern hydrogeophysical exploration of aquifers in this site is revealed by the borehole logging techniques. Well logging has been used in several studies, in particular for the identification of physical rock properties (Ikeda et al. 2008), characterization of volcanic conduits (Sakuma et al. 2008) and of hydrogeochemical parameters (Lysne and Henfling 1994; Diment 1967), for geothermal applications (Wisian et al. 1998), groundwater modeling (Boucher et al. 2009), and pumping test in the crystalline basement (Vouillamoz et al. 2005). This approach requires data from the wells and geophysical survey: well logging (camera, gamma-ray, temperature and electrical conductivity probes), seismic refraction, electrical resistivity tomography (ERT). The ERT has been extensively used in geophysical investigations (Dahlin 2001). The most common applications of ERT are for solute transport and modeling (Slater et al. 2000; Kemna et al. 2002; Zouhri and Lutz 2010; Zghibi et al. 2014); hydrogeological properties (Flathe 1955; Dahlin and Owen 1998; Pham et al. 2002; Descloitres et al. 2008; Koch et al. 2009); geothermal field exploration (Wright et al. 1985); environmental research (Rogers and Kean 1980; Van et al. 1991; Daily et al. 2004; Rings and Hauck 2009).

This multidisciplinary approach was used in this study in order to provide significant hydrogeophysical data for the unconfined chalk aquifer in the Picardie: (1) characterization of the hydrogeological units of the chalk aquifer; (2) identification of the petrophysical parameters of the aquifer (gamma-ray, temperature, electrical conductivity); (3) determination of the seismic velocity and electrical resistivity repartition in the chalk aquifer; and (4) monitoring fracturation from outcrops around the experimental site of the LaSalle Beauvais.

Geological and hydrogeological settings

The geographical location of the chalk aquifer of Beauvais (Oise, northern part of the Paris Basin) which is studied in this work is shown in Fig. 1. The geological history of the Pays de Bray is part of the Paris Basin and it starts from Cenozoic period. This region is characterized by the presence of an eroded anticline buttonhole. A vast part in the northern part of France is occupied by the intra-cratonic sedimentary basin (Pomerol 1978; Mégnien 1980; Beccalotto et al. 2011) and it is prolonged northward and palaeogeographically connected (West) to the English Channel (Dercourt et al. 2000), and in the north to the Belgian Basin.

The spatial occurrence in the Paris Basin highlights the facies variations ranging from the Triassic to Cenozoic (Fig. 2).

The geological deposits which are encountered in the Oise (Tirat and Belkessa 1969) and were crossed by the wells, encompass the following formations:

1. the Jurassic formations are represented by the Portlandian Stage, which shows successively:
 - the Lower Portlandian (10 m): beige grey lithographic limestone;
 - the middle Portlandian (150 m): grey marls with limestone intercalations and dolomitic calcareous sandstone;
 - the Upper Portlandian (15 m): green grey sand, sandy clay or marls.
2. the Cretaceous, which is composed of:
 - Hauterivian deposits (about 30–107 m from NW to SE). The Hauterivian is composed by grey to black clay, coarse white sand and brown compact clays and ferruginous sandstone.
 - Barremian (28–63 m from NW to SE): colourful plastic clay with gypsum and sandy clay intercalations, reddish sandstone with pyrite and lignite.
 - Aptian (3–4 m): The Aptian formations are sporadically represented by blue marls.
 - Albian: (1) the Lower Albian is composed by the green sand (20–30 m) including the coarse sand by location, clayey sand with lignite, pyrite and glauconite and (2) the Upper Albian is marked by the clay of “Gault” (50–60 m at the south-east): the clay is either black and compact, or yellow with chert.
 - The Cenomanian is formed by: (1) The “Gaise” (20–25 m), white-green siliceous limestone, from to the base to a bluish gray sandy clay; (2) white-green blood chalk with or without chert becoming glauconitic and clayish at the top.
 - Turonian (110 m): marly chalk or grey chalk with chert.
 - Senonian (70 m): white chalk, yellow or gray with chert.

Prior to the current study, two wells were drilled in order to obtain information about the vertical lithological variations in the Turonian aquifer, vadose and saturated zones. These drillings were completed by using the seismic refraction, electrical resistivity tomography, and well logging investigations. Hydrogeological and geophysical measurements were conducted in the hydrogeological experimental site of the LaSalle Beauvais Polytechnic Institute. The aquifer of Beauvais is composed essentially of the Senonian–Turonian chalk units, which rest on the Cenomanian formations. The geological configuration of this aquifer is shown in Fig. 2. The groundwater table level which is reported in Fig. 3 is about 43.8 m in the well 1 (Pz1) and 42 m in the well 2 (Pz2); the distance between the two wells is about 180.5 m. The water groundwater elevation that might explain the existence of the hydraulic

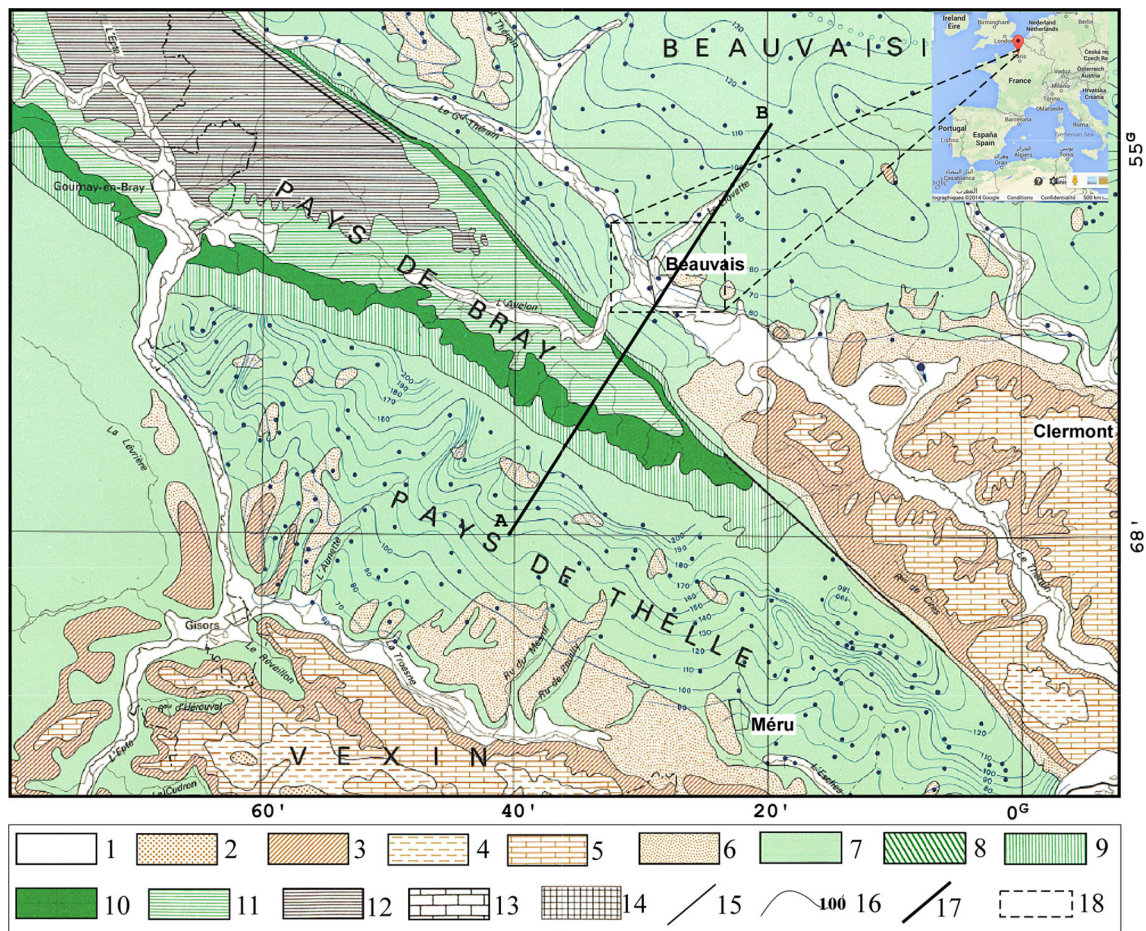


Fig. 1 Geological map around Beauvais (Parisian basin): 1 Alluvions; 2 Oligocene and Miocene (sand, sandstone and marls); 3 Upper Eocene, 4 Lutetian (coarse limestone); 5 Cuisian-Sparnacian (medium sand and clay), 6 Thanetian (fine sand), 7 Senonian-Upper Turonian (Chalk with flint), 8 Middle and Lower Turonian (marly chalk and

marls), 9 Cenomanian (glaucinit chalk), 10 Albian (Clay of Gult (green sand), 11 Neocomian (sand and clay), 12 Upper Jurassic (alternation of limestone and clay), 13 Middle Jurassic (limestone), 14 primary basement, 15 fault, 16 isopieze, 17 geological section (Fig. 2). 18 Location of the study area; (scale: 1/200 000)

gradient (about 3×10^{-2}) towards the river is about 115 m at well 1 and 118 m at well 2.

In the downstream portion of the experimental site, the pumping test which is realised to meet increasing the urban water needs and to define the hydrogeological characteristics of the chalk aquifer. The stepwise testings highlight a specific yield about 20–42 m³/h/m and the critical flow rate is about 215 m³/h. The maximum of the production discharge is about 200 m³/h.

Geophysical data

Seismic refraction approach

Numerous papers present the principal surveys of the seismic refraction approach. The refracted waves which arrive at the subsurface of a studied area can be identified by geophones which generate an electrical signal (Haeni

1986; Dobrin 1976; Telford et al. 1976). Seismic refraction gives more quality information about the identification of the hydrogeological units (permeable and hydrogeological basement units) and higher resolution of seismic velocity with depth.

The objective of seismic refraction is to reveal the different layers in the subsurface corresponding to an increase in the seismic velocity, which is related to the mechanical properties of the medium. These changes can be used, for example, to highlight the lithology of the underground (Karastathis et al. 2010; Hinojosa-Prieto and Hinzen 2015), to estimate the water-level depth (Grelle and Guadagno 2009; Desper et al. 2015), to evaluate the volume of the unstable mass in a landslide (Samyn et al. 2012), to delineate some of the shallow soil engineering characteristics for construction purposes (Khalil and Hanafy 2008).

The power of this method presents an important challenge in the characterisation of the contaminated site and of the migration of non-aqueous phase liquids (DNAPL)

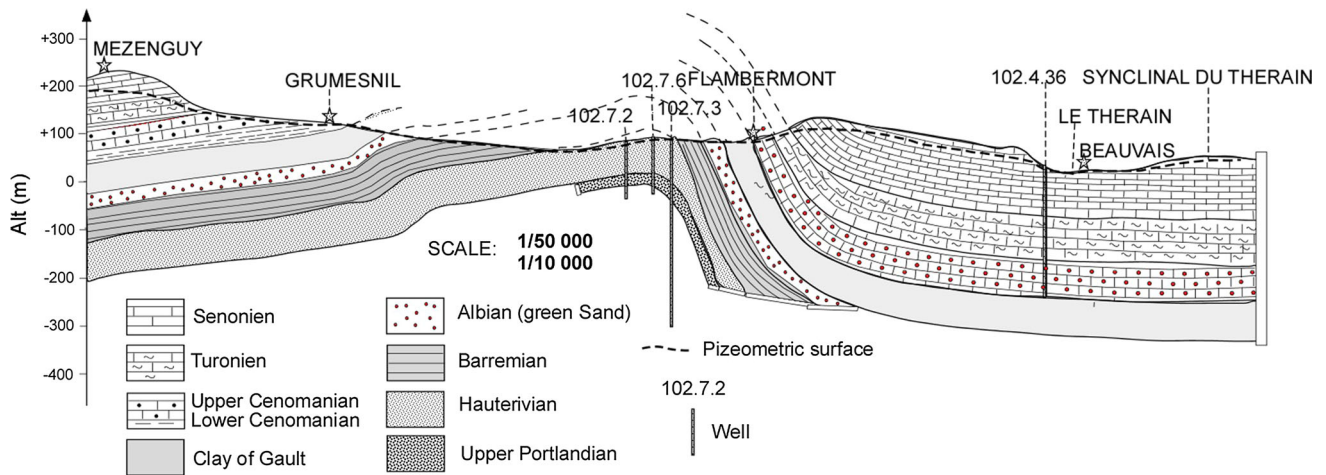


Fig. 2 Schematic geological section of the south-east part of the Bray (Roux and Tirat 1969, modified)

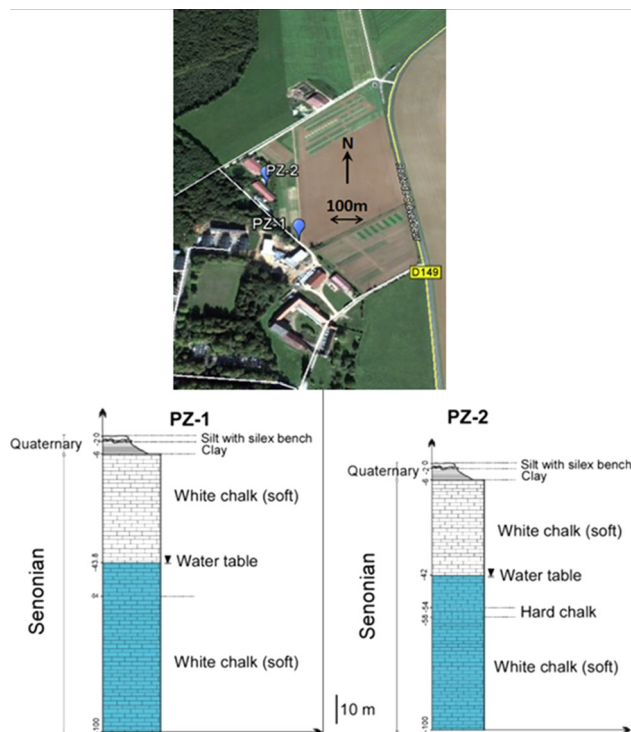


Fig. 3 Hydrogeological wells and groundwater levels in the LaSalle Beauvais Polytechnic Institute

(Murray et al. 1999; USGS 2006). The determination of layers is vital to predict the groundwater flow and the transport of the contaminant in the complex aquifer.

This method is based on the generation of seismic waves and the analysis of the travel times of the direct and refracted waves, provided that the layer velocity increases with depth. The maximum investigation depth depends essentially on the type of the source and the maximum distance between the sources and the receivers.

The seismic investigation in the area (Fig. 4a) was done on three seismic lines (S1, S2 and S3) which are, respectively, 144, 252 and 108 m of length. Each seismic line consists of several seismic profiles following themselves according to the same direction. The SUMMIT (DMT) system refraction was used with 24 vertical geophones of 14 Hz spaced of 1.50 m, a hammer of 4 kg and a stainless steel strike plate. For each profile, there were 5 shot locations, with a spacing of 9 m, and a total of 4–8 stacks were made per each shot location. S1 consists in 4 profiles and 20 shot locations, S2 in 7 profiles and 35 shot locations and S3 in 3 profiles and 15 shot locations. The data processing was done using the SeismImager/2D™ software. The first arrivals were picked using the Pickwin™ module. Two examples of picking presented Fig. 4b, corresponding to the direct shot gather and an intermediate shot gather of profile P2 of the line S1. The times were then assigned to the direct and refracted waves using the Plotrefa™ module (Fig. 4c). These assigned times were inverted using the Plotrefa™ module. Figure 5 shows the observed and calculated travel time curves relative to the three lines S1, S2, S3. The average error between the observed and the calculated times (RMSE) is respectively of 1.41, 2.47 and 1.56 ms.

The three resulting velocity models are on Fig. 6. The corresponding RMS errors in matrix inversion are: 0.572, 0.53 and 0.474 ms, which are acceptable values indicating that these models are reliable. The first two models, which are relative to S1 and S2, are similar as they are located along the same road. The higher values for the second and the third layers relative to the S3 model can be explained by the fact that its location is different (along a way towards fields). For each of these models, the most superficial geological layer is characterized by a propagation velocity of 0.4 km/s, with an average thickness of 2 m.

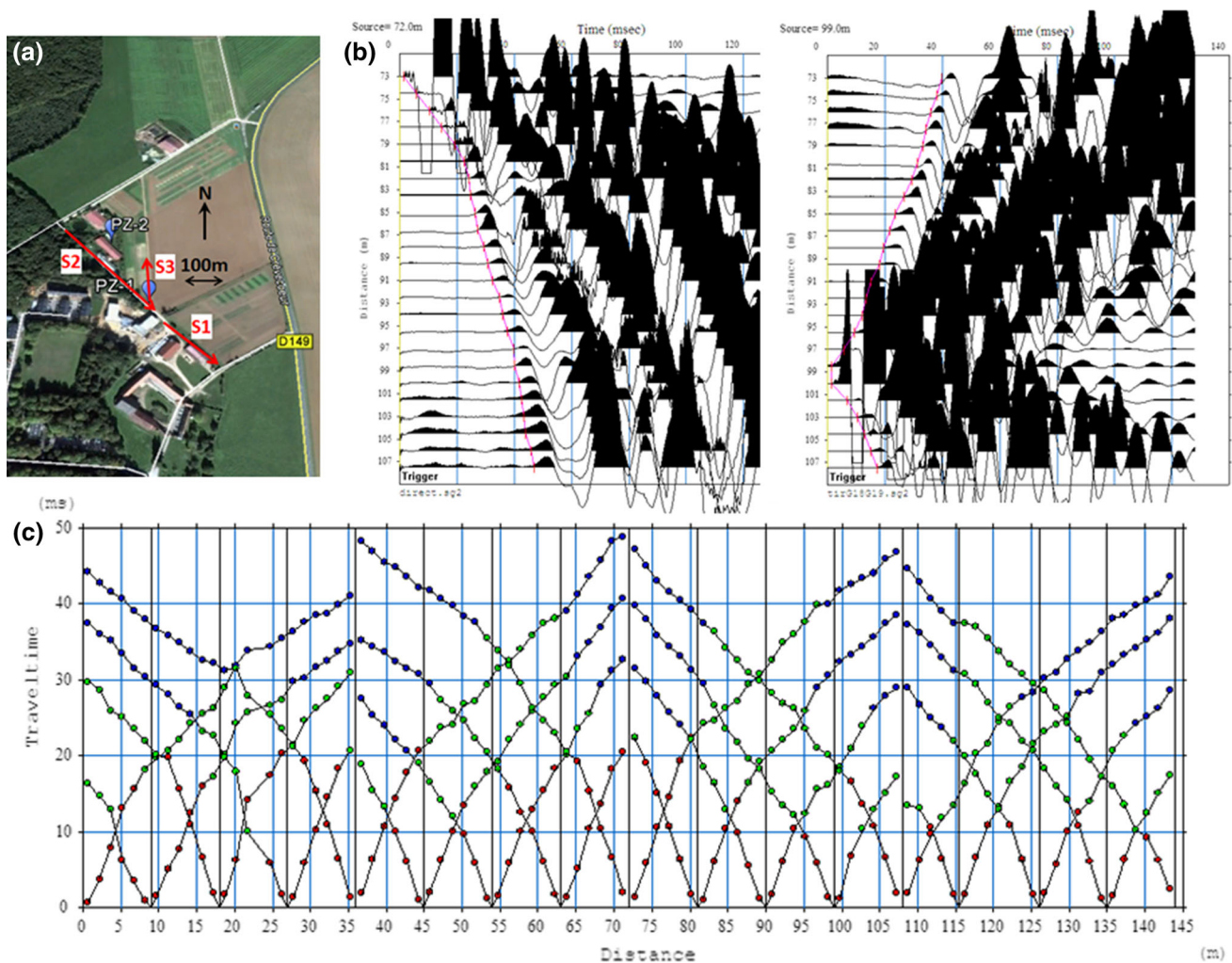


Fig. 4 Time analysis: **a** picking of the first arrival times (*pink curves*) from the measurements for the shots at 72 m (*direct shot*) and 99 m (*intermediate shot*) on profile P2 of line S1; **b** travel times for the 20

shot gathers of line S1 composed of 4 profiles (P1, P2, P3, P4) and waves assignment (the *red points* correspond to the direct wave, *green points* to the refracted wave 1 and *red points* to the refracted wave 2)

The seismic models relative to S1 and S2 show a second layer with a velocity of about 0.8 km/s and a variable thickness from 0 to 5 m, whereas S3 model highlights a thicker second velocity layer of 1.1 km/s. The velocity models show a third layer of 1.2 km/s (for S1 and S2) or 1.6 km/s (for S3).

From the wells realized in the experimental site (Pz1 and Pz2, Fig. 3) and the velocity values available in the literature (Table 1), the three different velocity layers can be interpreted as following: a thin layer of silts over clay and weathered/fractured chalk. The differences obtained from S1 to S2 with regard to S3 in the velocity values reveal some variability in the mechanical properties of the underground that is to say in the bulk, shear modulus and density (Khalil and Hanafy 2008; Karl et al. 2013; Hinojosa-Prieto and Hinzen 2015).

Electrical tomography approach

The ERT has been conducted in the experimental site in order to test the picks and plates electrodes by salt injections in the chalk aquifer (Zouhri and Lutz 2010). The objective of this paper is give more information and discussion about a new analysis in 2D sections which are realized up to 60 m of the depth and to precise the lithology and the location of altered and fractured zones. This method is based on the injection of direct current (50 Hz) using two electrodes and the measure of the apparent resistivity between two others. The measurements were undertaken with a multi-electrode 2D device (ABEM TERRAMETER SAS 4000), using 64 electrodes with a spacing of 5 m, so that each ERT section has a length of 315 m. A roll-along procedure, with a half-covering, has

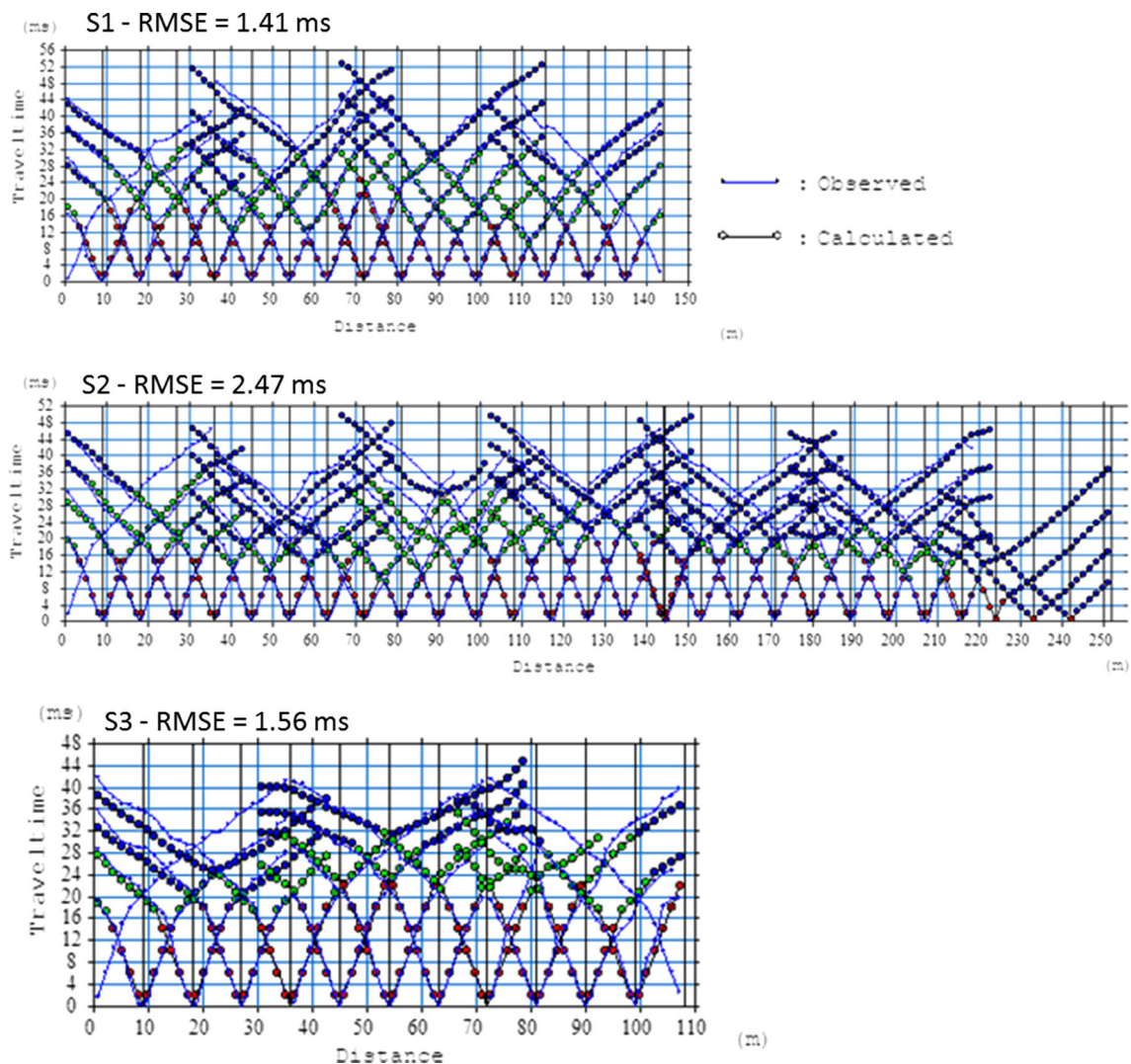


Fig. 5 Observed and calculated travel time curves for the lines *S1*, *S2* and *S3*

allowed covering the desired length along each line. Two arrays were used: (1) gradient array to obtain both high resolution and medium depth (1252 points of measure, 45 m of depth) and (2) pole-dipole array in order to increase the investigation depth (588 points, 70 m of depth). The gradient and pole-dipole arrays' data were concatenated to obtain combined apparent resistivity pseudo-sections. These were inverted using the standard Gauss–Newton code Res2dinv (Loke and Barker 1996), and allowed to obtain resistivity sections with both a good resolution and a great depth. As the datasets weren't particularly noisy, a standard constraint was chosen. A maximum of 5th iterations were done and if the RMS error was high (typically more than 7 %), some points corresponding to high error values were deleted, and the inversion was computed with this new data set (Loke and Barker 1996).

Four main electrical lines were acquired in the vicinity of the two piezometers Pz1 and Pz2: L1, L2, L3 and L4

(Fig. 7a) which are, respectively, 635, 635, 475 and 475 m of length. L1 is oriented NW–SE, passes not far from Pz1 and Pz2, and is located on the seismic profiles S1 and S2. L2, L3 and L4 are S–N. L2 is located on the seismic profile S3. The corresponding resistivity sections are presented in Fig. 7b–e.

These four sections reveal a superficial layer of low resistivity (less than $30 \Omega \text{ m}$) corresponding to the Quaternary loess and the clay provided from the chalk weathering. These sections reveal that the chalk is more or less altered and fractured. In particular, note that fracture zones are observed on section L1 (Fig. 7b), between (1) 245 and 295 m and (2) 445 and 495 m. Two slightly fracture zones are revealed on section L2 (Fig. 7c) at 280 and 400 m, and no fracture is observed on section L3 (Fig. 7d). Two conductive zones are observed on section L4 (Fig. 7e) (1) from 280 m at the surface to 320 m at 35 m depth, (2) from 445 m at the surface to 390 m at 35 m. These probably

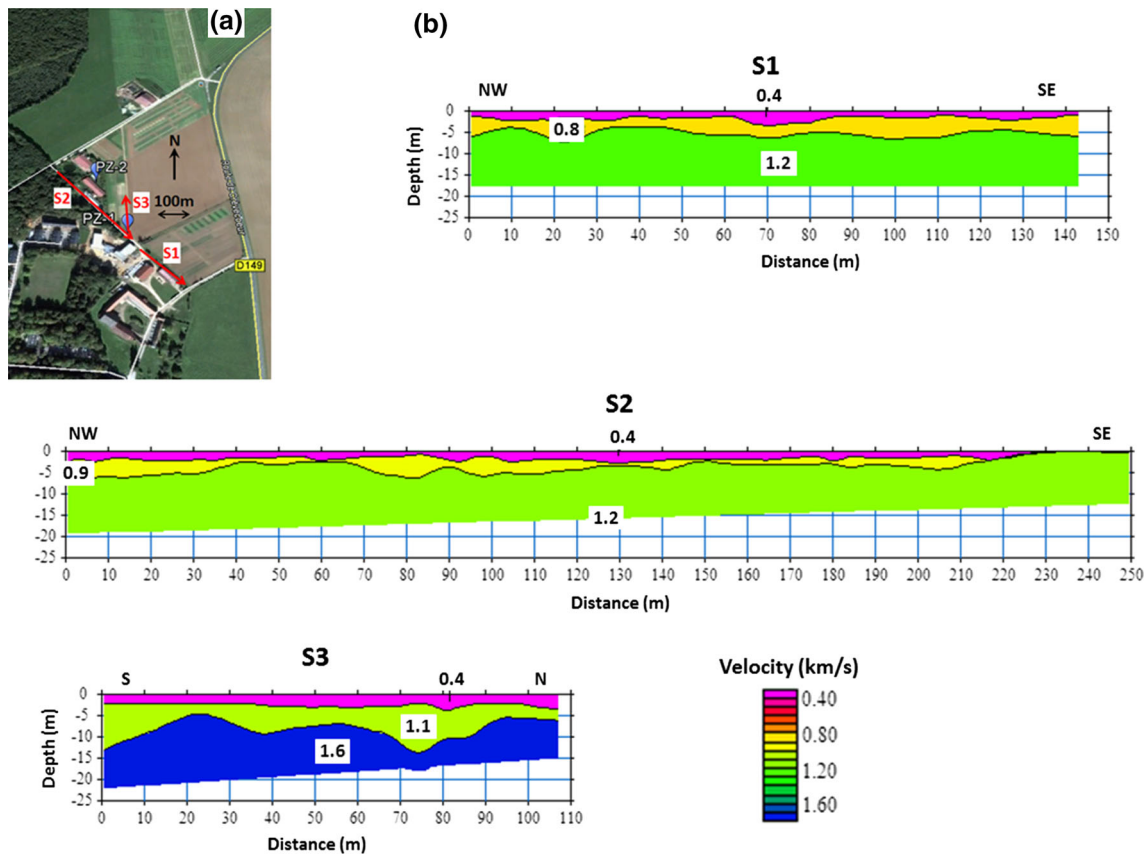


Fig. 6 Seismic refraction profiles carried out in the experimental site of the LaSalle Beauvais Institute (a location of the seismic sections; b velocity models of the seismic lines S1, S2 and S3)

Table 1 Velocity values according to lithology (modified from Magnin 2007)

Lithology	Velocity of compression waves (out of water) (m/s)
Soil	250–350
Fine sand	300–700
Clay	500–1400
Fractured chalk	900–2000
Healthy chalk	1800–2500

correspond to fracture zones and preferential water infiltration zones. However, the water level (around 40 m from Pz1 to Pz2) was not clearly observed on our resistivity sections. This can be explained by the high variability of the chalk electrical properties, which not only depend of the water content, but also of the porosity, matrix composition, weathering, fractures...

Borehole logging approach

The characterization of aquifers using borehole logging investigation is highlighted in numerous works (Audouin

et al. 2008; Paillet and Reese 2000; Schürch and Buckley 2002). The log investigation of the chalk aquifer of Beauvais was carried out using a multi-parameters approach: water conductivity, temperature, gamma-ray, central and lateral camera. Logging was carried out by using the GEOVISTA probes (Fig. 8) through the well 2. The recorded data were divided into two stages, namely down and up, and the depth sampling was of 1 cm. The monitoring of these parameters is function of the nature of the aquifer (vadose and saturated zones) and the level of the aquifer formation.

Gamma-ray log is a recording of natural gamma radioactivity of the geological deposits. Potassium, uranium and thorium are the main radioactive elements with a significant concentration in natural materials. In the sedimentary formations, the radioactivity is significantly recorded in clay formations that contain potassium (especially illite), in potassium salts, in the formations which are rich in organic matter and which may concentrate the uranium, and in the detrital formations containing potassium feldspaths or enriched in heavy minerals. A gamma-ray probe (GEOVISTA) was used in the well (Pz2) of the LaSalle Beauvais Institute; it was about 0.7 m long having

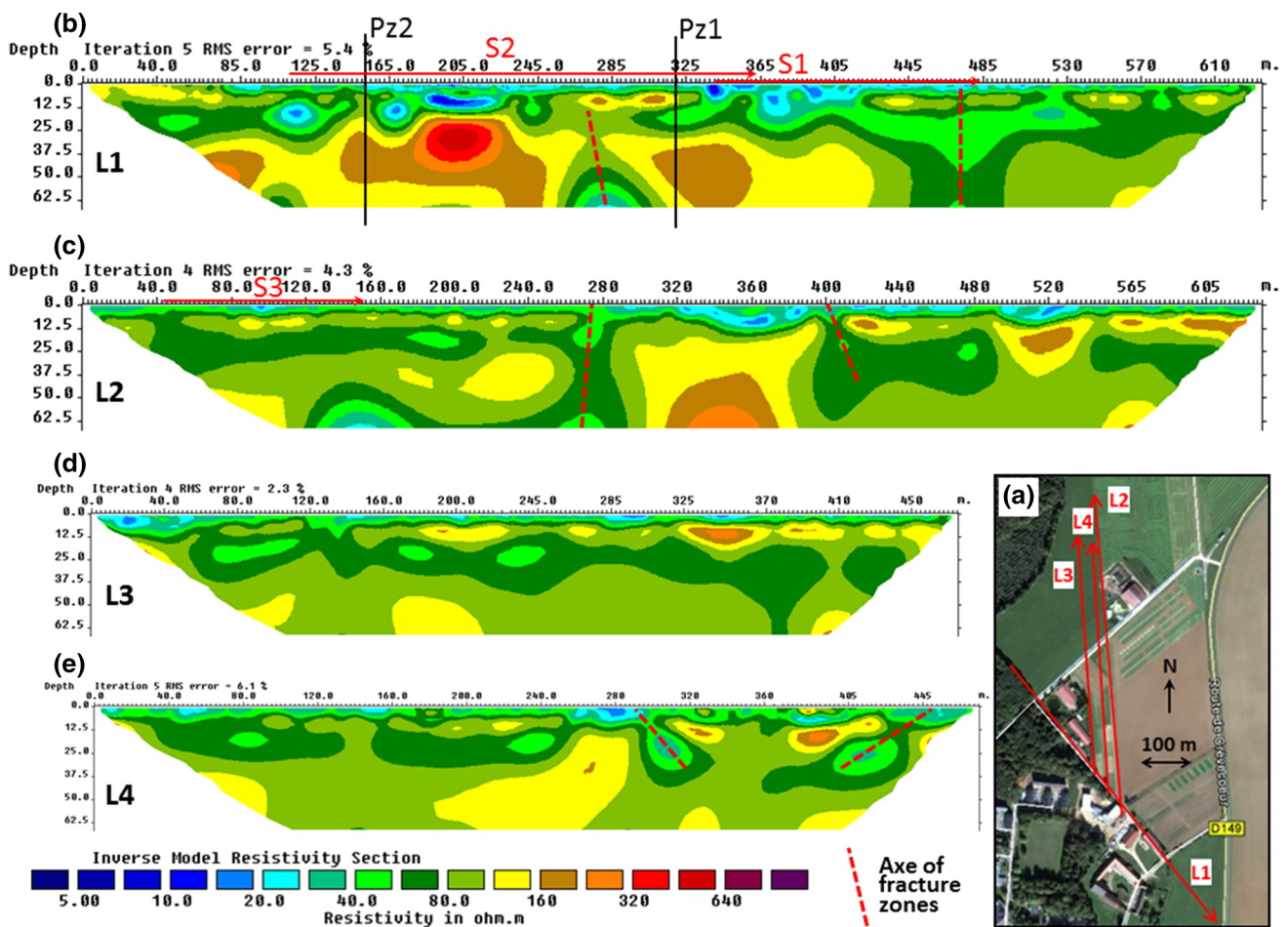


Fig. 7 Electrical resistivity sections *L1*, *L2*, *L3* and *L4* realized in the experimental site of the LaSalle Beauvais Institute

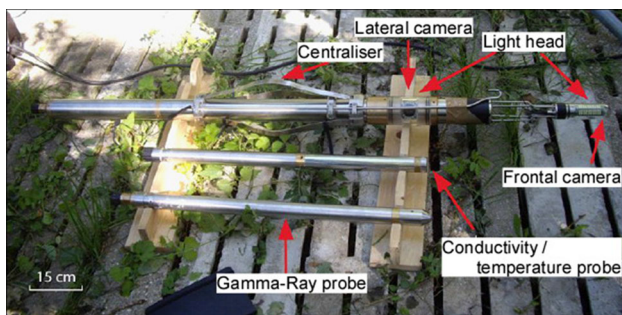


Fig. 8 Well logging probes (GEOVISTA) used for the hydrogeophysical log investigation

a diameter of about 28 mm and an approximately weight of 4 kg. This probe uses a sodium iodide scintillation crystal coupled to a photomultiplier to detect natural gamma radiation. The scintillation crystal has external dimensions of 50 mm long by 28 mm in diameter.

This probe was stacked to the temperature and conductivity probes. The advantage of this latter is that

Table 2 Characteristics of the temperature and conductivity sondes (Geovista probes)

Parameter	Range	Resolution	Accuracy
Temperature (°C)	0–80	0.001	±0.3
Conductivity (µS/cm)	50–50,000	0.05	±2 %

gamma-ray, temperature and fluid conductivity measurements are simultaneously made in the borehole. The main characteristics of these GEOVISTA probes are summarized in Table 2. The temperature measurement is useful both to normalize conductivity readings at 25 °C and to locate temperature anomalies caused by events such as fluid flow into the borehole. The conductivity measurement is a useful water quality parameter. The probe is about 0.71 m of length, the diameter is about 3.8 mm and weight is about 3.8 kg.

Integrating the detailed well logging and the geophysical results, the hydrogeophysical results show that the underground is composed by three main layers: soil (silts), clay (with chert) and chalk (Figs. 3, 9a). The results of the

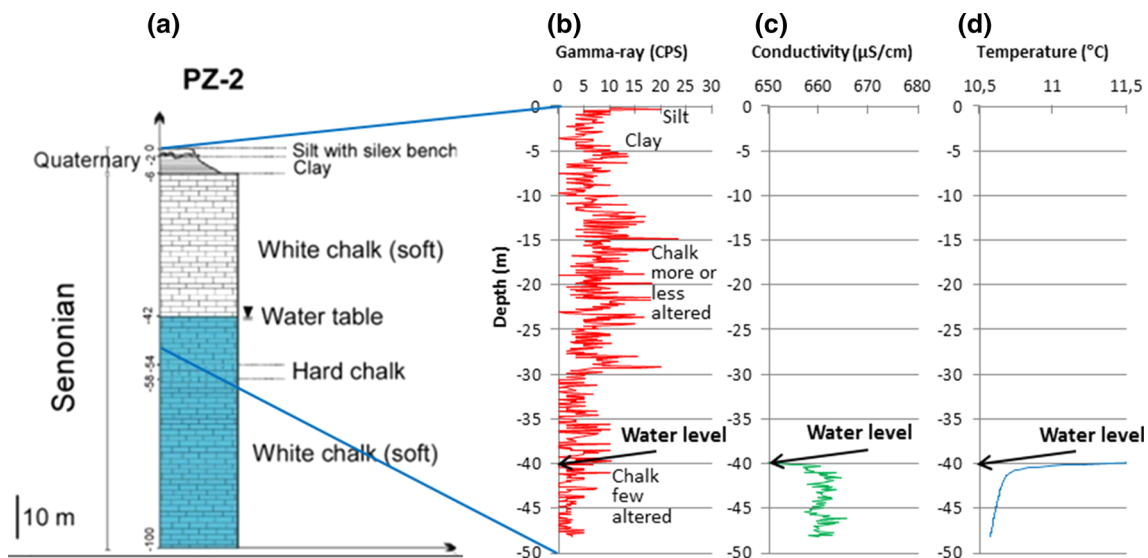


Fig. 9 Gamma-ray, conductivity, and temperature log curves obtained in the well 2 (Pz2) of the experimental site of LaSalle Beauvais

different measurements which are presented in Fig. 9 show that from 0 to 2 m deep, the value of the counts per second (CPS) decreases from 20 to 5 (Fig. 9b). This change is related to the lithological variation between the quaternary loess and the clay layers. From 2 to 6 m deep, the CPS value increases from a few CPS to 12 CPS explained by the presence of clay. From 6 to 29 m, the CPS value varies slightly (between few CPS and 20) with a mean value around 8 CPS, corresponding to the chalk more or less altered. From 29 m, the mean CPS value is around 2 CPS, revealing that the chalk is slightly less altered.

The water conductivity measurements have a meaning only from the water level (around 40 m). The presence of inorganic dissolved solids (e.g., nitrate, sulfate), anions or cations can influence the conductivity of the water. Conductivity is also affected by temperature: the warmer the water, the higher the conductivity. For this reason, raw data have been corrected from the temperature effect, namely, converted to the conductivity at 25 °C (Fig. 9c). The values are relatively constant, between 645 and 665 µS/cm, corresponding to a medium water quality.

The temperature value (Fig. 9d) quickly decreases from 13.3 °C at 39 m to 11 °C at 40 m due to the air heat. The temperature continues to decrease in the deep water masses but slightly.

Fracturation and discussion

Data logging which were recorded in the experimental site of the “Institut Polytechnique LaSalle Beauvais” confirmed the chalk aquifer and the interface between vadose and saturated zones. The full interpretation of data

collected in the hydrogeophysical investigation is enables to characterize the physico-chemical parameters of the chalk aquifer. In this study, since the hydrogeological wells are cased the characterization of fractures is difficult. However, the continuous monitoring coupled with the evolution of the physico-chemical parameters (pH and conductivity) and Ca and Cl concentrations enable to identify zones of water inflow. This monitoring is tested in order to carry out the fracturation of the Hettangian dolomite of the Ardèche project of the deep Geology of France programme (GPF) (Sureau et al. 1993; Sureau 1993), and the European geothermal project at Soultz-sous-Forêt (Vuataz 1987; Aquilina and Brach 1995).

In order to complete the electrical and the well logging interpretations, the analysis of drilling cuttings which were realized in 2014 in the experimental site provided more information about the variation of the lithological formations of the Senonian aquifer. The realization of this well (GPS position: 49°27'36.88"N 2°04'17.38"E) lasted 5 days and its achievement is part of building of the hydrogeological platform and hydrogeological site which will include around twenty drillings for following the groundwater fluctuation and the transport of pollutants in Picardy region. Cuttings have been analysed and interpreted each meter in terms of lithology and percentage of chert and clay deposits in the principal chalk aquifer. The lithostratigraphic column has about 52 m of depth because the loss of the fluid injection in the well does not allow it to recover the cuttings. Figure 10 shows a vertical distribution of the chalk aquifer with a heterogeneity of the chert percentage which is varying from 10 to 50 %.

In 2012, a campaign for the measurement of fractures was performed in the watershed Thérain (Oise). These

Fig. 10 Vertical distribution of the chalk aquifer deduced from the cuttings analysis

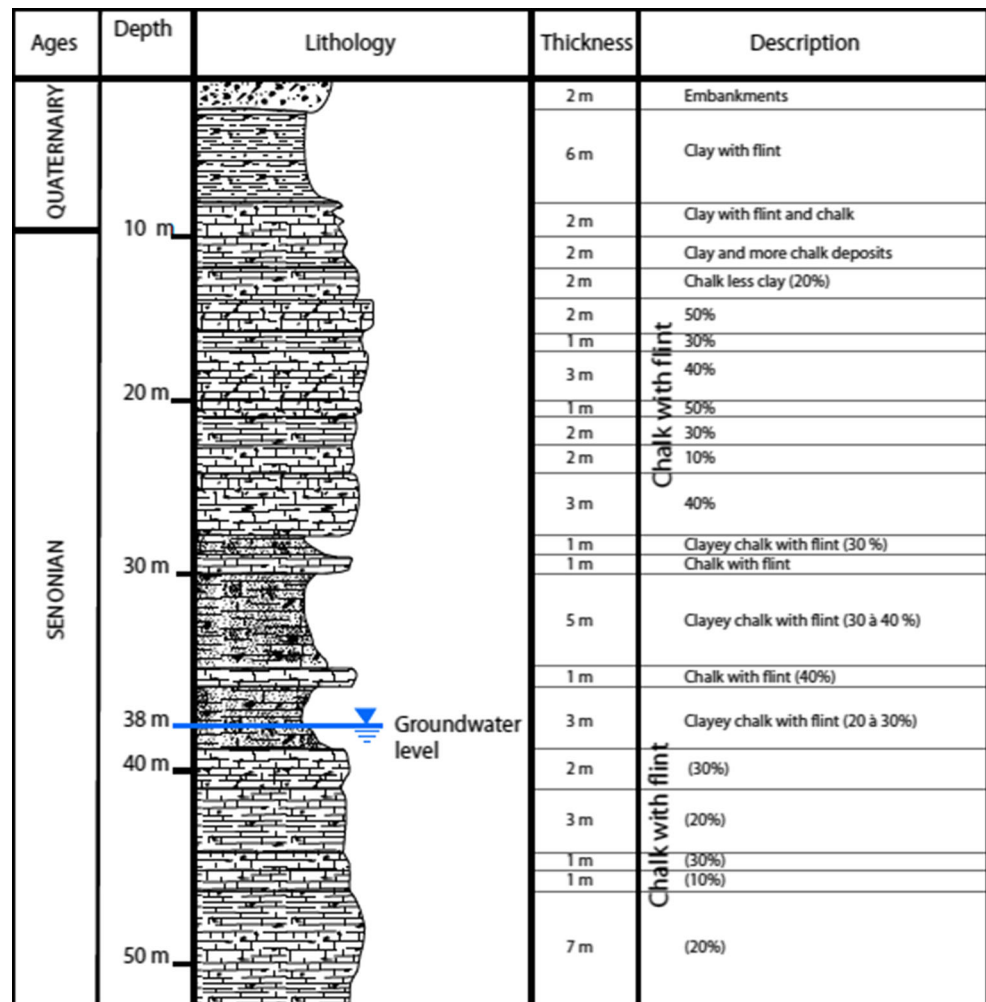


Table 3 Measurement points location of the fracturation in the watershed of Oise

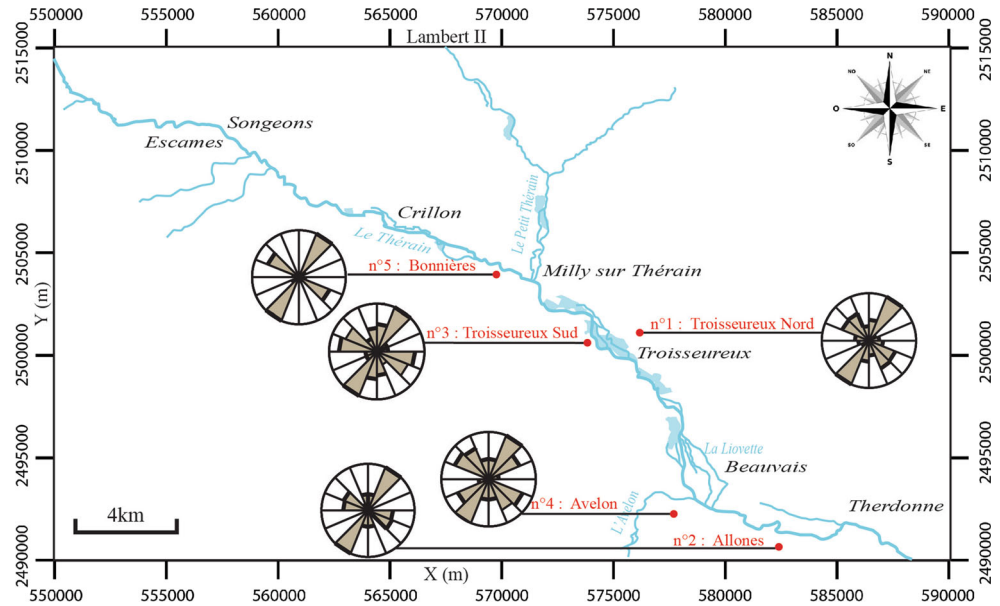
Quarry/outcrop	Extended Lambert coordinates II	Number of measurements	Date of measurements
No. 1	X: 580,113	117	09/2011
Troissereux-Clos Saint Maurice	Y: 2,498,305		
No. 2	X: 582,755	50	09/2011
Allonne-Bongenoult	Y: 2,488,719		
No. 3	X: 577,830	167	09/2011
Troissereux-Bracheux	Y: 2,497,442		
No. 4	X: 573,113	60	10/2011
Bonnières	Y: 2,500,720		
No. 5	X: 580,654	30	10/2011
Avelon	Y: 2,491,922		

results were interpreted to highlight the preferred orientations of fractures. The measurements were performed in five quarries and outcrops located close to the river Thérain. The details of these measurements are given in Table 3.

Three preferred orientations can be identified from the rosettes shown in Fig. 11. The first fracture orientation is

drawn NNE-SSW. This orientation is similar to the direction of many tributaries within the study area as Avelon or Liovette rivers. The second major fracture orientation is WNW-ESE. This is also the direction of the river before and after the Thérain River. The third important fracture orientation is N-S which is the orientation of the Small

Fig. 11 Fracturation directions in the study area of the Thérain



Thérain River between St-Omer-en-Chaussée and Milly-sur-Thérain.

In the porous media, the distribution of hydraulic conductivity and the lateral variation of deposits which compose the aquifer and which are deduced from the engineering geology methods (seismic interpretation and hydrogeological drillings analysis, Zouhri et al. 2004), can be controlled by faulting activity or the fracturation processes. The hydraulic conductivity is marked by two ranges: primary hydraulic conductivity which varies from 10^{-8} to 10^{-5} m/s. The secondary hydraulic conductivity ranges from 10^{-3} to 10^{-1} m/s (Domenico and Schwartz 1998). The variation of hydraulic conductivity value is recorded in the borehole which is composed by sand and chalk materials (Urban and Pasquarell 1992). The heterogenous distribution of the hydraulic conductivity is highlighted in several boreholes in USA (Urban and Pasquarell 1992) and is related to translate a significant drop in these hydrodynamic properties with depth. The distribution of the velocity shown in different layers of the chalk aquifer of the experimental site (Table 4) is governed by the hydrodynamical parameters:

1. The porosity of the chalk aquifer of the Beauvais aquifer: as a reservoir rock, the chalk is characterized by high porosity (25–50 %) and low permeability (Jorgensen and Andersen 1991). In the hydrogeological wells of the experimental site “Institut Polytechnique LaSalle Beauvais”, two formations have been recognized: soft and hard chinks in well 2 (the hard chalk has been recognized by SA RUCKERBUSCH, drilling company). Two types of porosity ranges are possible related to this vertical variation and the

Table 4 Relationship between the repartition of layers, the hydraulic conductivity, the Seismic velocity and fracture frequency by depth zone (Haeni 1986)

Layer depth (m)	Mean (K) (m/day)	Vp (m/day)	Ave. of fracture (m)
15–30	12.4	3500–7500	11
30–40	5	6500–9000	
40–50	2.5	9000–12,000	7.5
50–60	2.5	10,000–14,000	
60–70	1.7	10,000–15,000	4.5
70–80	0.8	12,000–16,000	
80–100	0.3	14,000–20,000	1.5

fissuring degrees: primary porosity (0.15–0.45) and secondary porosity (0.005–0.02) (Domenico and Schwartz 1998). The porosity shows significant regional and stratigraphic variations. The hydrogeological information about the complexity of the chalk aquifer is also obtained from other sites in England and from two thousand chalk porosity tests (Allen et al. 1997). The minima is varied between 3.3 and 24.1 %, the maxima between 31.4 and 55.5 % and the mean porosity is about 3.3–24.1 %. This variability is related to the median (d50) pore throat sizes for the data which was 0.49 μ m. Price et al. (1987) also identified a number of regional and stratigraphic trends in the Chalk pore size distributions from 104 samples: the mean pore size varied between 0.22 and 0.65 μ m. Our investigation takes into account the matrix and the texture of the chalk by using Scanning Electron Microscopy (SEM) analysis of the samples from the

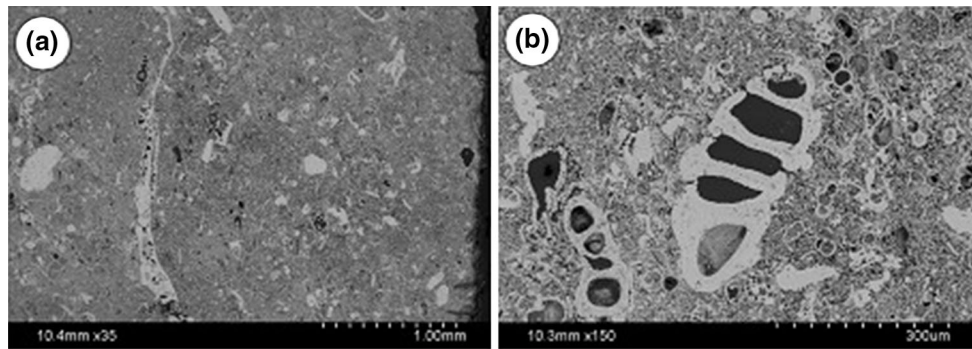


Fig. 12 Scanning electron microscopy (SEM) analysis of the chalk samples

outcrops near the experimental site. The chalk texture is wackstone type (Fig. 12a, b).

2. The carbonate matrix is dark, very fine and contains an intergranular microporosity. This chalk is exclusively bioclastic. Indeed, it is possible to observe Gasteropod such as *Heterohelix* and *Globotruncana Forminifera* (Fig. 12b) and other bioclastic elements. The porosity chalk from the experimental site is characterized by the SEM techniques. The porosity is intra-granular and about 25–30 %.
3. The degree of the fractures network connection that varied according to the depth (Table 3). The variations of the gamma-ray and the electrical signature are very complex in the chalk environment which constitutes heterogeneous aquifers. The decrease of the temperature is typically characteristic of the deeper waters. Indeed, in the shallow permeable aquifers the shallowest groundwaters are typically warmer than the deeper waters in the saturated zone during the summer, but cooler than them in winter (Younger 2007). Trend is observed for the groundwater between 5 and 150 m, considering that the water table in the study area is overall about 40 m. The abrupt change results from the transition unsaturated–saturated zone and the weak trend in the decline of the temperature in the saturated zone may be related to the temperature of the recharge waters or the water inflow from fractures of the chalk aquifer. The variations of the propagation velocity obtained from the seismic investigation (Fig. 4) and the variability of the electrical resistivity from the ERT sections (Fig. 5) reveal an heterogeneity in the distribution of deposits from soil to saturated zone. Dual-porosity fractured system with around 1 % and a matrix porosity of between 25 and 35 % (Price et al. 1993; Barker 1993; Zouhri and Lutz 2010) makes the complexity of the electrical repartition in the unsaturated/saturated zones. The presence of irregularities on the fissures (Price et al. 2000; Zouhri and Lutz 2010) can store the water. That might explain the spatial distribution of the electrical conductivity, notably in the

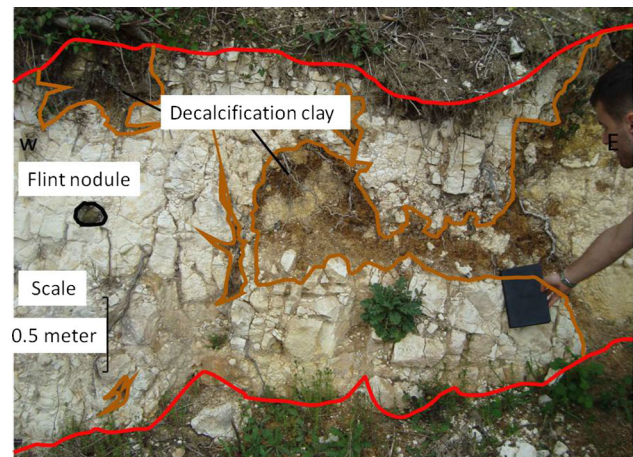


Fig. 13 Distribution of the fracturation in chalk formations (outcrop in the vicinity of Beauvais) and lateral variations of chert and clay (picture by Derely and Maceron 2014)

unsaturated zone. At this level and especially at the capillary fringe, the cuttings analyses show log irregularities highlight which the complexity of fractures network which is deduced from analysis outcrop around the Beauvais city (Fig. 13).

This vertical distribution of permeabilities which is not known until the hydrogeological test or for underground work (the Channel Tunnel, Lille underground), is proving very heterogeneous. In the northern part of France, in the Upper Turonian-Senonian chalk of the Channel Tunnel area, hydraulic conductivity values range from less than 10^{-8} – 1.7×10^{-2} m/s. Their vertical distributions are linked to cross fractures or open bedding planes (BRGM 2015). Preliminary investigations which were conducted in the chalk experimental site of LaSalle Beauvais by using the magnetic resonance sounding (MRS) (Lutz and Zouhri 2015) was employed in attempt to better to understand the variability of the hydrodynamical characteristics as function of the investigation depth. Indeed, the transmissive nature of the chalk aquifer of the study area is materialized by the transmissivity that

varied between 0.0015 and 0.45 m²/s while the vertical hydraulic conductivity is varied between 2×10^{-5} and 2×10^{-2} m/s (Lutz and Zouhri 2015). In contrast, the horizontal distribution of hydraulic conductivity is often correlated with the geomorphological features of the area, the most permeable areas generally corresponding to the drainage axes, themselves often linked to the development of directional fracturing (dry valleys, humid valleys under alluvium).

Conclusion

The combined hydrogeophysical approaches which are used to characterize the chalk aquifer near the “Institut Polytechnique LaSalle Beauvais” allowed to study the relationship between the variation of the physic-chemical parameters deduced from the well logging techniques, the lithology distribution obtained from the cutting analysis and the fracturation measured from the outcrop near the experimental site of LaSalle Beauvais. The repartition of the seismic velocities and the electrical resistivity highlights the heterogeneity of the chalk aquifer of the northern part of the Beauvais city (Oise). The identification of fissures which are deduced from the hydrogeophysical investigations (ERT analysis and fracturation measurements) in the field plays an important role in the comprehension of the repartition of the hydraulic conductivity and the physico-chemical parameters: the evolution of the conductivity, the temperature and natural radioactivity coupled to the seismic refraction and electrical resistivity tomography investigations provides a better characterization of the chalk aquifer.

The core drilling of the 110 m of depth which was realized lately in this experimental site will be the subject of future works on the frequency of fracture according to the depth. Our hydrogeological investigations of the chalk aquifer will use: (1) the MRS coupled with ERT in order to quantify the vertical variation of the water content, (2) the hydraulic conductivity and the transmissivity of the hydrogeological formation and (3) to determine favorable sectors for water exploration and management in the northern part of Paris Basin.

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