Contribution of stratigraphy to groundwater motion understanding in chalk: examples of karstogenic horizons of the Pointe de Caux, France

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Abstract: Chalk groundwater is the main renewable drinking water resource for many cities of the Paris–London Basin. Understanding karst groundwater motion enhancement appears to be a major issue in order to better protect drinking water, to define hydrogeological surveys and to explore the aquifer. In Normandy, the stratigraphy of chalk was investigated in the 1970s and 1980s but this newly developed stratigraphy was not introduced to hydrogeology where chalk aquifers are studied without considering the sequence boundaries and key event surfaces. Upper Normandy is a unique hydrogeological region where both stratigraphy and hydrogeology can be studied together. In this article we focus on field observations and their direct application to scientific theory. Eight hydrogeological surfaces, linked to sequence boundaries or key event surfaces, are identified. They increase porosity and permeability sufficiently to develop karstic features, hereafter called karstogenic horizons. These field observations lead us to propose a new stratified chalk groundwater model. Palaeokarsts and perched springs not aligned to the current base level can be explained from a geodynamic perspective. Global eustatism and regional uplift during the Quaternary Period have to be taken into account with the hydrogeological stratified model, as the controlling factors of the groundwater motion and the karstogenic horizon development. This theory will help hydrogeologists to determine the probability of encountering palaeokarsts above the piezometric level and thereby define well locations with a greater degree of confidence according to the karstogenic horizon drilled. Chemical studies may also be applied to show if this stratified model can enhance water quality by a new well design.

Hydrogeological characterization of a sedimentary basin aquifer is mostly formulated on stratigraphy. Following this concept, sometimes groundwaters are named after the lithostratigraphic unit that constitutes the aquifer: Albian groundwater (Paris Basin), Maastrichtian aquifer (Benin gulf) or Mississippian aquifer (USA). Based on this concept, Maxey (1964, p. 124) defined hydrostratigraphic units as ‘bodies of rock with considerable lateral extent that compose a geologic framework for a reasonably distinct hydrologic system’. Seaber (1988, p. 13) completed this definition with the introduction of hydrodynamic parameters. Hydrostratigraphic unit definition is then identified as ‘a body of rock distinguished and characterized by its porosity and permeability’. Upper and lower limits of these units were neglected until Klimchouk (2007) defined the concept of ‘low permeability beds’.

From a sequential stratigraphic point of view, system tracts are also ‘bodies of rocks’ limited by surfaces that are fundamental because they explain the geometric and temporal organization of depositional sequences (Yapaudjian 1972; Mitchum *et al.* 1977; Vail *et al.* 1977; Homewood *et al.* 2002; Catuneanu *et al.* 2009). Sequential stratigraphy use in hydrogeology is limited and the two concepts of ‘bodies of rocks’ retain their own definitions. However, sequential stratigraphy better constrains system tracts to be able to form hydrostratigraphic units. Thus, this correction allowed authors to reconsider clastic sediment geometries with the aim of a new conceptual model for groundwater flow (Hansen 1971; Sugarman and Miller 1997; Edington and Poeter 2006; Aunay 2007; Sharling *et al.* 2009; Velasco *et al.* 2012). System tracts could also explain the localization of high-transmissivity bodies such as gravel channels in a deltaic environment (Weissman and Fogg 1999) or on the platform (Stone 1981).

Despite their importance in sequential stratigraphy, sequence boundaries are rarely studied in hydrogeology. In some cases, their existence is highlighted to explain saltwater invasion in coastal

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environments (Nikishiwa *et al.* 2008), horizontal karst formation (Esteban and Klappa 1983; Audouin *et al.* 2008; Bosák 2008) and intrinsic permeability variation inside oil reservoirs (Reynolds 1993).

The object of this article is to study the role of stratigraphic surfaces (and more specifically sequence boundaries) as low-permeability beds under Klimchouk's definition, or high permeability beds. As the Paris Basin has a record of sea-level fluctuations since the Triassic Period, depositional sequences are well known and stratigraphic charts are defined, especially during the Cretaceous (Hardenbol *et al.* 1998; Jarvis *et al.* 2006). The cliffs of Pointe de Caux (Upper Normandy, France), in this view, constitute an exceptional hydrogeological site to study because both stratigraphic surfaces and springs can be identified in the same outcrop, and characterized by taking into account the condition of fractures and boundaries within the aquifer (Gaillard and Hauchard 2018). The Seine valley and coastal cliffs have been studied with the object to prove the existence of karst development in chalk (Martel 1908; Lepiller 1975; Calba *et al.* 1979; Rodet 1991*a*). Except for Juignet (1988), geologists attributed the karst in the chalk to tectonic stress such as vertical fractures and faults (Belgrand 1872; Foster and Milton 1974; Bloomfield 1996). Rodet (1991*a*) reconciled his own observations and the fracture theory by qualifying caves along the cliffs as 'restitution karst' in opposition to the 'introduction karst' that is due to sinkholes and fissured chalk. The generalized model of a karst network in chalk was then constituted of the two forms of karst defined by Rodet. This conceptual model was then summarized in some schematic geological sections where 'restitution' karsts are horizontal but with a random distribution of depth in the chalk (Laignel 1997; Masséi 2001). On the other side of the Channel, this model was reinforced in accordance with the English stratigraphy of the chalk. For example, some flowing features coincide with horizons that suggest a lithostratigraphic control (Schürch and Buckley 2002; Maurice *et al.* 2012). More recently, English and French hydrogeologists recognized some horizons that control karstification (Gaillard *et al.* 2012, 2019; Farrant *et al.* 2021, 2022). This article deals with the stratigraphic control of restitution karst in Upper Normandy in order to enhance water well design and groundwater models.

Study area and chalk stratigraphy

This study focuses on Pointe de Caux (Upper Normandy, France), which takes the form of a triangle limited by the Fécamp–Lillebonne fault, the Seine valley and the shores of the Channel (Fig. 1). The Upper Cretaceous chalk is exposed in the cliffs from Le Havre (Cenomanian) to Fécamp (Coniacian) and on the right bank of the Seine (Fig. 2).

Passy (1832), Lesueur (1843) and Lennier (1870) were the first to describe the stages of the Upper Cretaceous based on palaeontological divisions. Juignet (1974) revised the Cenomanian stratotype in the Pays de Caux on the basis of discontinuities (especially hardgrounds), and Ragot (1988) completed this approach for the Turonian and Coniacian along the Fécamp–Lillebonne fault. These two authors defined 20 depositional sequences bounded by hardgrounds (HG). More recently, Hoyez (2008) defined other event surfaces. Some examples of these surfaces are shown in Figure 3.

In sequential stratigraphy, hardgrounds correspond to marine erosion surfaces (regressive surface of marine erosion), transgressive surfaces or regression surfaces following the current standard terms (Catuneanu 2006; Embry 2009). Glauconite-rich hardgrounds with shell deposits are also associated with maximum flooding surfaces (Grant *et al.* 1999; Mortimore 2011). These studies of the chalk hardgrounds give rise to divergent interpretations in terms of sequences (Lasseur 2007; Mortimore 2011). Notwithstanding these sedimentological discussions, discontinuities are well identified both in Normandy (Juignet 1974; Ragot 1988; Juignet and Breton 1992, 1994; Hoyez 2008, 2013) and the UK (Mortimore 1983; Grant *et al.* 1999; Mortimore *et al.* 2001). Figure 2 presents the lithostratigraphical log of the Pointe de Caux with main surfaces and depositional sequences from Juignet (1974), Juignet and Breton (1992) and Ragot (1988) for the Cenomanian and Turonian stages. For the Coniacian, the authors refer to Ragot (1988), Quine (1988), Juignet and Breton (1992, 1994, 1997), Hoyez (2008) and Mortimore (2011). Correlation between the Coniacian cliffs in the Seine valley and the Channel shores is hypothetical, based on hardground successions, dolomitic facies and sedimentological figures. Thirteen hardgrounds are identified as sequence boundaries.

At the base of the series, Cenomanian chalk is composed of three formations (Glauconitic chalk, Craie de Rouen and Craie d'Antifer) and five depositional sequences (Juignet and Breton 1992; Hardenbol *et al.* 1998). For our purpose, special attention is drawn to two sequence boundaries (SB): (i) Bruneval 1 HG (see SB2 in Fig. 2) highlighted by black flints sometimes eroded (Bruneval flint), and (ii) Antifer HG (similar to SB4), below which Antifer marl and Antifer flint are present. The Cenomanian upper limit is assumed to be supported by Antifer 3 HG (Ragot 1988; Hoyez 2008).

The Turonian chalk is composed of two formations above Antifer 3 HG: the Tilleul formation (ending with the Craie du Val Saint-Nicolas member) and the Etretat member of the Etretat complex of

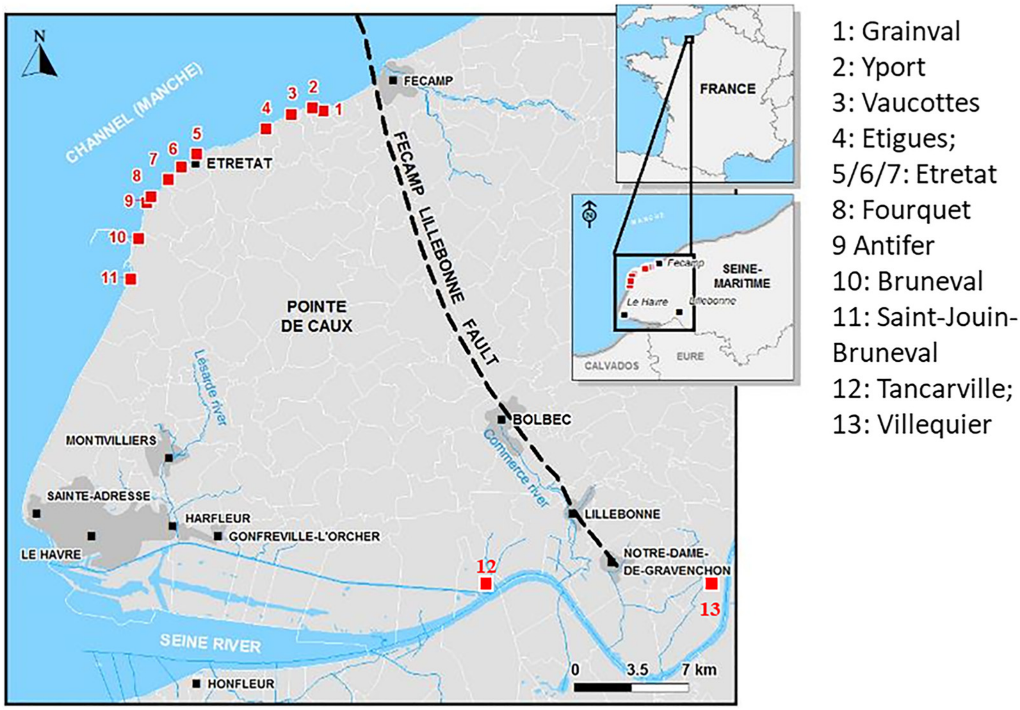

Fig. 1. Geological setting and location of the studied sites.

Mortimore (2011). The Tilleul formation retains a regular horizontal bedding. In the Etretat complex, sedimentation is marked by mounds and channels that erode the inferior sequences and are capped by discontinuous hardgrounds. Consequently, boundaries are not well defined and difficult to correlate. Nevertheless, one hardground has a regional extension and has been identified in the Tancarville cliffs (Ragot 1988) and coastal cliffs (Hoyez 2008). This is the Senneville hardground (Quine 1988) that marks the end of the dolomitic chalk of Etretat, here correlated with the Gravenchon 2 HG of Ragot, at the base of *Sternotaxis plana* chalk. Without ammonites, the Turonian upper boundary is correlated with the Pierre de Beuzevillette described by Ragot (1988) in the Seine valley and the Craie Rousse de Chicard (Gaillard *et al.* 2012) with the appearance of *Micraster normanniae* (Bailey *et al.* 1984; Ragot 1988). A typical bioturbated hardground is present at the top of this second dolomitic member: Chicard HG (Gaillard *et al.* 2012) is correlated with the Banc à Cuves HG (Juignet and Breton 1997) and, with some uncertainty, with Beuzevillette 3 HG in the Seine valley (Ragot 1988).

In Coniacian chalk, the sedimentation takes the same form of mounds, observable at the top of the Etretat cliffs. The Etretat complex ends with the member named here as Yport. Three hardgrounds are particularly well developed: (i) Bancs à Cuves HG (Juignet and Breton 1997), (ii) Belval HG assimilated, with some uncertainty, to Radicatel 1 HG (Ragot 1988; Hoyez 2008) and (iii) Etigues HG (Hoyez 2008).

From a marly bed developed in the Yport cliff (Les Loges marl *in* Hoyez 2008) and accompanied by vertical massive flints above (the paramoudras of Juignet and Kennedy 1976), chalk sedimentation returns to a horizontal bedding alternation of chalk and flint (post-Etretat complex of Mortimore 2011). The Upper Coniacian chalk retains this sub-horizontal stratification and presents other hardgrounds at the end of the sequence (Vattetot HG, Yport HG, Criquebeuf HG and Grainval HG in Hoyez 2008).

The total thickness of chalk from Cenomanian to Coniacian is about 200 m in the Pointe de Caux area.

Hydrogeological data

Methods

This study is based on three sets of observations and measurements: hydrostratigraphy of springs, stratigraphy of caves and core sampling associated with borehole logging.

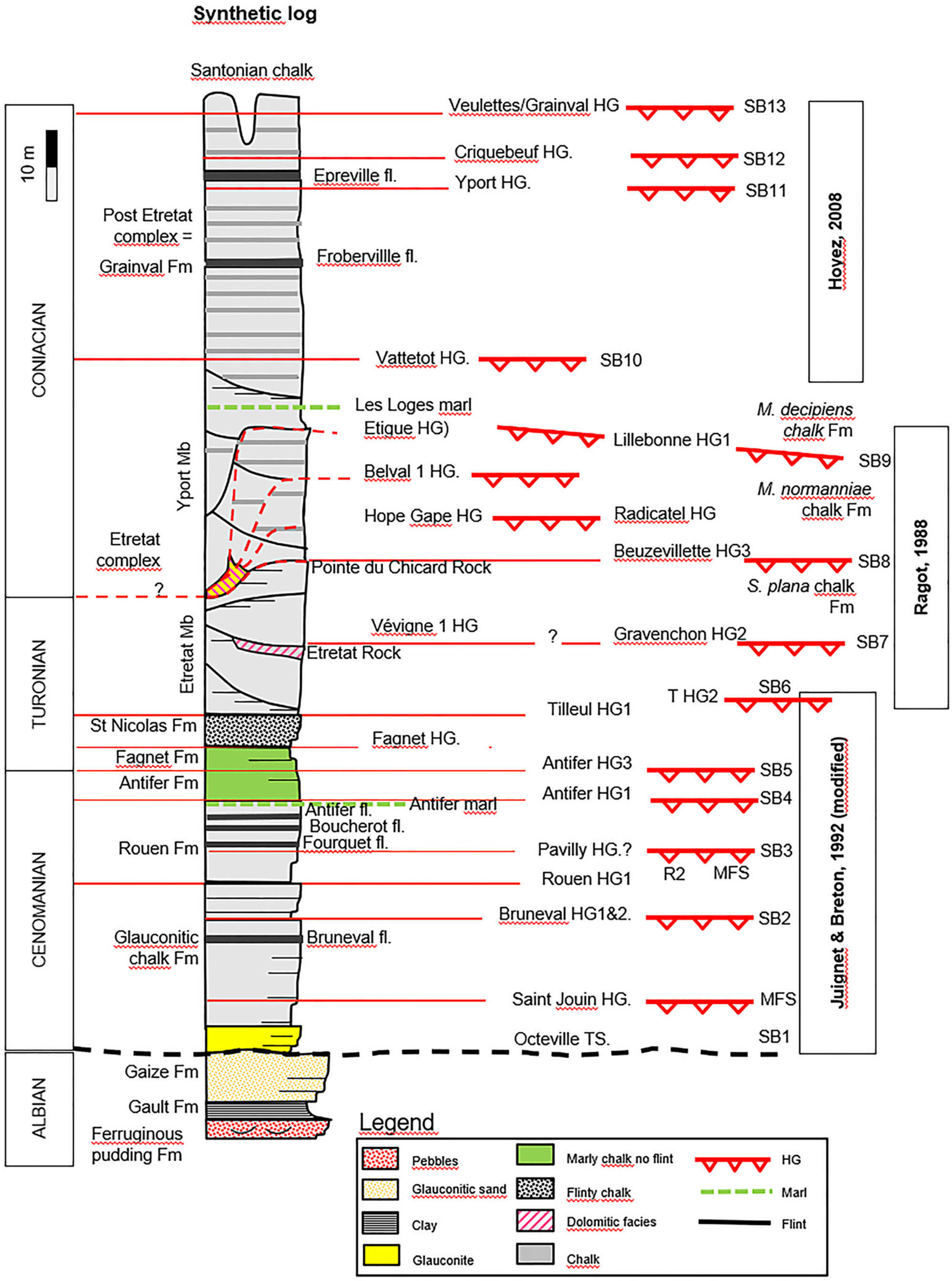

Fig. 2. Stratigraphic log of Pointe de Caux. Source: modified from Gaillard *et al.* (2018).

For each site, stratigraphical calibration was made strata by strata following the methods of Juignet (1974) and Ragot (1988). Stratigraphical description included lithological description and identification of discontinuities following the typology of Juignet and Kennedy (1976). Key surfaces were bioturbated erosion surfaces, ferruginous surfaces or nodulous chalk with diagenetic nodules (Juignet 1974; Kennedy and Garrison 1975). Flint strata and marl strata were also taken into account

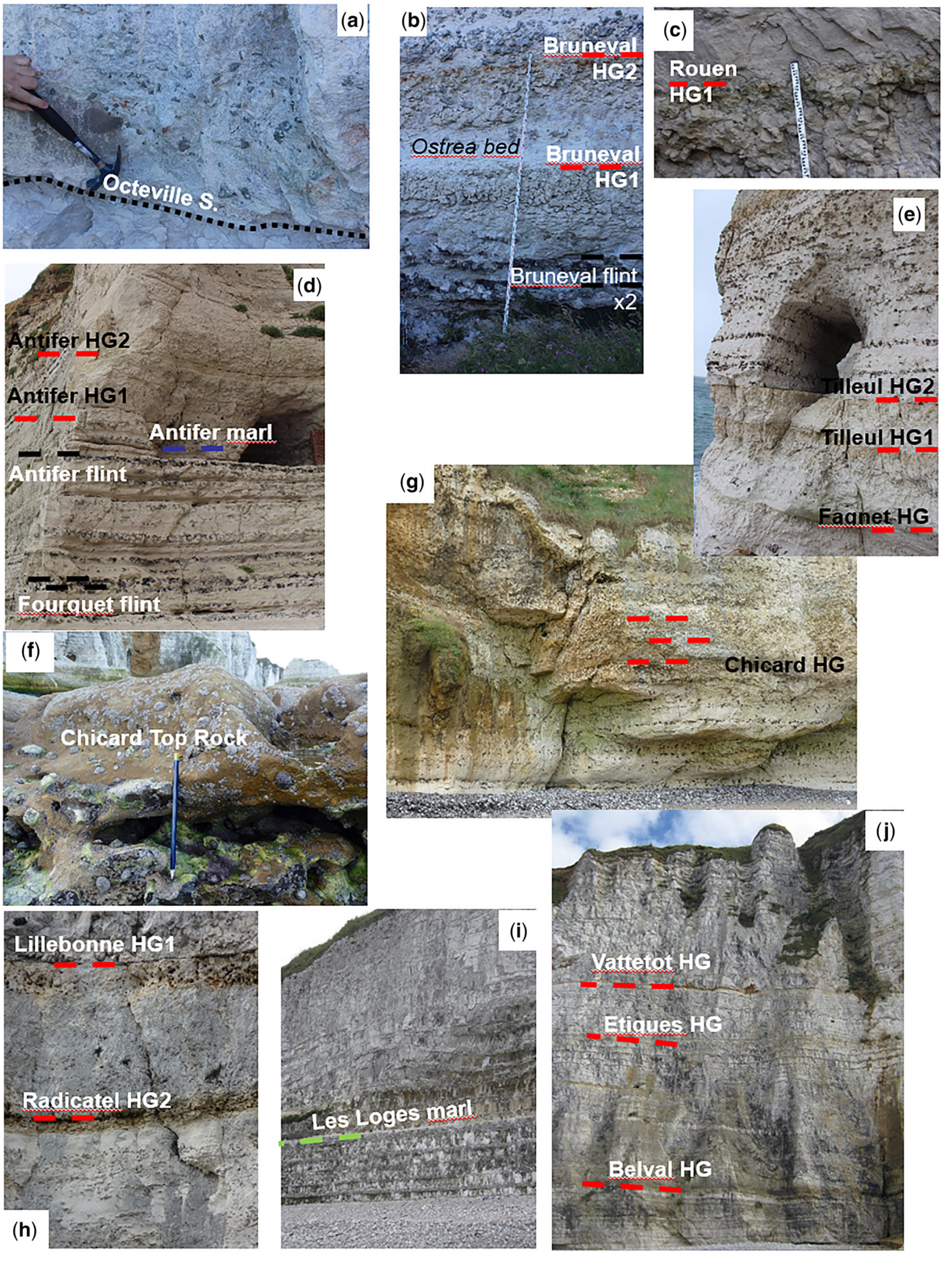

Fig. 3. Various aspects of the studied stratigraphic surfaces. (**a**) Octeville surface (Saint-Jouin-Bruneval cliff); (**b**) Bruneval HG (Bruneval cliff); (**c**) Rouen 1 HG (Saint-Jouin-Bruneval cliff); (**d**) Antifer chalk (Antifer cape); (**e**) Tilleul HG (Fourquet cape); (**f**) Chicard top rock (Pointe du Chicard); (**g**) Turonian/Coniacian chalk (Fond d'Etigues); (**h**) Coniacian HG (Tancarville cliff in Seine valley); (**i**) Les Loges marl (Yport cliff); (**j**) Various coniacian HG (Vaudieu cliff).

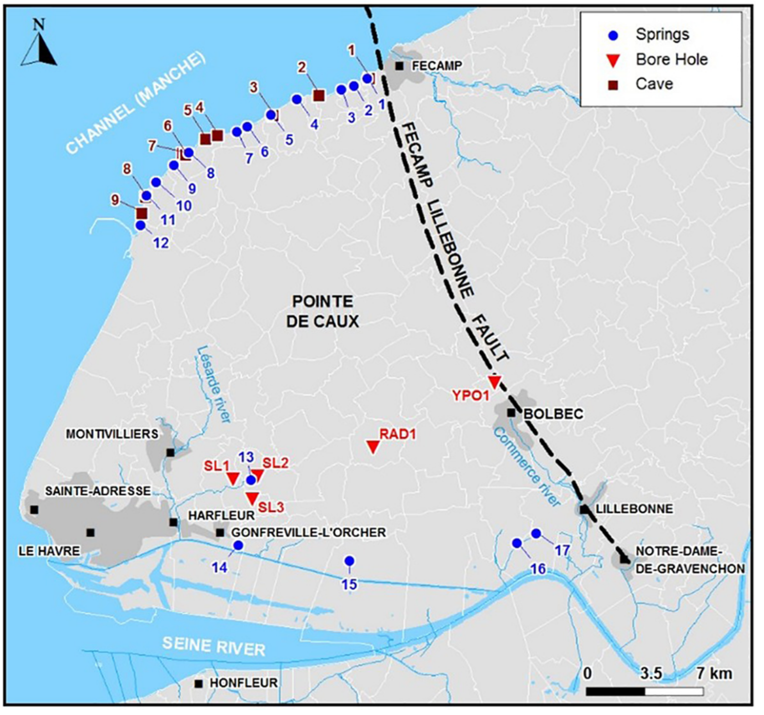

Fig. 4. Location of studied boreholes, cavities and springs.

and the corresponding key surfaces refer to Hoyez (2008). The strata description is also based on sedimentological components such as fossil accumulation (Horizon de Rouen), mineralogy (glauconite, phosphates, quartz) and lithology (chalk, marl, flint, dolomite). Where the outcrops were extended enough, key surfaces were followed to study their geometries (in the Etretat complex especially). The study did not benefit from micropalaeontology determination.

These field observations were completed with five core samples, east of Le Havre, and approximately in the middle of Pointe de Caux (Fig. 4). At each borehole the logging programme included BoreHole TeleViewer (BHTV), 16/64 normal resistivity, single-point resistivity (SPR) and gamma-ray resistivity (GR).

All sites studied are mapped in Figure 4.

Cave and karstic conduit stratigraphy

The chalky plateau forms capes on the coast, called ‘pointes’ in Normandy, which are favourable for cave exploration. The capes that were studied are Pointe du Chicard, Porte d’Amont, Porte d’Aval, Pointe de la Courtine at Etretat, Pointe du Fourquet and Cap d’Antifer (Fig. 1). These cliffs allow caves and conduits to be observed. Galleries were sometimes dug inside the cave entrances. Between Yport and Fécamp, the caves are located at the top of the cliff, above the Froberville flint key surface. The cavities and horizontal karstic features observed are shown in Figure 5 and listed in Table 1.

The caves and conduits observed are based on key surfaces fully identified in the lithostratigraphical log of the Pointe de Caux (Fig. 2). From the Cenomanian to Coniacian, these surfaces are the Bruneval HG (and flint associated), the Antifer flint–Antifer marl pair, Tilleul HG, Etretat rock and Senneville HG, Chicard rock and Banc à Cuves HG. These karstic figures are not distributed in a haphazard way but are associated with sequence boundaries that are hardgrounds and related diagenetic facies. The stratigraphy *pro parte* constrains the location of the restitution karsts as defined by Rodet (1991*a*). Indurated surfaces act as the ‘low permeability beds’ of Klimchouk (2007) and favour horizontal groundwater motion. When these beds are eroded, the caves typically take the form of a keyhole. The authors also observed, on occasion, that roots of buried dolines stop on hardgrounds (Sandouville quarry, Tancarville cliff). This observation

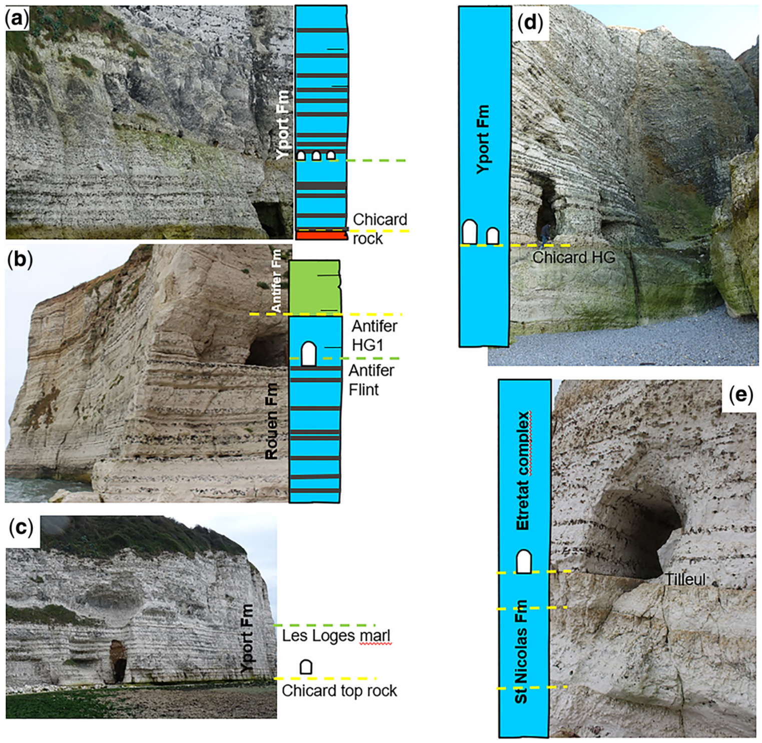

Fig. 5. Some observed cavities. (**a**) Yport (East); (**b**) Fourquet Cape; (**c**) Yport (West); (**d**) Etretat, Chaudron cavity; (**e**) Tilleul beach cavity.

leads to the conclusion that exportation of dissolved minerals became horizontal when the dolines intercepted a well-developed karstic horizon above hardgrounds. Another characteristic observation is the plane distribution of little conduits above hardgrounds and marly strata (see Les Loges marl, Fig. 5a).

These observations are listed in Table 1 and some of them are presented in Figure 5.

Spring stratigraphy

The chalk aquifer of the Pointe de Caux is drained by four main spring groups, which are: (i) Saint-Laurent

Table 1. *Location of cavities observed and associated key surfaces*

No.	Cavities	Longitude	Latitude	Flow	Formation	Stratigraphic surface
1	Grainval	49.7507	0.347242	Perched conduit	Coniacian	Froberville flint
2	Yport	49.7405	0.30615	Palaeokarst	Coniacian	Chicard/Belval (top rock)
3	Etigue conduit	49.7294	0.267717	Karst conduit	T/C	Chicard HG
4	Trou à la Mine	49.7178	0.222374	Spring	Coniacian	Belval HG1
5	Chaudron, Etretat	49.7153	0.212546	Palaeokarst	Coniacian	Chicard HG
6	Trou à l'Homme	49.7069	0.196131	Palaeokarst	Turonian	Chalk Rock/Tilleul HG
7	Etretat, Porte d'Aval	49.7073	0.193541	Karst conduit	T/C	Chicard HG
8	Antifer cave	49.6832	0.163781	Palaeokarst	Turonian	Tilleul 2 HG
9	Grotte Aux Pigeons	49.6744	0.161016	Karst conduit	Cenomanian	Bruneval 1 HG

T/C, Turo-Coniacian.

Table 2. *Stratigraphy of the springs*

	Springs	Longitude	Latitude	Elevation	Formation	Stratigraphic surface
1	Renneville W	49.7504	0.345474	Perched in the cliff	Coniacian	bypass
2	La Bonne Pierre	49.7462	0.334625	Perched in the cliff	Coniacian	Les Loges marl
3	Source Yport C	49.744	0.324485	Under the sea level	Turo-Coniacian	boundary T-C ?
4	Vaucottes	49.7382	0.287326	On the beach	Coniacian	Fissured cliff
5	Fonds d'Etigue	49.7291	0.266306	On the beach	Coniacian	Chicard HG ? boundary T-C
6	Fontaine aux Mousses	49.7223	0.246394	Perched in the cliff	Coniacian	Belval HG
7	Pisseuses de Bénouville	49.7193	0.238004	Perched in the cliff	Coniacian	boundary T-C ?
8	Etretat 'river'	49.7076	0.198516	On the beach	Turonian	Tilleul HG
9	Pisseuse de Valaine	49.7007	0.186615	Perched in the cliff	Turonian	Chalk rock/Tilleul HG
10	Pisseuses de La Place	49.691	0.172123	Perched in the cliff	Cénomanian	Antifer marl/Antifer flint
11	Source du phare Antifer	49.6836	0.164199	Into the cliff base	Cénomanian	Under Fourquet flint
12	Source de Bruneval	49.6675	0.160015	Into the cliff base	Cénomanian	Bruneval flint
13	Saint Laurent, Petites Sources	49.5314	0.257417	Alluvial plain	Cenomanian	Bruneval HG/flint
14	Chateau d'Orcher	49.496	0.248261	Perched in the cliff	Cenomanian	Antifer marl/Antifer flint
15	Sandouville quarry	49.4893	0.340936	Perched in the cliff	Cenomanian	Antifer marl/Antifer flint
16	Bruisseresse (Radicatel)	49.5011	0.479642	Into the cliff base	Turo-Coniacian	boundary T-C ?
17	Moulin B (Radicatel)	49.5067	0.495349	Into the cliff base	Turo-Coniacian	boundary T-C ?

T-C, Turo-Coniacian.

springs (300 l s^{-1}), (ii) Radicatel springs (500 l s^{-1}), (iii) Yport submarine spring (2400 l s^{-1}) and (iv) Etretat submarine springs (not gauged). The groundwater circulation has been studied by numerous dye tracer-tests, which provide apparent velocities from 10 to 450 m per hour. These results prove the karstic flow component of the Pointe de Caux chalk. Chalk cliffs help to determine the local stratigraphy of these main springs, except for the Saint-Laurent springs, which were studied by core sampling. Other perched springs, called 'pisseuses' in Normandy, are easy to place in the lithostratigraphical context of the Pointe de Caux because they occur on cliffs. Springs are shown in Figure 4 and described in Table 2.

At the top of the Craie de Rouen, the Sandouville quarry springs emerge between the Antifer flint and the Fourquet flint. Other springs are observed in Cap d'Antifer, in exactly the same stratigraphic position. The Antifer 1 HG–Antifer marl pair and Fourquet marl, between these two flints bands, could act as lower permeability beds at the end of sequence 4 (SB4, Fig. 2). During field investigations, other small springs were located above the Bruneval flint or the Fourquet flint, and the La Place perched springs emerge exactly on the Antifer marl hollow joint (Gaillard *et al.* 2018).

The Etretat spring emerges at low tide and is associated with Tilleul 2 HG at the end of sequence 6. The Etretat spring is the resurgence of the Etretat river, which disappeared in the seventeenth century (Parmentier 1890). The 'restitution' karst is, therefore, constrained by both the Channel level and the Tilleul hardgrounds, at approximately the same altitude in Etretat. Not far from Etretat, the Valaine perched springs are typical 'pisseuses' flowing just above Tilleul HG (end of SB6).

The Yport spring, Radicatel springs and Etigues springs are located above Chicard top rock, associated with hardgrounds that are sometimes coalescent (Banc à Cuves HG/Chicard HG), probably at the Turonian–Coniacian limit. This limit forms the bottom of a great karst with an approximate total discharge rate of 2000 l s^{-1}.

Following this is the Fontaine aux Mousses spring, perched above Belval HG, in a syncline position (Gaillard *et al.* 2019).

As was observed for cave locations, springs are not distributed in a haphazard way inside the chalk. They are concentrated near sequence boundaries where low permeability beds, constituted by hardgrounds and marl strata, are present.

Some of these field observations are reported in Figure 6, with a blue arrow for a spring.

Core sampling and logging data

Inland, some core samples were taken by the Le Havre Seine Métropole Urban Community in order to more accurately define the hydrostratigraphical context of the Saint-Laurent springs (Fig. 4, Table 3) and the distribution of Upper Cretaceous stages from Le Havre to the Fécamp–Lillebonne fault. In two boreholes (YPO1 and SL1, Fig. 7), flowmeter observations were taken to determine

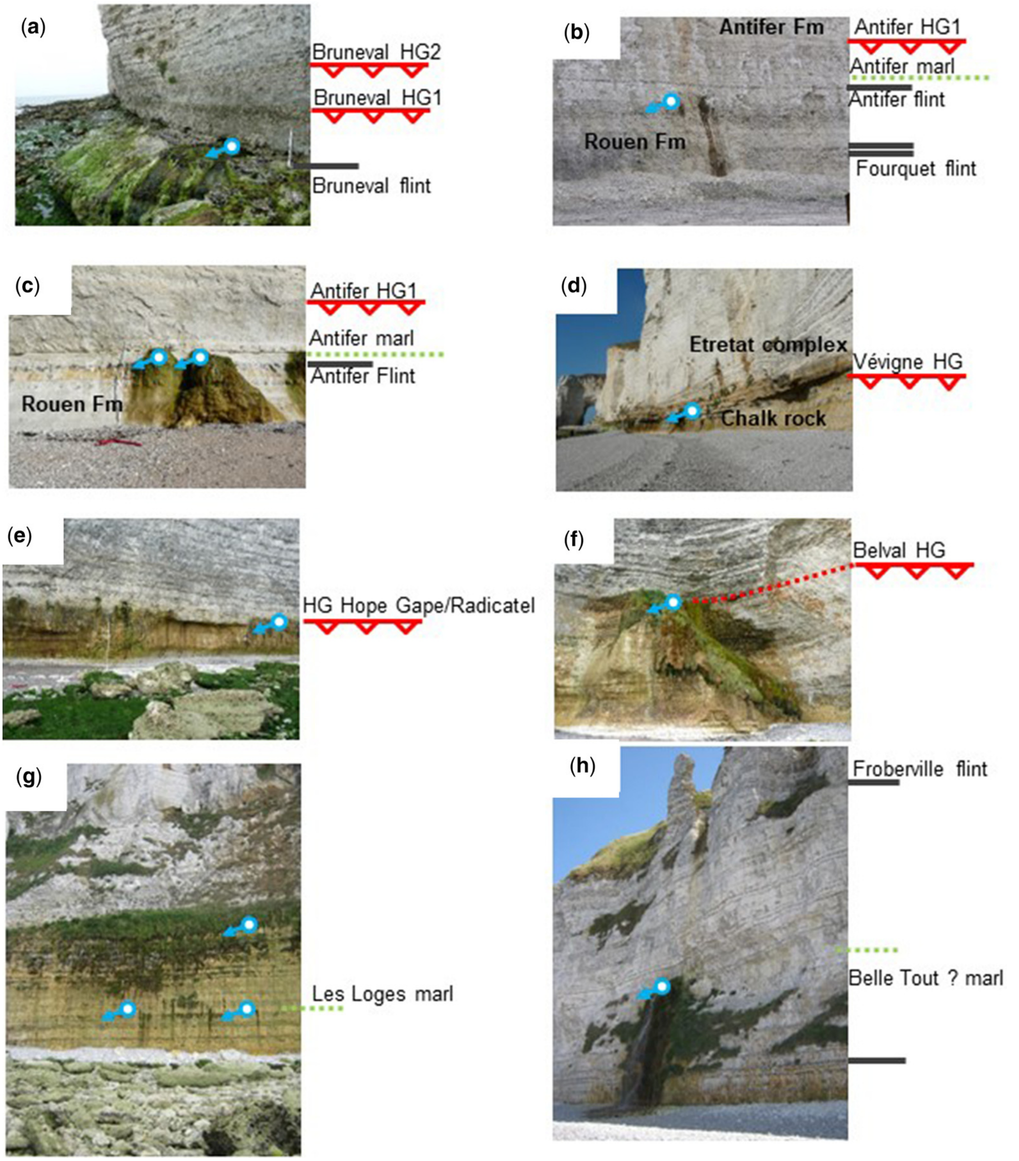

Fig. 6. Some observed springs. (**a**) Bruneval spring, (**b**) Sandouville quarry; (**c**) La Place springs; (**d**) Valaine springs; (**e**) Bénouville springs; (**f**) Fontaine-aux-Mousses spring; (**g**) Roche-qui-pleure springs; (**h**) Renéville spring (by-pass).

Table 3. *Core sampling location and depth*

Name	Commune	Longitude	Latitude	Elevation (NGF) above mean sea level (m)	Depth (m)
SL1	Saint-Martin-du-Manoir	49.53187	0.242788	90	120
SL2	Saint-Laurent-de-Brévedent	49.534098	0.262701	41	66
SL3	Gainneville	49.521675	0.259139	98	110
RAD1	Gommerville	49.55128	0.358368	125	165
YPO1	Nointot	49.589325	0.462300	75	94

NGF, Nivellement Général de la France.

the location of water inflow. Logging results (gamma ray and resistivity) were used to correlate the borehole data but are not included in this article.

In each borehole, the Cenomanian chalk is easily identified between the Octeville surface and the Antifer hardground 3 of Ragot (1988). This last-mentioned hardground is supposed to materialize in the Cenomanian–Turonian transition. In core samples, dissolution figures appear under the Antifer flint (SL2) with conduits filled by silts. Cross-sections between SL1, SL2 and SL3 boreholes help to identify the base level of the Saint-Laurent springs as the upper Cenomanian doublet Antifer flint and Antifer Hardground 1 (Grandes Sources, Petites Sources, Pruniers and Durécu). This key surface is at 24 m above sea level.

Another important lesson from the core sampling programme concerns the Cenomanian chalk. Although the discharge rate during vertical flowmeter testing is not significant (1 m^3 per hour), water inflow induces a clear velocity increase in the borehole. In the YPO1 borehole, the water inflow was registered on the Octeville surface (bottom of Cenomanian glauconitic chalk) and just above two flint beds (thought to be the Bruneval flints). In the SL2 borehole, the main water inflow corresponds once again to chalk just above the Bruneval flints. The results of the core sampling and flowmeter logging are summarized in Figure 7. RAD1 is the most complete with 140 m of chalk cores, and a water level on the Beuzevillette HG3. This means that the main horizontal karst horizon drains the upper part of the aquifer at this point. Turonian chalk is saturated in the east, where the speed of dye tracer tests are the most significant, and the first main, saturated karstic horizon is linked to Tilleul HG at this point.

Discussion

The results obtained can be discussed in terms of speleogenesis control factors from a geodynamic perspective.

The main object of the study was to understand the distribution of water motion in chalk in order to enhance groundwater protection and to adapt prospecting and drilling programmes.

Speleogenesis control factors are largely debated by hydrogeologists and karstologists (Salomon 2000; Ford 2003). The four stages development theory (Ford and Williams 1989; Ford 2000) introduces the importance of fissured zones, a phenomenon currently acknowledged to explain the karstogenesis of chalk in the Pointe de Caux area since the first cave explorations (Martel 1908; Sion 1909). Nevertheless, other recent cave descriptions do not confirm this model in the conduit genesis at a local scale (Willems *et al.* 2003; Rodet *et al.* 2013). In the Pointe de Caux area, the coastal springs of Etretat and Yport and other perched springs emerge in a non-fissured chalk. Faults were suggested to explain the location of the Radicatel springs' location (Ragot 1988; Hanin 2010), but after examination of the stratigraphy of the Tancarville cliffs, the springs were found not to be directly related to the faults, which are more than 500 m apart. Our observations of caves and springs in chalk cliffs lead us to discuss the hydrogeological base level as a speleogenesis boundary condition. Indeed, some spring levels do not coincide with palaeofluvial levels in the Seine Valley or the Channel coast (Rodet 1991*b*; Bauer 1996). Therefore, current perched springs reveal that lithology is fundamental to understanding their disconnection with present sea level. In order to explain the vertical spring succession, Lowe and Gunn (1997) proposed the concept of 'inception horizons', defined as a stratigraphical level more sensitive to vuggy formation than the other parts of the aquifer. The work of Lowe and Gunn focused on harder limestones with very low primary porosity and permeability. In chalk, the situation is different because chalk has very high primary porosity (15–45% in Quine 1988; Rodet 1991*a*; Saïag 2016; Gaillard *et al.* 2018). Therefore, in Upper Normandy, hardgrounds and some key surfaces play a similar role by limiting vertical motion and favouring sub-horizontal restitution with karst development. Thus, in a 150 m thickness chalk log this study identified several karstogenic horizons explained by successive vertical karstic planes:

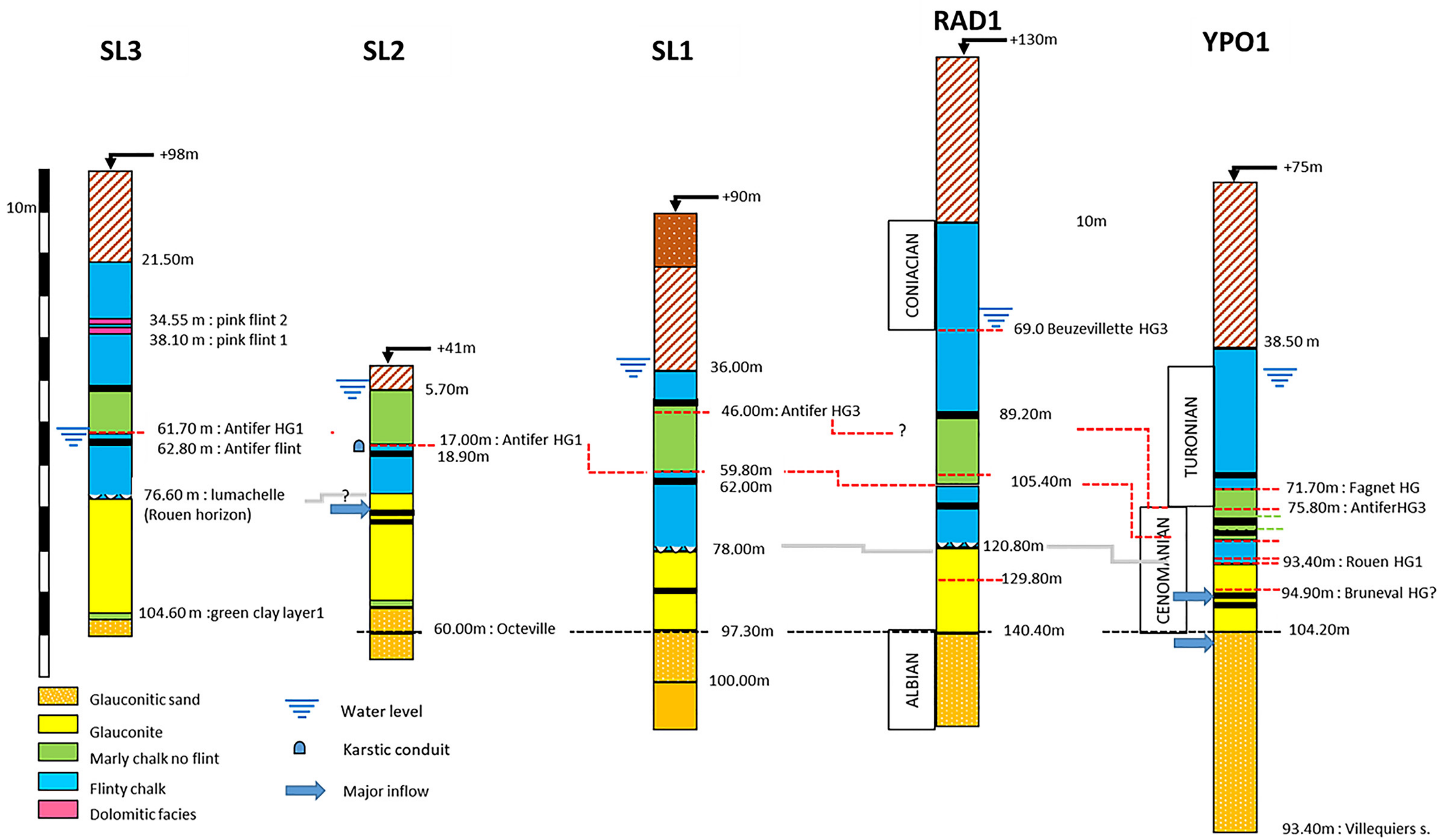

Fig. 7. Hydrostratigraphic log correlation between boreholes.

marl levels (Belle Tout, Les Loges, Antifer), hardgrounds (Etigues–Lillebonne, Belval–Radicatel, Chicard–Beuzevillette 3 HG, Tilleul, Bruneval) and dolomitized chalk linked with hardgrounds (Etretat rock, Chicard rock). In this list of karstogenic horizons, the Belle Tout marl is named in reference to the stratigraphy of English cliffs. This correlation must be verified with palaeontological proof. The Tight Chalk project financed by Total focused on the dolomitized chalk of Etretat rock and Chicard rock. The condensed dolomitized facies is described as a totally dolomitized formation. The diagenesis progressed by the replacement of dolomite with calcite. This process is responsible for high porosity and high permeability in a horizon where fluids occur primarily during the dolomitization–dedolomitization process (Saïag 2016; Gaillard *et al.* 2019). Nowadays, this horizon plays a similar role by draining groundwater inside the chalk.

These field observations, confirmed by the five core samples and logging, lead us to propose a new karstification model for chalk in Upper Normandy, based on stratigraphy and chalk lithology. Karstogenic horizons (KH) are linked to sequence boundaries (in the sense of Sloss 1963) or event beds (Antifer marl or Les Loges marl). These surfaces provide a main hydrogeological control from which it is possible to define six hydrogeological units of chalk from Cenomanian to Coniacian (Fig. 8). In this new model, Coniacian chalk is called the Great Karst, because the springs of greatest importance are located at the base of this chalk (Yport and Radicatel springs). In the Great Karst, perched springs could be observed on hardgrounds (e.g. Belval HG) and marl beds (les Loges marl, Belle Tout marl). In Turonian chalk, Tilleul hardgrounds seem to play a major karstic role with caves, perched springs and the Etretat river. Finally, water in the Cenomanian chalk is drained by associated surfaces at the bottom of the Antifer chalk (Antifer chalk–Antifer hardground) and in glauconitic chalk (Bruneval hardground–Bruneval flint).

This model shows some palaeokarsts at the top of the chalk log. These karsts must be considered as intermediate steps of chalk diagenesis in time. Indeed, this model also evolves in response to a geodynamic context. First, the Pointe de Caux area is affected by an active uplift. Two models are described to explain the phenomena. The first suggests that the uplift is structured around three steps corresponding to an alpine crisis, an early

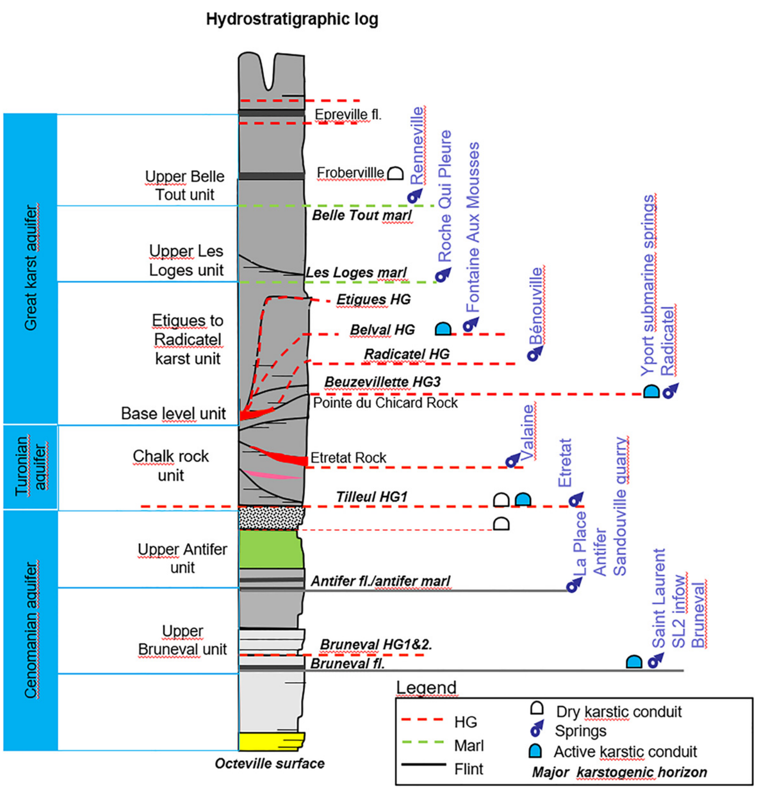

Fig. 8. New model of hydrostratigraphic units of the Pointe de Caux chalk.

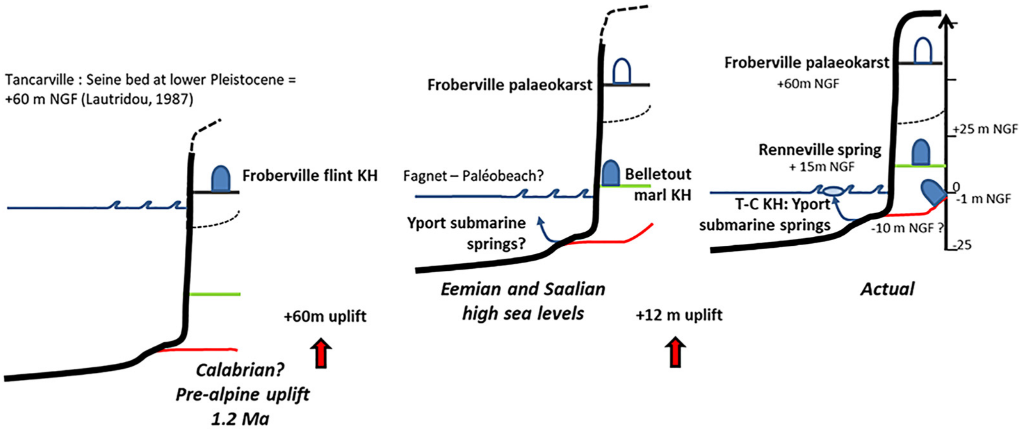

Fig. 9. Geodynamic reconstitution of hydrogeological base level. T-C KH, Turo-Coniacian karstogenic horizon; NGF, Nivellement Général de la France.

Pleistocene crisis and an early Holocene crisis (Wazi 1988; Antoine *et al.* 2000). The second suggests a constant uplift with a rate of 0.05 mm a^{-1} (Dewolf and Kuntz 1980; Jost 2005). At the same time, major rises are recorded in global ocean levels: 42 ka ago (isotopic stage 11 of the Holsteinian stage), about 20 ka ago (isotopic stages 7a–7e of the Middle Saalian), and 12 ka ago (isotope stage 5 of the early Eemian). In the bay of Criquebeuf, from Yport to Fécamp, three karstic horizons are easy to identify in cliffs from west to east. The first corresponds to the main drainage system of the submarine spring of Yport. Inland, the spring conduit was levelled in the Yport well around 1 m below sea level and emerges in the continental platform with a hole explored to 10 m below sea level. The second corresponds to the Réneville springs elevated around 15 m above sea level and supported by Belle Tout marl. This karstic horizon is probably an old drainage level with a base sea level near to the present day (Eemian or Saalian high sea level), which supposes a difference elevation of 15 m. The first uplift model is adapted to this hypothesis with an uplift of 12 m 12 ka ago (Wazi 1988) and is probably responsible for the elevation of the Fagnet palaeobeach (14 m above sea level). Before the Holocene crisis, the Réneville springs were at sea level. The third karstic horizon is located at the top of the cliff (around 60 m above present sea level) and corresponds to the Froberville flint karstogenic horizon.

Table 4. *Karstogenic horizons in the upper chalk of Pointe de Caux, Normandie*

Karstogenic horizon	Stratigraphical context	Main springs	Drainage unit (Fig. 8)	Aquifer (Fig. 8)
Belle Tout Marl*		Renneville perched springs	Upper Belle-Tout	Great karst aquifer
Les Loges marl		Roche Qui Pleure perched springs	Upper Les Loges	
Chicard rock/ Beuzevillette HG	Probably sequence boundary (SB8)	Yport and radicatel springs	Etigues-Radicatel	
Etretat rock	Probably sequence boundary (SB7)	Valaine perched springs	Chalk rock	Turonian aquifer
Tilleul HG	Sequence boundary (SB6)	Etretat river		
Antifer marl Antifer flint	Sequence boundary (SB4)	La Place (perched springs)	Upper Antifer	Cenomanian aquifer
Bruneval HG Bruneval Flint	Sequence boundary (SB2)	Saint Laurent	Upper Bruneval	
Octeville surface	Sequence boundary (SB1)	Inflow in borehole	Not represented	

*Hoyez (2008) suggests that this marl horizon is the same horizon as Belle Tout in England, though this is not yet proven.

Table 5. *Correlation of surfaces between English coast and Upper Normandy coast*

Chalk formation in Normandy	Karstogenic horizon (KH)	Other surfaces	Supposed equivalent surface in English chalk	Chalk formation in England	Stage
Grainval Fm	Belle Tout Marl		Belle Tout Marl	Seaford Chalk	Coniacian
Etretat Complex		Vattetot HG			
	Les Loges marl		Shoreham marl	Lewes nodular Chalk	
		Etigues HG	Bar End HG		
		Belval HG	Beeding HG		
		Radicatel HG	Top rock/ Navigation HG		
	Chicard rock/ Beuzevillette HG/ Senneville HG		Second dolomites? Hitchwood HG		Upper Turonian and Horizon A
	Etretat rock		First dolomites Fognam Farm HG = Spurious chalk rock		Turonian
St Nicolas, Fagnet and Antifer Fm	Tilleul HG		Pewsey HG?	New Pit Chalk & Holywell Chalk	
	Antifer marl Antifer flint		Monument marl under Plenus marl	Zig Zag Chalk	Cenomanian
		Rouen HGs			
Rouen Fm	Bruneval 3 HG Bruneval Flint		Double Limestones B23-24	West Melbury marly chalk	
Glauconitic chalk	Octeville surface		Glauconitic marl bed		

This means that a change of 60 m in sea level was necessary to have this karstogenetic horizon at sea level, corresponding to the Seine terrace in the lower Pleistocene (Lautridou 1987). The two models of Normandy uplift converge to identify this karstification period in the Calabrian, around 1.2 Ma ago (supposed to be marine stage 38). This geodynamic reconstitution is illustrated in Figure 9.

Conclusion

The first goal of this article is to share ten years of experience in chalk hydrogeology in the Pointe de Caux area. Founded on stratigraphy, these observations highlight the main role of sequence boundaries and key event surfaces in the constitution of groundwater flow drainage. Eight karstogenic horizons are defined, six of them directly linked to sequence boundaries formed by hardgrounds (Table 4).

The validity of this hydrostratigraphical approach to chalk can be tested in the London–Paris Basin cliffs and other European areas. Indeed, some key surfaces have a large area and offer opportunities to correlate the English chalk with the French chalk (Robaszynski and Amèdro 1986; Mortimore and Pomerol 1987). The correlations are proposed in Table 5 from Hoyez (2008) and Mortimore (2011). Correlation is difficult from the Upper Turonian to Lower Coniacian due to the Etretat Complex being composed of erosional surfaces. In the Upper Coniacian, Belle-Tout marls are less thick in Normandy than in the UK. In spite of this, they support the Roche-Qui-Pleure perched springs (Belle-Tout marl 1, supposed). Other dried-up springs are localized below the Seven Sisters–Epreville flint and can be correlated with other Belle-Tout marls.

The Belgian chalk or the Aquitaine chalk present some similarities with the Turonian–Coniacian karstic horizon (Platel 1996). The extension of the model to these chalks offers scope for further research. Coupled with chemical data, the stratified model presented here could open new opportunities for chalk aquifer exploitation.

The activation of karstogenic horizons is also the consequence of the geodynamic context. The superposition of many caves or springs with horizontal development is the result of a long drainage history, which probably started more than 1 million years ago, as is suggested for the bay of Criquebeuf.

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Author contributions **TG**: conceptualization (lead), investigation (lead), methodology (lead), writing – original draft (lead); **BH**: formal analysis (supporting), supervision (equal), writing – review & editing (equal); **EH**: data curation (supporting), resources (supporting), writing – review & editing (supporting).

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