9

The Deffend hydrogeological model

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Hydrogeological knowledge before Hydrogeological Experimental Site (HES) of Poitiers

Historical groundwater flow model of the Poitou Threshold

The hydrogeology of the Poitou Threshold has been studied since the 19th century, beginning with the work of Longuemar (1856). This author proposed a conceptual model of groundwater flow based on vertical fracture networks that drain groundwater toward valley-bottom springs located at the contact with the Toarcian marls. This hydrogeological model was later adopted and used by academics (Welsch, 1912), as well as by public service practitioners and engineering consultants for the location of boreholes and the interpretation of dye tracer tests. Observing the presence of water at the base of numerous quarries, Welsch expanded Longuemar's model by introducing the concept of "quarry water", corresponding to a continuous groundwater table within the limestones of the Supra-Toarcian Aquifer. Figure 1 presents the historical hydrogeological models of Longuemar and Welsch. It is worth noting, however, that Longuemar had described perched springs in cliffs,

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which his model does not adequately explain. Welsch's model envisions dry valleys as preferential drainage axes for groundwater flowing toward springs located at the contact with Toarcian marls or with alluvial deposits (Welsch, 1912). This model, therefore, implies that springs should emerge at the outlets of dry valleys; however, in practice, springs are also found outside valley axes.

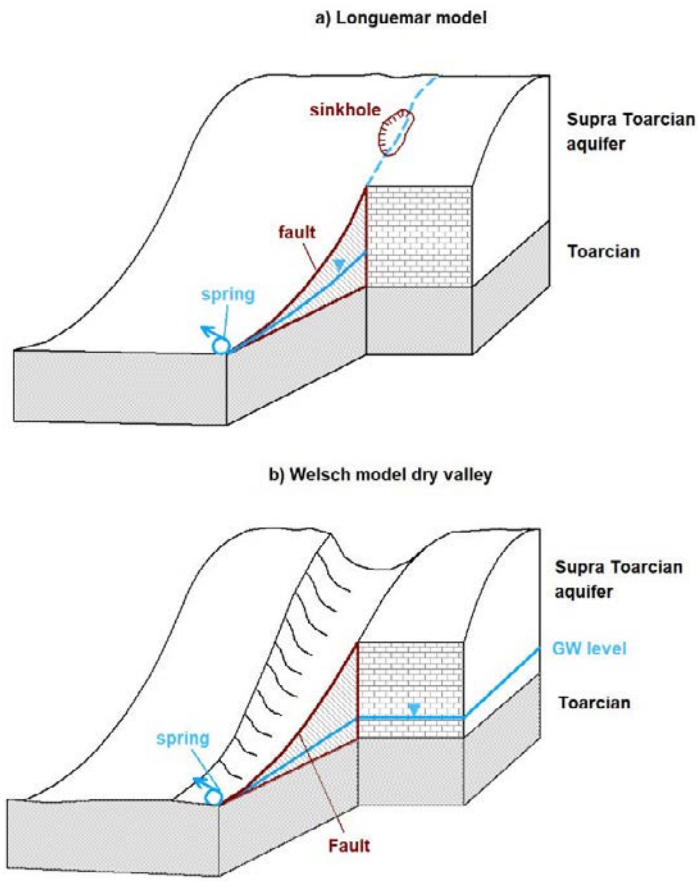


Figure 1 *Historical conceptual models of groundwater flow on the Poitou Threshold; (a) Longuemar's model (1856), (b) Longuemar's model modified by Welsch (1912).*

Another feature is that the Poitou Threshold is not particularly favourable to the karstification of Jurassic limestones. Hydraulic gradients are low due to the relatively low elevation of the plateaus, around 130 to 150 meters above sea level (m asl) around Poitiers, with riverbeds around 70 to 60 m asl. The plateaus are overlain either by red clays resulting from limestone weathering or by Plio-Pleistocene clayey-sandy sediments that inhibit infiltration. Poor descriptions of drilling cuttings and the lack of geophysical logging have further hindered understanding of the positioning of karst conduits. When a borehole encountered a sudden inflow of water, it was often attributed by drillers and hydrogeologists to the presence of a "fault". The facture model proposed by Longuemar and Welsch therefore seemed to be confirmed until the research on the Hydrogeological Experimental Site (HES) of the Poitiers University.

The Poitiers HES groundwater model

By the 1970s, the stratigraphy of the Middle Jurassic formations in the Poitou Threshold was already well established, and research conducted at the University of Poitiers helped bridge a century-long gap in paleontological investigations of the Poitou carbonate platform. However, it was not until the establishment of the Hydrogeological Experimental Site (HES) near Poitiers that new data on the karst systems of the Poitou Threshold became available.

Initial results demonstrated that the geometry of karst levels within the saturated zone is predominantly horizontal rather than vertical (Mari and Porel, 2008; Mari et al., 2009). Moreover, these horizontal karst levels are not randomly distributed but are strongly constrained by stratigraphy (Gaillard, Moreau, and Mari, 2024). Testing and experiments conducted at the HES established a direct link between stratigraphy and hydrogeology, leading to a substantial revision of earlier theories regarding the spatial organization of karst horizons in the Poitou Threshold.

The hydrogeological model developed from HES investigations is based on the superposition of several karst horizons within the Supra-Toarcian Aquifer. Borehole Optical Televiewer (OPTV) logs reveal that fractures predominantly affect the unsaturated zone and are less frequent in the saturated zone. Groundwater flow occurs mainly through karstified levels that show very little fracturing. The caves visible in cliff outcrops are relic features of these ancient karst systems (Gaillard et al., 2024; Gaillard, 2026). Current groundwater flow is partly routed toward overflow springs discharging into valleys, and partly beneath the valleys of the Clain and Vienne rivers. Figure 2 presents a block diagram of this conceptual model, referred to as the Deffend model

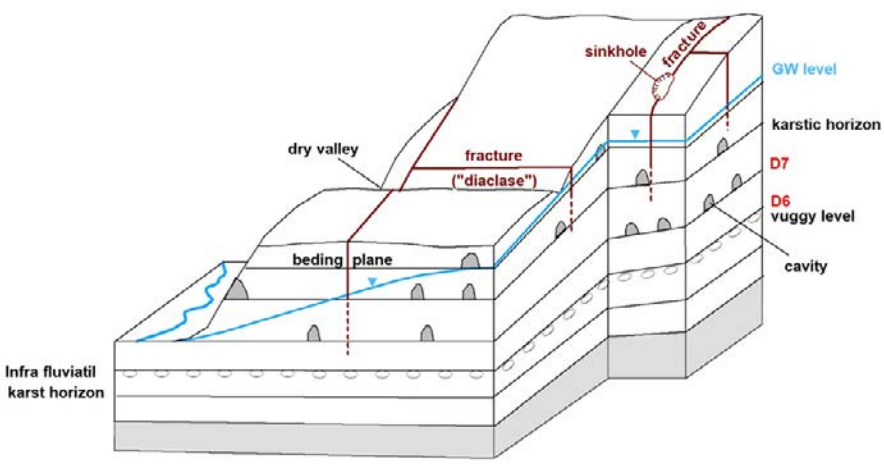


Figure 2 *The Deffend model.*

after the site name. In this model, fractures near the surface play a role in distributing groundwater recharge, while water in the saturated zone flows predominantly along horizontal karst horizons. For example, discontinuities D6 and D7 of Gabilly et al. (1985) correspond to two main karstic horizons. Each horizon acts as a drain for water percolating through the overlying limestone sequence. Some of these karst levels are not intersected by rivers (infra-fluvial karst horizons), and the relationship between such levels and modern river systems remains to be clarified.

Karst dating

The age of the Poitou Threshold karst has also been the subject of divergent theories. Gabilly et al. (1978, p. 19) correlated the three levels of caves around Poitiers with phases of valley downcutting of the Clain and Vienne rivers during the Quaternary, particularly during the Middle Pleistocene to the Riis glacial stage, the Mindel, and the Würm glacial stages. However, the infilling of some cavities by black clays and glauconitic sands dated from Cenomanian had long been recognized within the Middle Jurassic limestones (Cariou and Mathieu, 1959; Mathieu, 1960; Alvarez, 1980; Legendre, 1984). On the HES, palynological analyses of clays trapped within karstic conduits below the *Parkinsoni* biozone (Upper Bajocian) yielded ages ranging from the Cenomanian to the Santonian (Bassil, 2014). Recently, Valentin et al. (2021) discovered abundant and diverse fossil assemblages ranging from the Albian to the Cenomanian in cross-stratified deposits infilling a Bajocian paleokarst near Persac, on the east of the Poitou Threshold. However, Cenomanian formations do not outcrop on the Poitou Threshold itself. These examples demonstrate that karst horizons are older than the Cenomanian transgression (Tab. 1). These karst systems trapped marine sediments of Cretaceous age before their complete erosion on the Poitou Threshold (Fig. 3).

Table 1 *Location of Cretaceous sediment trapped in karst on the Poitou Threshold.*

Location	X Longitude	Y Latitude	Reference
Chardonchamp	0.3488°	46.6269°	Alvarez, 1980 (p. 93)
Persac	0.6985°	46.3577°	Valentin, 2021
Vouneuil-sous-Biard	0.261°	46.6035°	Mathieu, 1960
Poitiers SEH	0.4062°	46.5522°	Bassil, 2014
Lavoux	0.5248°	46.5964°	Cariou, Mathieu, 1959
Luzay	-0.1965°	46.9205°	Legendre, 1984 (p. 50)
Moulins, Smarves	0.3482°	46.5314°	Mathieu, 1960

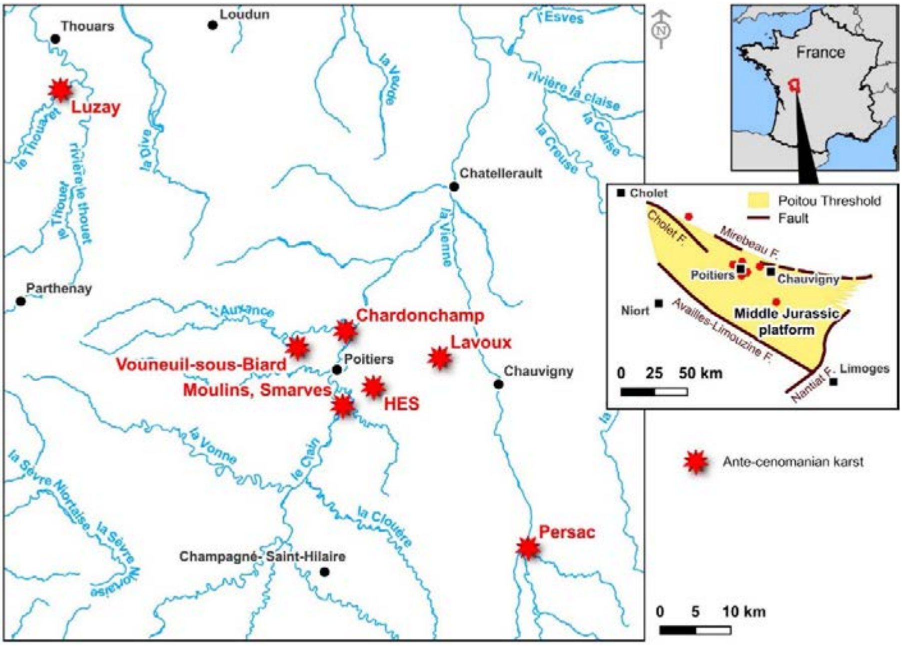


Figure 3 *Location of evidence of ante-Cenomanian karsts.*

Thus, between the Cenomanian transgression and the reactivation of karst associated with Quaternary valley downcutting, several million years of karst evolution remain to be reconstructed.

The absence of Albian and even Purbeckian sediments on the Poitou Threshold led some authors to conclude that the platform remained fully emergent during the Lower Cretaceous (Gabilly et al., 1978, p. 17; Alvarez, 1980, p. 86; Mourier et al., 1986). An initial phase of karstification is thus theoretically conceivable. This long-lasting subaerial exposure would therefore correspond to an ancient karstification episode, at least partially predating the Cenomanian. The absence of Lower Cretaceous sediments implies that the Poitou threshold uplifted by at least 100 m, simply assuming that the sea has risen in accordance with the Hardenbol sea level chart (1998). This tectonic phase could correspond to the beginning of the Atlantic north opening during the Tithonian stage (Dercourt et al., 1993).

The Cenomanian transgression subsequently deposited black clays, followed by glauconitic green sands over part of the Poitou Threshold. These formations, now largely eroded, extended southwards as far as the area around Poitiers (Mathieu, 1960) within a context of high stand sea level (Hardenbol et al., 1998). The discovery by Valentin et al. (2021) confirms that this marine transgression covered the entire Poitou Threshold and filled the karst from the surface (Fig. 3).

The red clays overlying the Bajocian and Bathonian limestones were interpreted as the result of weathering of the limestones from the late upper Cretaceous to the Eocene (Gabilly et al., 1978, p. 19). From the Eocene onward, the plateau was once again overlain by continental deposits coming from the Massif Central mountains. A fluvial network draining westward gave rise to the so-called Ypresis River, named after its Ypresian age, determined at its mouth on the Atlantic coast (Godard et al., 1994). The overlying lacustrine limestones, though poorly dated — except at Fonliasmes (Mazerolles commune), where a Bartonian age was determined (Brunet and Gabilly, 1981), also contributed to covering the Jurassic karst. The Poitou Threshold was then entirely covered by the argillaceous-sandy complex of the Bornais Formation during the Plio-Pleistocene, lying between the Thouars-Mirebeau and Champagné-Saint-Hilaire fault zones.

Assuming that the downcutting of the valleys eroded the Bornais formation, the onset of plateau erosion likely corresponds to the lowering of sea level during the Günz glacial period (1.2 to 0.7 My BP). The corresponding fluvial terraces (Fv on the French geologic map) are clearly visible only north of the Threshold, around Châtellerault city, and may correspond to the Günz/Mindel interglacial (Bourgueil et al., 1976). The high terraces of the Vienne and Clain valleys (Fw) are mainly Middle Pleistocene in age. Their formation occurred in the context of a rising base level associated with the Mindel-Riss interglacial (421–395 ky).

The karst systems of the Passelourdin and Lussac-les-Châteaux sites are each located at elevations below those of the Fw terraces (Gaillard et al., 2024). In both cases, these cavities are altitudinally above the Fx terraces, which are dated to the Saalian (>110 ky BP) through the presence of Acheulean-Levallois and Mousterian industries, as well as faunal remains of *Elephas primigenius* and *Rhinoceros tricorhinus* (Facon, 1955; Voinchet et al., 2020). The reactivation of karst is therefore constrained between these two alluvial deposition events, i.e., between 421 and 110 ky BP. This karstic morphology extends beneath the entire Poitou Threshold plateau.

A significant issue remains, however: at the HES site, the karstified levels are clearly controlled by the Middle Jurassic stratigraphy, with no connection to the Clain valley downcutting or the terrace altimetry. The elevation of lower karst levels is below the current riverbed elevation of the Clain (Poitiers HES) and the Vienne (Civaux nuclear power plant area in Gaillard et al., 2024). These rivers could not have exported carbonates from below these levels.

Syngenetic karstification hypothesis

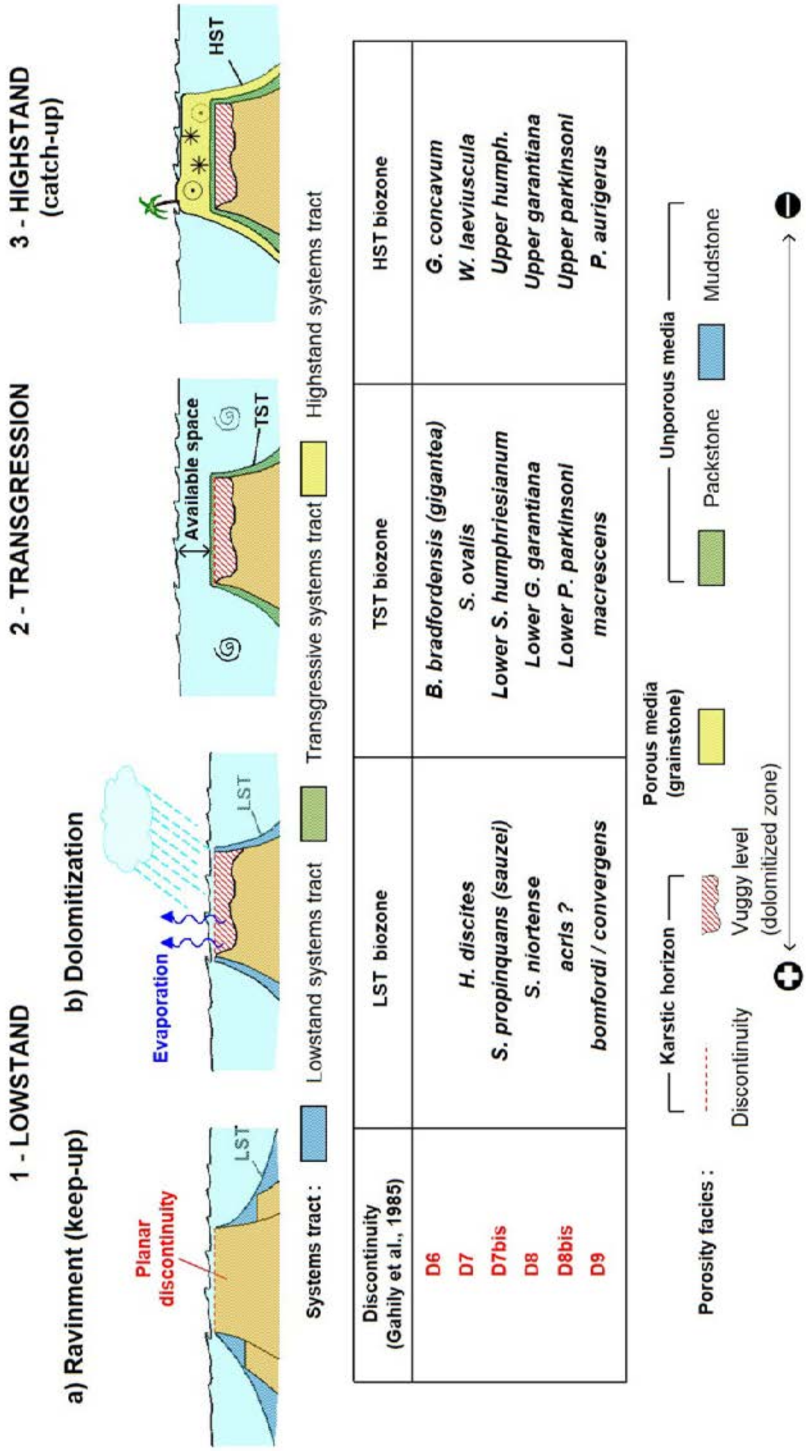
Karst systems located beneath river valleys cannot be explained by Quaternary valley downcutting. Furthermore, late-stage karstification of a carbonate massif requires the export of calcium and bicarbonate ions. Such export via drainage pathways is difficult for deep groundwater located below the current riverbeds. Syngenetic karstification therefore, remains a plausible hypothesis (Jennings, 1968; Grimes, 2006). Such karstification processes, associated with discontinuities, have been described in the

Bajocian and Bathonian formations of the Grands Causses in France (Charcosset et al., 2000) and in the Betic Cordillera in Spain (Molina et al., 1999). These discontinuities are defined by some authors as inception horizons (Filipponi et al., 2010) and play a key role in controlling karst development (Bosák, 2008).

On the Poitou Threshold, deposits ranging from the Aalenian to the Bathonian are primarily controlled by eustatic variations (Branger, 1989; Gonnin et al., 1992). Each depositional sequence is bounded by discontinuities characterized by the absence of one or several ammonite zones (Gabilly, 1962; Gabilly and Cariou, 1974; Gabilly et al., 1985; Branger, 1989). The model that best explains sedimentation on the Poitou Threshold platform is the Catch-up/Keep-up model (Emery, 1996). The Emery Catch-up / Keep-up model describes the response of carbonate platforms and reefs to relative sea-level rise. In the keep-up mode, the vertical accretion rate of the platform equals or exceeds the rate of sea-level rise, allowing the carbonate surface to remain close to sea level continuously. In the catch-up mode, carbonate growth is initially too slow to match rapid sea-level rise, leading to partial drowning. A third outcome, often referred to as the give-up mode, occurs when carbonate accumulation cannot compensate for accommodation creation, resulting in permanent drowning of the platform. Emery's Catch-up / Keep-up model can be directly related to the systems tracts of sequence stratigraphy in carbonate platforms. Keep-up platforms, where carbonate production matches relative sea-level rise, are expressed as aggradational successions typical of the transgressive systems tract (TST) or the highstand systems tract (HST). In contrast, keep-up platforms, which drown permanently, correspond to low systems tract (LST) or major sequence boundaries, often overlain by condensed pelagic deposits or siliciclastics.

In each depositional sequence, a lowstand systems tract formed along the edges of the platform, either on the outer platform or in basins bordering the threshold. On the platform itself, limited accommodation space prevented the development of lowstand systems tracts. The low accommodation was expressed by early lithification, the presence of benthic faunas, bioturbation, and abrasion by intertidal currents. During this low sea level phase, the limestones were dolomitized by continental freshwater or rainwater according to the Coastal Mixing Zone Dolomite theory (Humphrey and Quinn, 1989) or the reflux model (Patterson and Kinsman, 1982).

During transgression, when the sea level rose, the platform was drowned, and pelagic facies were deposited. Along the platform margin, these are represented by marly–calcareous condensed beds, forming thin strata enriched in ammonites and belemnites, which typify drowning intervals within the carbonate succession. Then, a highstand systems tract developed across the platform, characterized by increased carbonate production, consistent with the hypertrophic late sequence model of Gabilly and Cariou (1974). Concurrently, slope deposits thinned as carbonate accumulation declined in deeper, light-limited environments. The resulting highstand wedge subsequently served as a substrate for benthic colonization during the following sea-level fall.



Discontinuity (Gahily et al., 1985)	LST biozone	TST biozone	HST biozone
D6		*B. bradfordensis (gigantea)*	*G. concavum*
D7	*H. discites*	*S. ovalis*	*W. laeviuscula*
D7bis	*S. propinquans (sauzei)*	*Lower S. humphriesianum*	*Upper humph.*
D8	*S. niortense*	*Lower G. garantiana*	*Upper garantiana*
D8bis	*acris ?*	*Lower P. parkinsoni*	*Upper parkinsoni*
D9	*bomfordi / convergens*	*macrescens*	*P. aurigerus*

Figure 4 *Stratigraphic control of aquifer porosity.*

On the Poitou Threshold, the catch-up/keep-up model recurred several times during the Middle Jurassic. The main discontinuities identified by Gabilly et al. (1985) correspond to phases of low sea level. Figure 4 shows a synthetic diagram of the systems tract during a transgression-regression cycle. A table shows the correspondence with ammonite zones, and porous bodies are represented by dolomitized strata with vuggy levels and discontinuities.

At the outcrop scale, the genetic units corresponding to lowstand and highstand deposits repeat this pattern. This model also makes it possible to suggest a sequence of diagenetic events affecting the limestones during deposition. During sea-level falls, dolomitization found favourable conditions due to the evaporation of marine waters trapped within the sediments around isolated shoals, combined with meteoric water input across the platform, promoting the precipitation of calcium and sulphates (Morda et al., 2012). The advance of the dolomitization front within the limestones would then be controlled by the freshwater/saltwater interface. This process could repeat with each cycle and would be particularly intense in the eastern part of the Poitou threshold, where the Montmorillon dolomite is located.

Within this framework, the depositional sequences that influenced the porosity of the supra-Toarcian limestone aquifer are as follows:

(i) at the end of highstand, when sedimentation has filled the available accommodation space, the platform is subjected to intense currents that scour the limestones and formed a more or less cemented sub-horizontal discontinuities, expressed as a bioturbated hardgrounds (Gabilly, 1962). These discontinuities, sometimes underlined by remnants of palaeosols, are conducive to the formation of highly porous hollow bedding planes;

(ii) during the lowstand, for example, the *discites* horizon (corresponding to the lowstand of sequence Bj1 of Gonnin et al., 1992), per descensum dolomitization occurred (Mourier, 1983). The limestone becomes more porous and forms vacuoles and vuggy levels, probably due to the dissolution of calcite geodes into the *laeviuscula* limestone;

(iii) the transgressive system tract is formed by thin strata, rich in pelagic fauna, but with relatively low porosity;

(iv) the highstand system tract is made up of metric strata, often oolitic and rich in crinoid debris, which can form a porous aquifer (grainstone facies).

In this schema, the absence of the *niortense/subfurcatum* zone could be related to a relative uplift of the Poitou threshold. Karstification associated with the D8 (and D8bis) discontinuity could be explained by this depositional gap, accompanied by intense bioturbation that enhanced subsequent dissolution (Figure 4).

The emersion event at the end of the *Parkinsoni* zone (*Bomfordi* subzone), identified by ostracod-bearing clays in the Vienne valley (Mourier and Almeras, 1986), is associated with the deposition of black clays in submerged areas and karstification marked by red clays observed in boreholes from the HES site (Gaillard, 2026).

Conclusion

Geophysical (Mari and Porel, 2008, 2009; Delay et al, 2022; Mari, 2026), hydrogeological investigations (Audouin et al., 2008; Bodin et al, 2022; Boulais et al., 2026), and borehole logging conducted at the Poitiers HES site have completely renewed the understanding of the supra-Toarcian aquifer.

The first scientific contribution is the demonstration that the productive horizons within the Middle Jurassic limestones (from Aalenian to Bathonian) are sub-horizontal. Fracturing, which was previously invoked as the main factor controlling the spatial distribution of transmissivity and porosity within the limestones, is in fact restricted to the upper part of the aquifer, particularly within the unsaturated zone. Below a certain depth, within the Bajocian limestones at the HES, horizontal structures form distinct superimposed karstic levels.

The second contribution is the demonstration that these levels are not randomly distributed. Stratigraphic analysis of borehole sections has shown that discontinuities associated with marine lowstands are well correlated with ravinement of the depositional surface, combined with dolomitization (Gaillard, 2026). The correlation between stratigraphy and the depths of karstic levels is a major scientific contribution.

The resulting hydrogeological model explains the formation of syngenetic karstic horizons within the context of a non-rimmed carbonate shelf. These levels were subsequently reactivated throughout geological time. The karst is thus highly polyphasic, evolving from an initial pre-Cenomanian stage to the Quaternary, with the downcutting of fluvial valleys that actually drain the Poitou Threshold. This model explains the presence of Cretaceous sediments within the Bajocian or Callovian limestones. Similarly, the presence of karstic levels beneath present-day riverbeds' elevation is consistent with the theory of syngenetic karstification at the top of the highstand systems tract.

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