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Geological fluid flow in sedimentary basins

Les fluides géologiques dans les bassins sédimentaires

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1 Introduction

For over 50 years, sedimentary basins have been considered as the lithosphere's surface film, belonging to the subsurface domain and containing the vast majority of accessible mineral and energy resources. Beyond their human use, sedimentary basins are more importantly the ultimate exchange interface between the earth's main reservoirs. Firstly, between the upper lithosphere and the atmosphere-hydrosphere reservoirs, exchanges are mainly vertical. Next, between the onshore reservoirs, *i.e.*, on the continental part, and the offshore reservoirs, *i.e.*, in the submerged part of the margins, exchanges are lateral and may take place over great distances. Unexpected low accumulations and/or dry holes are becoming more frequent in petroleum exploration and gaining an understanding on lateral migration of fluids and bypass system are one of the geological challenges that must be addressed to reach ultimate reservoirs in the coming years.

In such context, the French coordination program Action Marges (AM) has been launched in 2008 in order to focus the continental margin research on a cross disciplinary research and develop new concepts that have an important impact for society, for resources and for risk assessment. The Action Marges project is coordinated by INSU with financial contribution of TOTAL, CNRS, BRGM and IFREMER. One of the themes is dedicated to "Fluids − Organic Matter − Mineral Matter" (FO3M) and the challenge was to define fluid flow as the centerpiece of a cycle starting from the organic matter preservation at seabed, its transformation during burial forming fluids, the upward fluid migration through fine-grained sediments, the temporarily fluid storage into reservoirs such as sedimentary bodies or gas hydrates, the fluid expulsion at seafloor, to its implications on seabed stability or climate change.

This special issue on geological fluid flow in sedimentary basins aims at bringing together recent results from the scientific community involved in the FO3M project since 2012, with a special focus on the interplay between mineralogical, geochemical, physical and biological processes occurring during fluid remobilization and migration within the shallow interval (0–1000 m) of sedimentary basins.

2 Organic matter preservation and shallow fluid migration

The initial sediment lithification starts with complex interactions involving minerals, shallow interstitial water, decomposing organic matter and living organisms. This is the eogenesis domain (0–1000 m below seafloor) in which the sediments are subjected to physical, chemical and mechanical transformations defining the early fabric of rocks (Fig. 1). This interval is intensively prospected for its geological resources (hydrocarbons, metal deposits, geothermal energy). In most basins worldwide, it consists of very fine-grained sediments and it is supposed to play the role of a seal for fluid migration. Local sand-prone deposits of various origin, architecture and thickness can also be found, acting as pathways or reservoirs for fluids.

For the first time, the solid phase BrOrg has been evidenced as a conservative tracer of the debromination of sedimentary organic matter in a shallow core (< 50 m) taken on the Nile deep-sea fan (Murat *et al.*, this issue). The rate of debromination illustrates the complex interplay between organic matter, microbes and inorganic compounds in unconsolidated sediments. It obviously depends on the TOC, meaning that it increases with TOC up to 3% due to the availability of the bacterial population. However, the debromination process decreases for TOC higher than 4%. This is of high interest for organic-matter transformation as the BrOrg tracer determines how fine-grained organic-rich intervals become potential source rocks at depth and how bacterial populations modify fluids and organic matter characteristics during early stages of burial (Fig. 1). In addition, the BrOrg can be used as a tool for defining intervals that were "fluid engineers" in the eogenesis domain once the organic matter has been transformed at depths where diagenesis is the most active process for lithification (> 1000 m below seafloor).

However, the eogenesis domain is commonly affected by polygonal faulting due to a volume loss by contraction of smectite-prone clay sediments during burial (Andresen and Huuse, 2011; Cartwright, 2011; Gay *et al.*, 2007). This process

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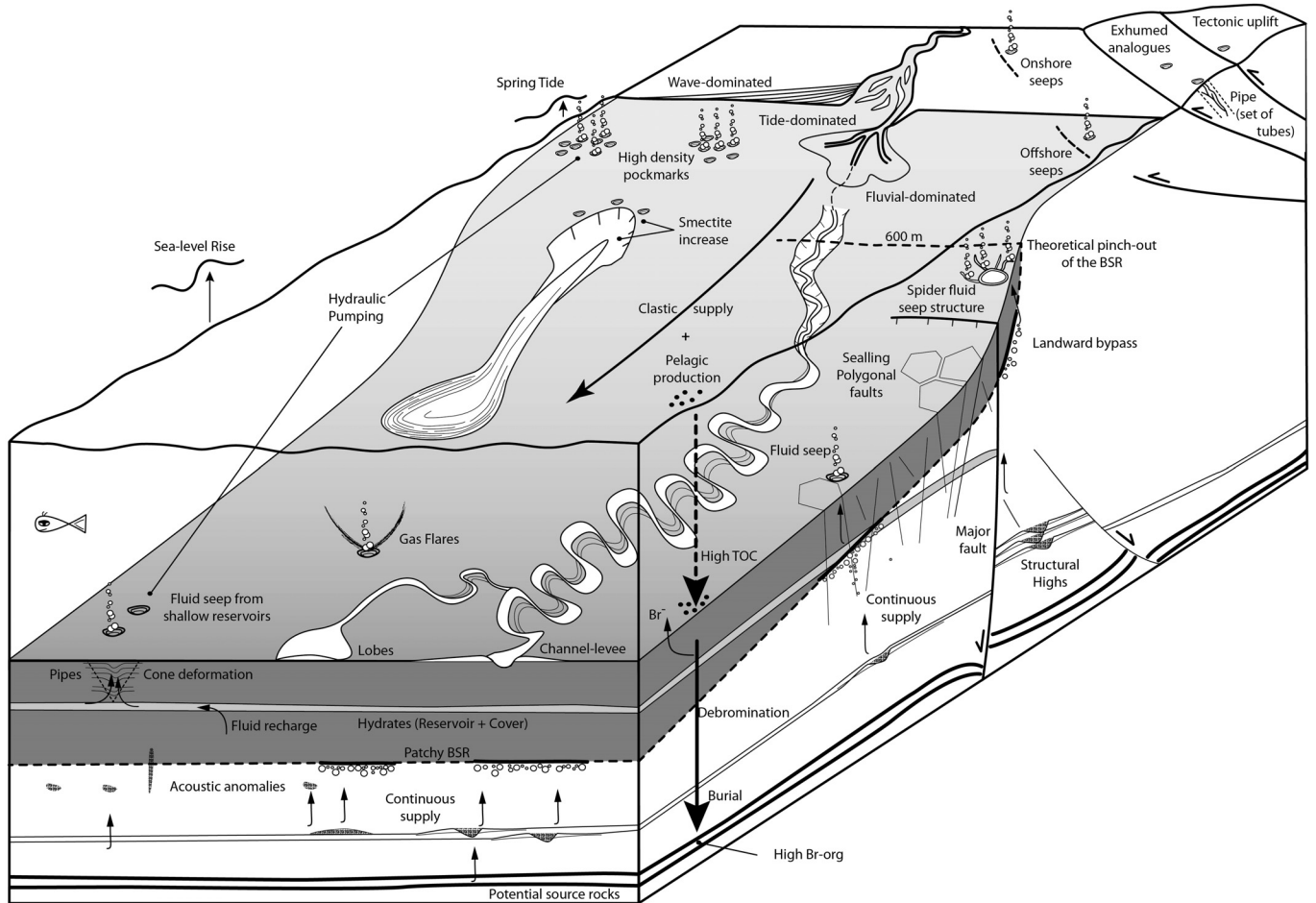
Fig. 1. Schematic block illustrating new developments since 2012 in geological fluid production, migration and expulsion in sedimentary basins, based on studies conducted through the FO3M thematic action in the Action Marges project.

is of high interest to constrain fluids circulation within fractured reservoirs and/or preservation of the sediment-cover integrity but it is still not well constrained as this interval can either promote the migration of fluids from underlying reservoirs (Gay *et al.*, 2004; Lonergan *et al.*, 1998). In addition, mineralized fluids intensify diagenesis in the fracture planes, rendering this interval all the more impermeable (Laurent *et al.*, 2012). The detailed analysis of the geometric relationships between high-impedance seismic anomalies and polygonal fault pairs reveals that they can act as a seal during early stages of burial (Ho *et al.*, 2016). In the Congo Basin, the Pliocene-present interval contains widespread fluid escape features, at seabed and in the subsurface, indicating past and ongoing bypass of the regional seal which is intensely affected by a major polygonal fault system (Gay *et al.*, 2004). Casenave *et al.*, this issue have shown that this polygonal fault interval might also have sealing properties. In this case, fluids are mainly driven along major faults to reach the seabed, leading to more focused and localized fluid seeps (Fig. 1). The next challenge will be then to define where, when and how does this polygonal fault interval occur. This can only be done by understanding the behavior of clay grains and fluids during early burial stages.

In the Sobrarbe Delta (Eocene Ainsa Basin), diagenetic conditions were limited to low temperatures (up to 75 °C),

meaning that sediments have been buried to a maximum of 2 km (Odonne *et al.*, this issue). Both some sliding surfaces and their surrounding deposits were investigated. Results reveal higher smectite ratio close to the sliding surfaces and smectites were found at the wall of dissolution voids of K-feldspars (Fig. 1). This indicates that fluids preferentially circulated following the sliding surfaces that acted as major heterogeneity within the sediment pile. In these conditions, clay minerals such as smectite appear as a robust marker of shallow fluid circulation as the kaolinite requires a temperature of 130–140 °C to change into illite.

3 Seafloor fluid seepage

Once fluids (water, gas, oil or a mix) reach the seafloor, they are expelled in the water column forming sub-circular depressions called pockmarks (Hovland and Judd, 1988). Pockmarks have been reported in various depositional systems at water depths ranging from 30 m to over 3000 m (for a detailed review see Rollet *et al.*, 2006; Gay *et al.*, 2007). They generally form in unconsolidated, fine-grained deposits. They are cone-shaped circular or elliptical depressions, ranging from a few meters to 800 m or more in diameter

and from 1 m to 80 m in depth. They concentrate in fields extending over several square kilometers. For the last decade, discoveries of new fluid seep structures were not reported although both academic and industrial surveys intensified.

However, the use of high-resolution geophysical imagery systems leads to the identification of unknown high-density field of pockmarks (about 3500 sub-circular pockmarks per square km) in unsuspected shallow marine environment (about 35 m water depth) like the Bay of Concarneau (France) (Baltzer *et al.*, this issue). The pockmarks appear to be active as the fields limits coincide with the settlements of *Haploops* tube mats covering muddy deposits. To date, this is the highest density of pockmarks ever found in marine environment (Fig. 1). The acquisition of bathymetry and other geophysical tools in the same area in 2011 and 2014 was essential in order to determine lasting of *Haploops* communities related to fluid seeps within pockmarks.

In the Lower Congo Basin (LCB), the combined use of various datasets acquired during the last 15 years and including multibeam bathymetry, seismic data, seafloor videos, seafloor samples and chemical analyses of both carbonate samples and of the water column allowed the identification of two distinctive associations of pockmark-like seabed venting structures, located in water depths of 600–700 m (Casenave *et al.*, this issue). These two features are called "spiders structures" because of their morphology consisting of a large and flat sub-circular depression (the body) surrounded by elongated depressions (the legs). The body consists of muddy low-reflective hemipelagic sediments, covered by patches of bacterial mats and empty shells, and seems dormant while the legs appear to be the present-day active seep location (Fig. 1). This observation is similar to what was already described for more conventional pockmark structures on the Nile margin (Bayon *et al.*, 2008; Dupré *et al.*, 2010; Migeon *et al.*, 2014; Praeg *et al.*, 2014) but it is the first time that such a specific seabed planform morphology associated with such a fluid-circulation activity is reported.

Pockmarks and gas seeps can also be detected on acoustic records as long as they are active (Dupré *et al.*, 2015). This is the case in the Bay of Concarneau where acoustic flares were identified on Chirp profiles (Baltzer *et al.*, this issue). This is also the case on the Romanian sector of the Black Sea where widespread gas flares were evidenced in the water column related to high fluid fluxes escaping from the seabed (Riboulot *et al.*, this issue). Gas flares are a useful tool to easily identify active pockmarks during multibeam and 2D high-resolution seismic surveys (Fig. 1). They develop above active pockmarks and might be related to the presence of a gas-hydrate stability zone.

4 From the source to the seafloor

On the geophysical record, either 2D or 3D seismic data, vertical fluid pathways called pipes (or chimneys) are usually imaged as systematic disruptions and/or offset of the reflections within sub-vertical zones, 50–1000 m wide and up to 1000 m high (Løseth *et al.*, 2011). This interpretation is also supported by observation of amplitude enhancement or dimming. On seismic profiles, the internal structure of pipes is characterized by bent reflections with offset upward (pull-up effect) or downward (pull-down effect) relative to the host stratigraphy by 20 to 150 ms TWT. Pipes are interpreted to represent a high-permeable vertical zone called a seal bypass system (Cartwright *et al.*, 2007). They are thought to be caused by high fluid overpressure hydro-fracturing sediments of low permeability (Arntsen *et al.*, 2007; Rodrigues *et al.*, 2009). This geophysical characterization seems actually well constrained in space and time. However, using a set of derived seismic attributes, it is now possible to identify the root of a pipe (*i.e.*, the depth at which fluids are originating from) and the paleo-pockmark surface (*i.e.*, the level representing the paleo-seafloor at the time the fluid expulsion started [was active?]). In the Gulf of Lion, the fluid pipe induces a deformation of surrounding unconsolidated sediments during upward migration, leading to the formation of a cone in cone or V-shaped structures (Gay *et al.*, this issue). A multi-attribute calculation made on 3D seismic data allows the precise 3D mapping of the points of fluid injection while the top of the cone structure marks the top of the focused migration (Fig. 1).

It is classically invoked that most of the fluids reaching the seabed are originating from shallow buried levels (Fig. 1) although when carbonate crusts build at the seafloor there is undoubtedly a contribution of deeper fluids allowing oil or thermogenic gas to be expelled (León *et al.*, 2010, 2014). This is the case in the Gulf of Lion (Gay *et al.*, this issue), on the Romanian shelf (Riboulot *et al.*, this issue) or in the Bay of Concarneau (Baltzer *et al.*, this issue) where fluid releasing is attested. These vertical chimneys or pipes are among other acoustic anomalies usually present in the shallow sub-surface due to gas accumulations or carbonate precipitation (Fig. 1). In the Lower Congo Basin, such anomalies were identified on either 3D seismic data, HR 3D seismic data or 2D-AUV data (Casenave *et al.*, this issue) corresponding to bright spots, elongated acoustic anomalies or black patches.

However, even with 3D seismic imagery, the full architectural pattern of the fluid network remains very complex to determine. Only a few examples of modern fluid-related systems have been studied in details at sea, probably because of the limited number of areas where VHR investigations of the seafloor/sub-surface together with 3D seismic data exists. It is then possible to better understand these features on field analogues, once the stratigraphic intervals hosting them have been uplifted due to tectonic activity and brought above the sea-level (Fig. 1). For instance, in the uplifted accretionary prism of Hikurangi Margin (New-Zealand), tubular concretions are outcropping in several Miocene mudrocks intervals (Malié *et al.*, this issue). Most of the pipes are sub-vertical with their length-axis perpendicular or sub-perpendicular to the bedding plane. They are 10 to 40 cm in diameter and 50 cm to 10 m in length. In some cases, they are inter-connected, forming a real plumbing system. A direct comparison with seismic-scale features is still not realistic to manage because their dimensions are far below the seismic resolution. Anyway, this suggests that a fluid pipe few hundred-meters wide identified on the seismic record is most probably a set of several small-scale pipes together propagating in a large area of sediment impregnated with fluids (Fig. 1). This should be the target for the development of future research fields.

5 The dual role of hydrates in cover integrity

The sub-vertical fluid pipes (or chimneys) are often disrupted at depth by a high-amplitude reflection parallel to the seafloor. This reflection is interpreted as a bottom-simulating reflector (BSR) corresponding to the lower thermodynamic limit of the gas-hydrate stability zone (Shipley *et al.*, 1979; Kvenvolden 1988; Hyndman and Spence, 1992). This can be also considered as the top of the free-gas zone beneath the hydrates (MacKay *et al.*, 1994). BSRs are characterized by a reverse polarity reflection compared to the seafloor. This is due to a decrease in seismic impedance and, therefore, of seismic velocity. The main restriction for the occurrence of hydrates is the presence/supply of sufficient amounts of stabilizing gas molecules (Rempel and Buffett, 1997). As outlined by Egorov *et al.* (1999), the steady-state model for gas hydrates requires a methane flux from below to compensate for its diffusive dissipation into the pore water (Sultan *et al.*, 2014). This statement is confirmed on the Romanian shelf where BSRs are deflected upward (Riboulot *et al.*, this issue), suggesting a localized positive heat flow anomaly probably due to an ascending movement of fluids through the sedimentary column (De Batist *et al.*, 2002; Gay *et al.*, 2006). It means that gas hydrates are locally not impermeable, allowing fluids to migrate upward along any major discontinuity such as faults, and then to form pockmarks at the seabed (Fig. 1). So, there is a close association between BSRs at depth, indicating an active fluid flux, and seafloor pockmarks. This is also the case in the Lower Congo Basin where the new "spider structures" are located above patches of BSR (Casenave *et al.*, this issue).

As gas hydrates are usually considered impermeable, additional free gas may migrate laterally right beneath the hydrates. Once they find a way up, they can escape to the seabed. On the seismic record, this kind of seepage is often evidenced by hyperbolae located at the landward termination of the BSR and overlaid with seafloor gas escape structures (Fig. 1) (Riboulot *et al.*, this issue; Casenave *et al.*, this issue).

Gas hydrates have a dual role in sedimentary basins as they temporarily store fluids migrating from deeper geological horizons to their stability zone or as free gas beneath them and they avoid fluids to reach the seabed with properties similar to a barrier. In consequence, they can be considered as both a reservoir and a cover in the shallow subsurface (Fig. 1).

6 Triggering and control mechanisms

In the uplifted accretionary prism of Hikurangi Margin (New-Zealand), trending of fossil tubular carbonate concretions coincides with tectonic lineament suggesting that the main factor controlling the fluid expulsion and location is the tectonic activity (Malié *et al.*, this issue). It is suggested that the tectonic uplift together with fault activity can shift the depth of the Hydrate Stability Zone (HSZ), leading to dissociation of pre-existing hydrates and releasing of methane.

Gas hydrates are also "climate sensitive" as they form or dissolve in response to sea-level variations controlling bottom seawater temperatures. In the Lower Congo Basin, the various stratigraphic levels hosting fluid escape structures have been correlated to sea-level rises following the latest Holocene lowstands (Casenave *et al.*, this issue). This is due to free gas naturally migrating landward due to the pronounced tilting of the base of the gas hydrate stability zone at 600–700 m water depths (close to theoretical pinch-out of the BSR).

This relation with sea-level variations has also been evidenced in the Gulf of Lion where most of the modern pockmarks were formed during the last sea-level rise (Gay *et al.*, this issue). León *et al.* (2014) have shown that in the western Mediterranean Sea, the propagation of internal waves alongshore may act together with the general sea-level rise at the beginning of the transgressive period as a hydraulic pump for fluids trapped at shallow depths, resulting in the formation of pockmarks (Fig. 1). It suggests that, at the beginning of each transgression, large amount of methane-rich fluids might be released into the ocean and atmosphere, possibly increasing the greenhouse effect (Dunkley Jones *et al.*, 2010).

The effect of hydraulic pumping can be responsible for the formation of the large fields of pockmarks in the Bay of Concarneau (Baltzer *et al.*, this issue). At a shorter time-scale, the high-frequency expulsion activity may be related to the action of spring tides (Fig. 1). Although the initial pockmark craters are thought to be formed during seismic events (Baltzer *et al.*, 2014), pockmarks could be activated when the tidal pressure would be high enough during spring tides, leading to the formation of plumes in the water column.

As previously proposed by Hasiotis *et al.* (1996), these observations imply that gas supply towards pockmarks is a continuous process during the life-span of the seep structure (Fig. 1). It also means that the sediments within the migration pathways are loaded with gas, which is of high interest for seafloor hazards.

7 Conclusion

Recent studies of fluid migrations in sedimentary basins have shown that these phenomena are ubiquitous and interact with the surrounding sedimentary rocks over the basin's history, from its early opening stages, to the mature infilling, or even the ultimate exhumation stages. Finally, these fluids act as major markers for the geodynamic events that structure the basins.

In order to understand the role of fluids in sedimentary basins, several challenges must be met. We must, in particular, determine the source of the fluids, their pathways and the timing of these migrations and releasing at the seafloor. Thus, depending on the geodynamic context of a given basin and on its evolution over time, several fluid migration histories may overlap, though these fluid events are all preserved in the sedimentary record. The goal is thus to identify a number of geophysical, mineralogical and geochemical markers of fluid migration and expulsion. They are closely controlled:
 – by early sediment deformations and fracturing;
 – by the location of bodies and sedimentary sequences likely to temporarily store and/or conduct fluids laterally all along the margin;
 – by allocyclic phenomena such as sea-level variations.

In this special issue, the methods have combined complementary approaches to analyse fluid migrations in sedimentary basins:

- geophysical characterisation based on 2D, 3D and 2D-AUV seismic data, core and exploratory well data;
- sedimentological and mineralogical characterisation based on petrophysical data and crystallographic and texture analyses;
- identification of geochemical markers on samples collected at various depths of the sedimentary column up to the surface;
- definition of the mechanical parameters triggering and controlling fluid re-mobilisation.

The final goal of this research field will be to generate a concept of "fluid sequences" that, in a similar fashion to sequence stratigraphy, will be used as a direct approach to determine the migration pathways and potential traps, and to quantify the volume and nature of expelled fluids. This is of major importance as it will help determining the timing and activity of seafloor fluid expulsion leading to geohazard assessment (catastrophic fluid blow-out, landslide triggering, etc.). As a reverse approach, it will make possible to define the evolutionary status of a sedimentary basis and to infer its geodynamic context at any given period of its history. The aim is thus to significantly improve fluid expulsion models in sedimentary basins, which is a challenge for basin exploration (open window over the petroleum system, seafloor stability and fluid accumulation).

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