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Brittle tectonics and fluids overpressure during the early stage of the Bay of Biscay opening in the Jard-sur-Mer area, (northern Aquitaine Basin, France)

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Abstract – Ba, F, Pb, Ag, Zn mineral deposits are widespread at the northern and eastern boundaries of the Aquitaine Basin. In most cases, they are hosted within high permeability carbonates that rest over the Hercynian basement and below an impermeable layer. Such a position suggests a Mississippi Valley Type (MVT) model for the formation of these deposits. This model is characterized by the lateral flow of sedimentary fluids expelled from the deeper part of the basin and mixed with other sources of water as they reach the basin boundaries. In the Jard-sur-Mer area, which sits in the north of the Basin, these deposits are also found higher in the sedimentary series suggesting that fluids have flown through the impermeable layer. Our field observations demonstrate that a brittle deformation episode, compatible with an upper-Jurassic N-S direction of extension, occurred as the mineralizing fluids were over pressured. The overpressure was the result of a large input of hydrothermal water ascending along inherited faults affecting the Hercynian basement and released at the onset of the tectonics event. When compared with the rest of the basin, these new results at the northern boundary suggests that the Aquitaine Basin recorded several stages of fluid overpressure both at the onset and during the opening of the Bay of Biscay.

Keywords: fluids / overpressure / Aquitaine Basin / brittle tectonics / mineral deposits

Résumé – Tectonique fragile et surpression de fluides au début de l'ouverture du golfe de Gascogne dans la région de Jard-sur-Mer (nord du bassin Aquitain, France). Les gîtes minéraux Ba, F, Pb, Ag, Zn sont fréquents aux limites nord et est du bassin Aquitain. Dans la plupart des cas, ils sont hébergés dans des carbonates de forte perméabilité et limités par le socle hercynien à la base et une couche imperméable à leur sommet. Une telle position suggère un modèle de gisement du type « vallée du Mississippi » (MVT) caractérisés par l'écoulement latéral de fluides sédimentaires expulsés de la partie la plus profonde du bassin et mélangés à d'autres sources d'eau lorsqu'ils atteignent les limites du bassin. Sur la zone de Jard-sur-Mer, au Nord du bassin, ces dépôts se retrouvent également plus hauts dans la série sédimentaire suggérant que des fluides ont traversé la couche imperméable. L'étude, sur le terrain, des structures tectoniques et des dépôts minéraux met en évidence qu'un épisode de déformation fragile, compatible avec une direction d'extension N-S du Jurassique supérieur, s'est produit lorsque les fluides minéralisateurs étaient sous pression. La surpression des fluides résulte d'un apport important d'eau hydrothermale, issues du socle hercynien, qui ont remonté le long des failles héritées et ont été libérée au début de l'événement tectonique. Comparées au reste du bassin, ces nouveaux résultats suggèrent que le bassin aquitain a enregistré plusieurs stades de surpression fluide au début et pendant la phase de rifting associées à l'ouverture du Golfe de Gascogne.

Mots clés : fluides / surpression / Bassin Aquitain / tectonique cassante / minéralisations

1 Introduction

Fluid migration in sedimentary basins is a first order process that controls the formation of hydrological, geothermal, mineral or hydrocarbon resources (Bjørlykke, 1993; Andresen 2012; Gay and Migeon, 2017). Fluids usually migrate through the natural porosity of sedimentary rocks. However, when the fluid pressure is greater than the lithostatic pressure, hydraulic fracturing generates open fractures, which provide additional migration paths for the fluids though brittle structures (Swarbrick

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et al., 2004; Tingay *et al.*, 2009). Hydraulic fracturing can be initiated in a wide range of geological contexts: 1) as a consequence of a porosity decrease during burial (Bureau *et al.*, 2013; Frazer *et al.*, 2014; Suppe, 2014) or sea level rise (Gay and Migeon, 2017), 2) during fluids production associated with devolatilisation reactions (Aarnes *et al.*, 2012), ice melting (Lelandais *et al.*, 2016) or hydrocarbon maturation (Zanella *et al.*, 2015), 3) as the result of heat advection or the build-up of a hydraulic head (Rice, 1992; Laurent *et al.*, 2017), or 4) deformations (Beaudoin *et al.*, 2014). In the field, widely accepted geological evidence for fluids overpressures can be 1) breccias characterized by *in-situ* angular fragments organized in a jigsaw puzzle pattern (Sibson 1986; Jebrak, 1997; Tartarotti and Pasquaré, 2003; Chi and Xue, 2011), 2) coexisting vertical and horizontal veins (Cobbold *et al.*, 2013; Zanella *et al.*, 2015) and 3) decreasing fault dip angles induced by the lowering of the friction angle (Davis *et al.*, 1983; Dahlen 1984; Mourgues and Cobbold, 2006; Collettini, 2011).

Basal unconformities in sedimentary basins are preferential interfaces for fluid circulation as shown by the ubiquity of fluid-related mineral resources located in the first meters of numerous basin deposits (Anderson and Macqueen, 1982; Sverjensky, 1986; Leach *et al.*, 2001). Mississippi Valley Type deposits (MVT), where abundant Cu and U ore fields and half of the worldwide Pb and Zn extraction worldwide are located, represent the striking examples of such fluid circulations (Frazer *et al.*, 2014). In MVT deposits, Pb and Zn deposits are formed through the migration of saline brines from the basin center toward its border within carbonate sequences below a low-porosity layer (Robb, 2005; Leach *et al.*, 2010). In such context, fluid migration can be either due to gravity (*e.g.* hydrostatic head during an uplift), to orogeny (*e.g.* rock compaction and deformation in a fold-and-thrust belt) or to a thermal gradient (*e.g.* thermally induced circulation in permeable sedimentary units; Garven and Raffensperger, 1997, Robb, 2005).

In France, MVT deposits of fluorite and/or barite are documented in the Paris Basin and the Aquitaine Basin (Boiron *et al.*, 2002; Fourcade *et al.*, 2002; Leach *et al.*, 2006; Sizaret *et al.*, 2009, 2004; Cathelineau *et al.*, 2012; Gigoux *et al.*, 2015, 2016). In the Aquitaine Basin (Fig. 1), most of the mineralization have been observed in the Hettangian (ca. 201–199 Ma) units, which are considered as a high permeability layers and below the Toarcian (ca. 182–174 Ma) unit, which forms an impermeable barrier (Boiron *et al.*, 2002; Fourcade *et al.*, 2002; Cathelineau *et al.*, 2012) (Fig. 2). Fluid temperatures and salinity measurements obtained from baryte and fluorite deposits at the northern and eastern boundaries of the Aquitaine Basin, indicate fluid migration from the evaporitic units located in the deeper parts of the Basin (Boiron *et al.*, 2002) (Fig. 1). The age of this fluid event has been estimated at 145–155 Ma (Kimmeridgian to Tithonian times) by $^{40}Ar/^{39}Ar$ on adularia and K/Ar dating on illite (Cathelineau *et al.*, 2012) (Fig. 1).

In this context, the mineral deposits of the Jard-sur-Mer area (northern edge of the Aquitaine Basin, Fig. 1) are an exception because their presence in Callovian units shows that particularly hot fluids have crossed the low-permeability Toarcian unit (Cathelineau *et al.*, 2012).

Recently, several episodes of fluid overpressure-related fracturing have been documented at the southern boundary of the Aquitaine Basin: during the Lower Cretaceous first (Salardon *et al.*, 2017; Renard *et al.*, 2019) and then during the Eocene (Crognier *et al.*, 2018). We focus here on an area that offers good outcropping conditions in the north of the Basin and shows a thick mineralization-bearing cover (Fig. 1). Our objectives are to investigate fluid overpressure occurrences and to explain why mineralization affects a thicker part of the sedimentary series in this area compared to the rest of the Basin. We performed a new structural analysis and mapped observations of fluid/mineral relationships. These new constraints allow us to unravel the relationships between brittle deformation and fluid-related mineralization within the structural framework of this poorly described region.

2 Geological setting

The Aquitaine Basin is located in the southwest of France. This 35 000 km^2 triangular shaped domain is limited to the north by the Armorican Massif, to the east by the French Massif Central, to the south by the Pyrenean mountain belt and to the west by the Bay of Biscay deep basin (Fig. 1). The Armorican Massif and the French Massif Central were intensely deformed as parts of the Hercynian belt from the late Devonian to Carboniferous times. They mainly consist of metamorphic rocks intruded by granitoïds (Ballèvre *et al.*, 2009) and equivalent rocks probably form the basement underlying the Aquitaine Basin.

The Aquitaine Basin recorded a complex Mesozoic to Cenozoic tectonic and sedimentary evolution. During the Mesozoic, the opening of the Atlantic Ocean induced two rifting events. The first one was distributed over the Basin and associated with the deposition of a thick evaporitic sequence; it took place from the Triassic to the Lower Jurassic, prior to the development of an extended Jurassic carbonate platform made up of dolomitic limestones, limestones and marls (Fig. 1; Biteau *et al.*, 2006). The second event occurred in transtension from latest Jurassic to Lower Cretaceous (early Aptian) times, and induced the main rifting phase of the Bay of Biscay (Berriasian to Barremian; Nirrengarten *et al.*, 2018). In the Aquitaine Basin, this event saw the formation of two E-W elongated rift basins, the Parentis and the Arzacq subbasins, which were later aborted (Tithonian to early Aptian; Biteau *et al.*, 2006; Tugend *et al.*, 2015). This rifting phase also led to extreme crustal thinning prior to the onset of oceanic accretion in the Bay of Biscay in latest Aptian-earliest Albian (Montadert *et al.*, 1979; Curnelle and Dubois, 1986; Jammes *et al.*, 2010; Tugend *et al.*, 2015; Nirrengarten *et al.*, 2018). Then, the Iberia-Eurasia convergence resulted in the onset of compression from late Albian to Campanian times (Biteau *et al.*, 2006; Tugend *et al.*, 2015) prior to the main compression phase from uppermost Cretaceous-Paleocene to Chattian (Biteau *et al.*, 2006; Ortiz *et al.*, 2020). Related tectonic inversions were mainly recorded by the southern margin edge of the Aquitaine Basin which became a retro-foreland basin of the growing Pyrenean mountain belt (Biteau *et al.*, 2006; Ford *et al.*, 2016; Angrand *et al.*, 2018; Ortiz *et al.*, 2020). Additionally, seismic profiles indicate that Jurassic deposits in the northern Aquitaine Basin are affected by numerous normal faults that do not affect Upper Cretaceous formations (Huerta *et al.*, 2010; Fig. 1). Faulting is therefore inherited from latest Jurassic transtensional and/or from latest Aptian-earliest Albian crustal thinning (Huerta *et al.*, 2010).

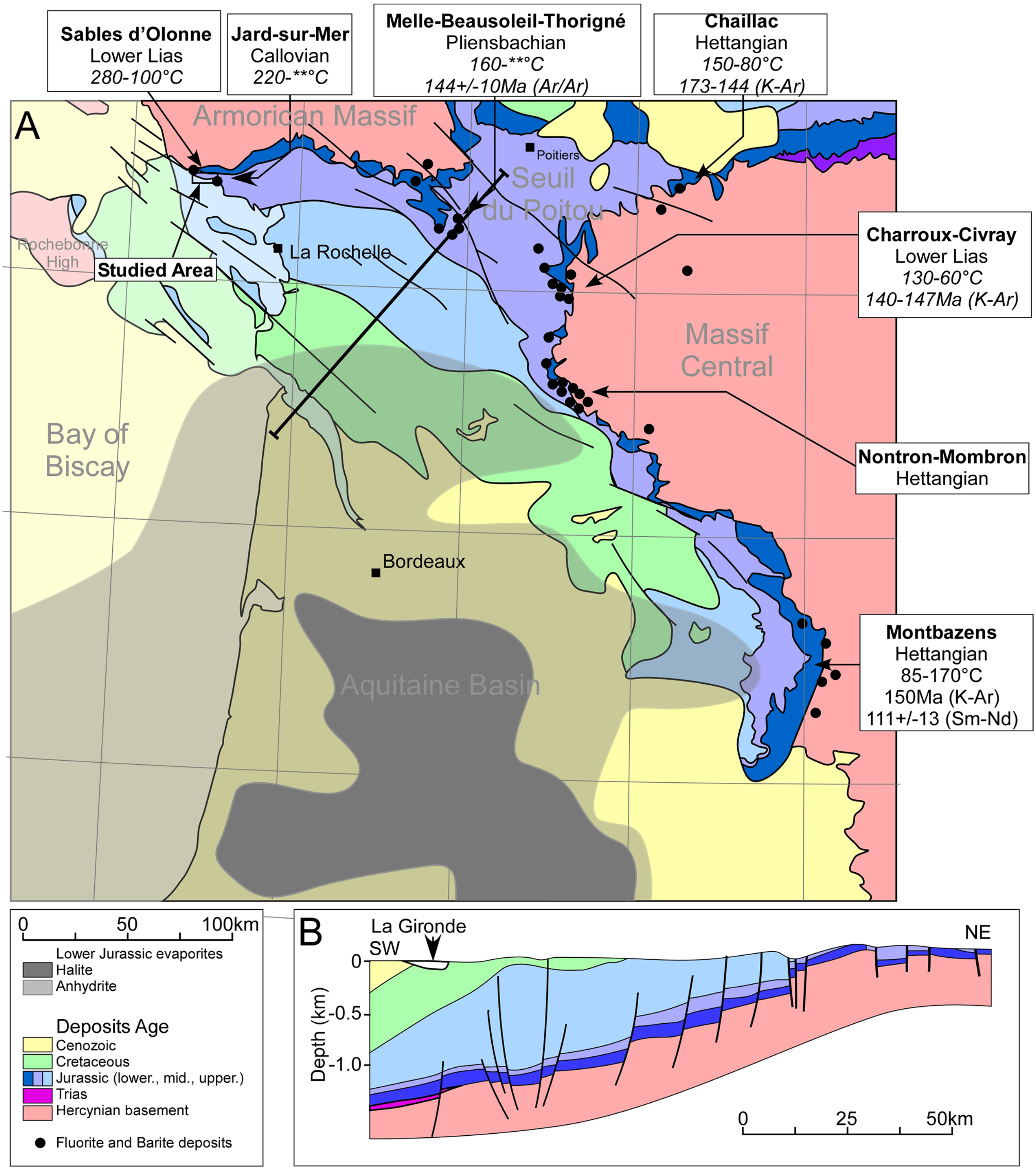

Fig. 1. A: Structural framework of the Aquitaine Basin (after Chantraine *et al.*, 1996). The ages and temperatures of fluorine fluid inclusions and barite deposits are indicated (Boiron *et al.*, 2002; Fourcade *et al.*, 2002; Munoz *et al.*, 2005; Cathelineau *et al.*, 2012). The mapping of the lower Jurassic evaporites is from (Curnelle and Dubois, 1986). B: Cross-section of the southern part of the Poitou High ("Seuil du Poitou", after Karnay *et al.*, 2004).

2.1 Sedimentary formations and basement of the Jard-sur-Mer area (northern edge of the Aquitaine Basin)

The Jard-sur-Mer area is located at northern edge of the Aquitaine Basin, at its present-day boundary with the Armorican Massif (Fig. 1). The Armorican basement which is mainly composed of metamorphic rocks in its southern part here consists of kyanite-, garnet- and staurotide-bearing micaschists with a well-expressed eastward dipping foliation. This foliation is related to at least two folding events caused by

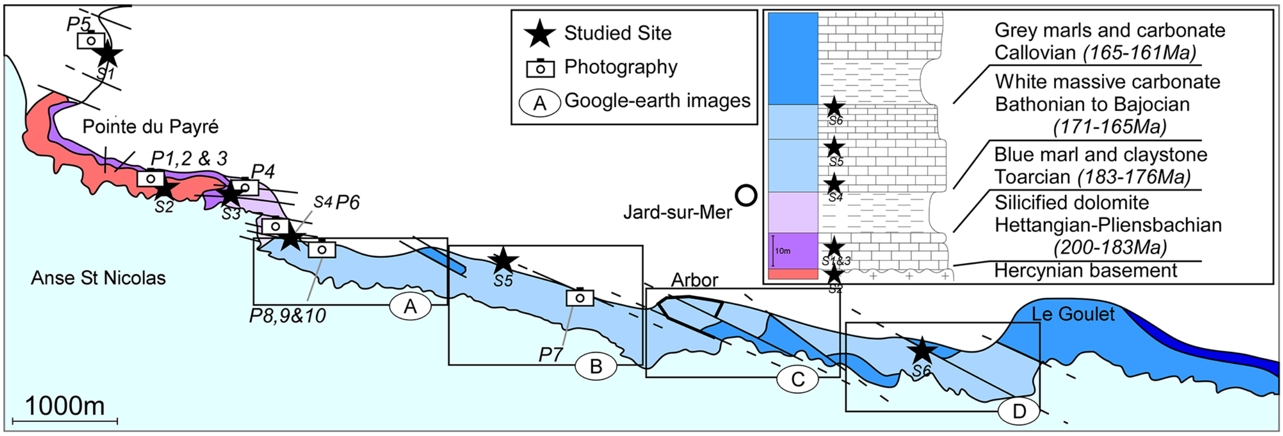

Fig. 2. Location of the photographs and diagrams shown in Figures 4–6: on a geological map and on a stratigraphic column (inset, after Goujou *et al.*, 1994).

a complex polyphased tectonic history during the Hercynian orgeny (Fig. 2; Goujou *et al.*, 1994). The micaschists crop out to the west of the Jard-sur-Mer area where they are topped by the Hercynian unconformity (Fig. 2; Ters and Gabilly, 1986; Goujou *et al.*, 1994). Geomorphological analysis have shown that the Hercynian belt was almost leveled through denudation processes that resulted in a first generation of pre-Hettangian (ca. pre-200 Ma) planation surfaces. The Hercynian unconformity corresponds here to these surfaces associated with partly stripped weathering products (Ters, 1988; Wyns, 1991; Bétard, 2010).

The basement and this unconformity are overlain by the transgressive Jurassic cover that gently dips to the southwest. The sedimentary succession is composed of four units that consist of 10 m to 30 m thick carbonates alternating with 10 m to 40 m thick marls and can be described in details as follows (Fig. 3; Goujou *et al.*, 1994):

- *Hettangian to Piensbachian unit* (201–183 Ma; 13 m thick);
- Dolomitic limestones that laterally grades to dolomitic clays and locally overlain a thin transgressive dolomitic conglomerate composed the base of the unit whereas argillaceous limestones forms its upper part. This unit is locally strongly silicified and some dolomitic limestones have penetrated the basement through foliation planes;
- *Toarcian to Aalenian unit* (183–170 Ma; 18 m thick) – Blue marls form most of the unit with some argillaceous limestones and nodular limestone levels;
- *Bajocian – athonian unit* (170–166 Ma; 37 m thick) – Fossiliferous grey limestones that stand upon a thin conglomerate are located at the base of the unit. Most of the succession is made of sandy to pebbly limestones that are locally ferruginous. Thin levels of phosphate cobbles occur close to the top of the unit, which ends with a hardground;
- *Callovian unit* (166–163 Ma; more than 60 m) – The basal part consists of argillaceous limestone that grades into 30 m thick grey marls, which subsequently grade to alternating argillaceous limestones and marls. These limestones are overlain by impermeable blue marls that are at least 10 m thick.

Several authors provides geomorphological (*e.g.* Bétard, 2010), sedimentological (*e.g.* Enay *et al.*, 1980) and thermochronological (*e.g.* François *et al.*, 2020) evidence for a larger extension of the Aquitaine Basin across the Hercynian basement during Jurassic times and even during Upper Cretaceous times whereas denudation during the Early Cretaceous and the Eocene induce the formation of two generations of planation surfaces (Wyns, 1991; Bétard, 2010; Bessin *et al.*, 2015).

2.2 Occurrence of mineralization in the Jard-sur-Mer area (northern edge of the Aquitaine Basin)

The occurrences of mineralization of Jard-sur-Mer area were described by Cathelineau *et al.* (2012). These authors show that the widespread mineralization within the first metres of the dolomitic to argillaceous limestones of the Hettangian to Pliensbachian unit (Fig. 3), under the blue marls of the Toarcian to Aalenian unit (Fig. 3) are related to fluid circulations. The evidence is the almost complete silicification of the Hettangian to Pliensbachian unit (Fig. 2; Goujou *et al.*, 1994) together with occurrences of mineralized lenses and veins composed of quartz, barite, sulfides, Ag-rich galena and sphalerite within this unit. Quartz and calcite veins located upward in the sedimentary units especially within argillaceous limestones of the Callovian unit were also described by Cathelineau *et al.* (2012). Fluid inclusion microthermometry, oxygen and carbon stable isotope analysis, and Sr analysis on the Aquitaine Basin edges have shown heterogeneous compositions and heterogeneous trapping temperatures of the fluids (see compilation in Fig. 1; Boiron *et al.*, 2002; Fourcade *et al.*, 2002; Cathelineau *et al.*, 2012).

At least tree possible sources of fluid have been identified (Boiron *et al.*, 2002; Fourcade *et al.*, 2002; Cathelineau *et al.*, 2012):

- *Sedimentary brines*: this source is indicated by highly saline brines trapped at temperature ranging between 100 and 200 °C. Brines were expelled from the Triassic evaporites that migrated from the central part of the basin along the sediment cover/basement;
- *Meteoric/Hydrothermal waters*: low salinity water trapped at temperature higher than 250 °C indicate such a source. Meteoric waters infiltrated from emerged zones and

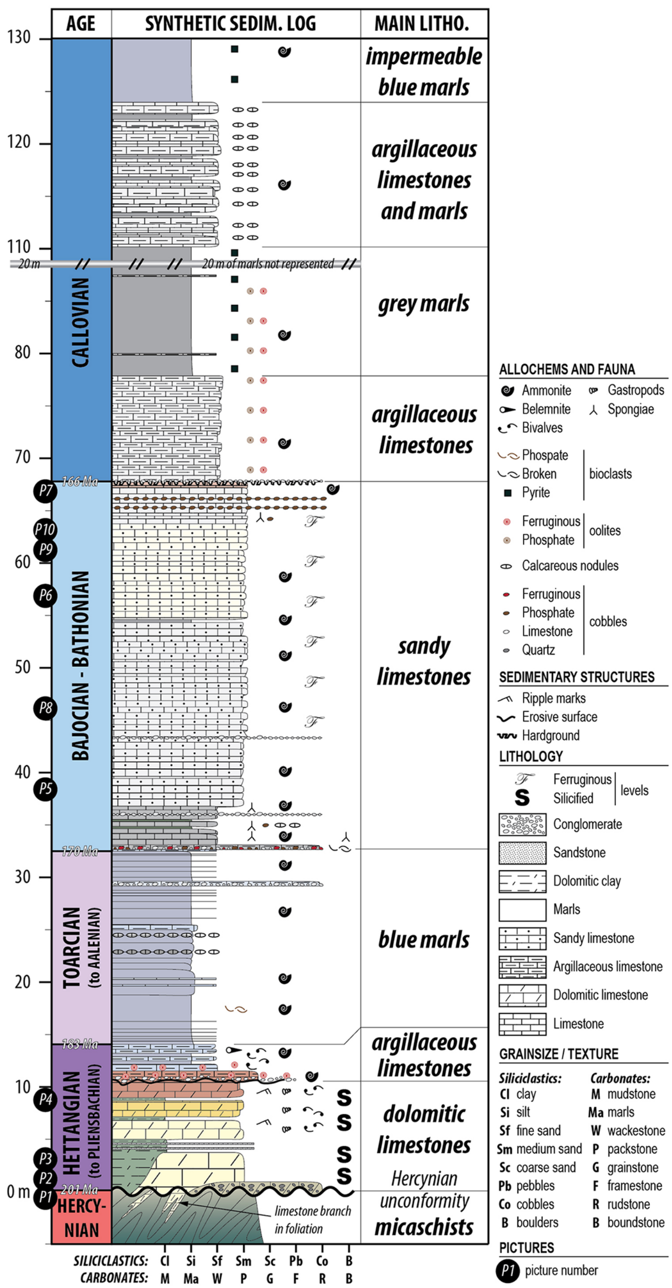

Fig. 3. Synthetic log of the sedimentary succession of the Jard-sur-Mer area (drawn after Goujou *et al.*, 1994).

underwent convection when heated at depth prior to their ascension;

– *Penetrating seawater*: this source is typically associated with low salinity and low temperature (around 50 °C) fluids. Seawater penetrating sedimentary cover (and basement) or connate water released during dissolution of carbonate.

3 Data and methods

In this study, we mapped brittle structures and performed structural field work focused on faults and mineralized veins within a coastal area near Jard-sur-Mer (northern Aquitaine Basin) to unravel relationships between deformation and fluid-related mineralization. We use GIS program to map at a 1:1500 scale the sedimentary layers and brittle structures (lineaments) affecting mainly the Bajocian-Bathonian and Callovian units. These structures can be identified easily on this high-resolution imagery thanks to the low dip angles of the layers and the favorable outcropping conditions. Mapping is based on high-resolution (ca. 5 cm) aerial and satellite imagery dataset available in Google Earth©. Secondly, we performed field observations in the Jard-sur-Mer area, mainly focusing on the sea-cliffs where mineralized veins and faults are well exposed. Along the study area, we measured and geolocalized faults and mineralized veins directions, dips and striae plunges (120 measures). We paid a peculiar attention to the structural and chronological relationships between faults and mineralizations, which are best observed in six stations (S1 to S6, Fig. 2). We also conducted a field petrography analysis on outcrops in order to define the paragenetic succession within the mineralized deposits. During low tides, we made further structural observations on the rocky foreshore to control our GIS mapping of faults and to determine if they are associated with mineralized deposits or not. We used the Stereonet© and Faultkin© computer programs to plot our structural measurements in stereographic canvas and to produce stress tensor inversions following the stress inversion method of Allmendinger *et al.* (2011).

4 GIS mapping and structural analysis results

Thanks to its location on the present-day shore of the Atlantic Ocean, at the edge between the Armorican Massif and the Aquitaine Basin (Fig. 1), the Jard-sur-Mer area provides excellent conditions for field observations of the Hercynian basement and the Lower to Middle Jurassic sedimentary cover over several kilometres. The Hercynian basement and unconformity can be exceptionally well observed all along the 2 kilometers long cliff of the *Pointe du Payré.* The Hettangian to Pliensbachian unit outcrops along the 300 m long rocky foreshore of the *Anse St-Nicolas* (Fig. 2 and Fig. 4-P1; Ters and Gabilly, 1986). The Bajocian– Bathonian and the Callovian units outcrop well from the east of the *Anse St-Nicolas* to *Le Goulet* whereas the Toarcian to Aalenian unit only outcrops at low tide in the *Anse St-Nicolas* where it is covered by algae (Fig. 2).

On every unit, we observed fault planes (which typically bear striae) and mineralized veins (Fig. 4 and Fig. 5). Mineralized veins are filled with quartz (*e.g.* Fig. 4-P4, Fig. 5-P5, P8 and P10), barite (*e.g.* Fig. 4-P2 and P4, Fig. 5-P8 and P9), calcite, and sulfides crystals (*e.g.* Fig. 4-P4). Veins are generally 3 to 4 cm thick in the sedimentary cover (Fig. 4-P2 and P4) and can be followed over tens of metres. We also observed the same mineral association on the fault planes and the striae indicate normal displacements, sometimes combined with strike-slip movements (*e.g.* Fig. 4-P3 and Fig. 5-P10).

4.1 Brittle structures and mineralized veins within the Hercynian basement

Most of the basement deformation is recorded in the eastward dipping foliation of the garnet-, kyanite- and

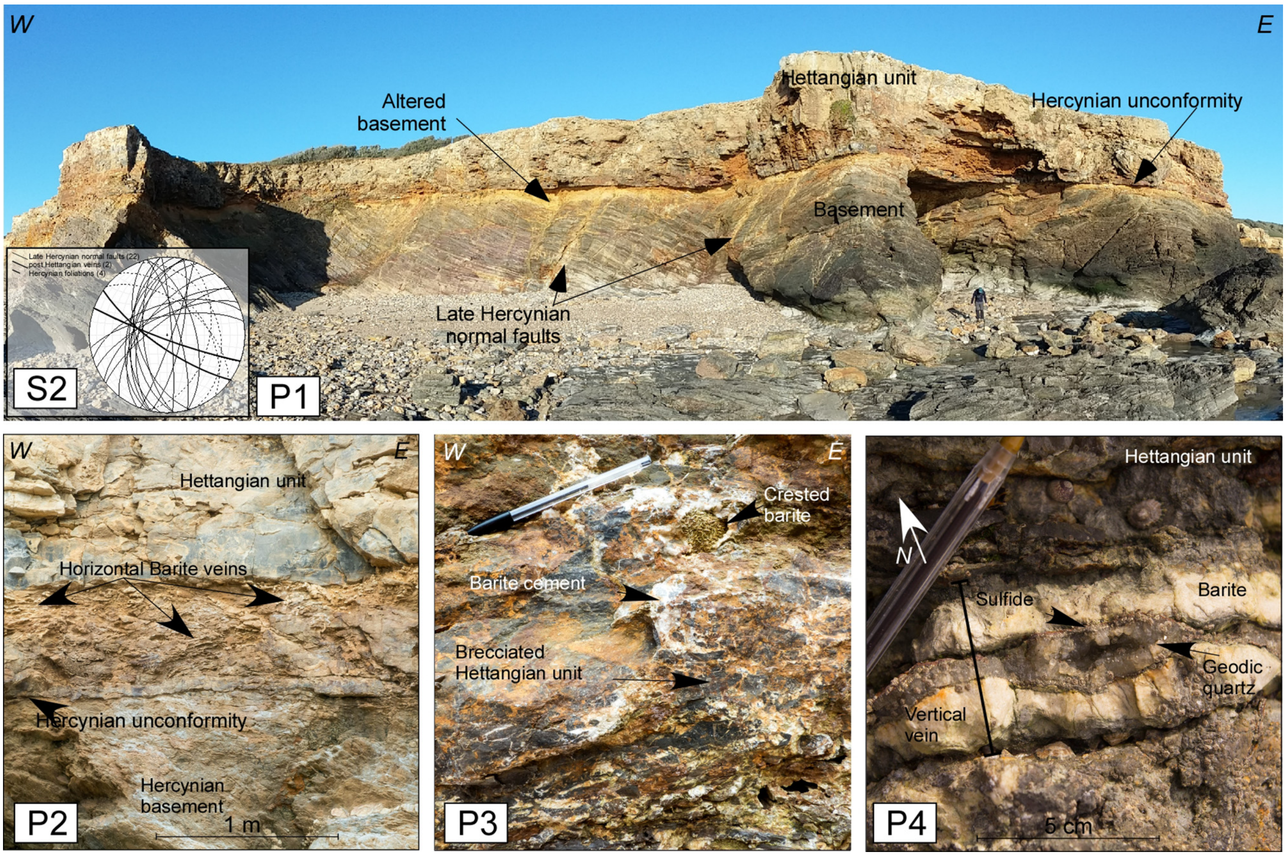

Fig. 4. Interpreted photographs of brittle structures in the Armoricain Massif and Aquitaine Basin. See Figure 2 for location. P1: panoramic view of the discontinuity between foliated micaschists and the Hettangian sedimentary unit. Note the alteration of the basement below the discontinuity and along inherited late hercynian faults. P2: horizontal veins crosscutting the Hettangian unit. P3: hydraulic breccias sealed by barite and quartz deposits. P4: vertical vein crosscutting the Hettangian unit. S2: Stereographic projection of faults and schistosity planes; late hercynian and Jurassic faults planes have been recognized on the basis of their relationship with the discontinuity.

staurotide-bearing micaschists (Fig. 4-P1). However, we observed several brittle structures that cross-cut the foliation and are almost all truncated by the Hercynian unconformity and sealed by transgressive dolomitic limestones of the Hettangian to Pliensbachian unit (Fig. 4-P1). The strike directions of these fault planes range from N-S to NNW-SSE, dipping mostly westward (Fig. 4-S2). Fault plane surface is covered by clay and per place baryte masking the striaes. Drag folds within the micaschists foliation indicate normal motions associated with faulting.

We observed only two occurrences of a fault affecting both the basement and the overlying Hettangian to Pliensbachian sedimentary unit along the 2-km long cliff where the basement outcrops (Fig. 4-P1). These fault planes have a E-W strike directions and show normal displacement similar to those observed in the Mesozoic sedimentary cover (Fig. 4-S2; see §4.2).

Within the first metres of basement rocks below the Hercynian unconformity, we also identified an upward colour change from grey or blue-grey to pale yellow (Fig. 4-P1). We observed a similar colour change within the rocks adjacent to each fault plane in the basement (Fig. 4-P1).

4.2 Brittle structures and mineralized veins within the Hettangian to Pliensbachian unit

According to our field observations, the Hettangian to Pliensbachian unit is the most intensely faulted and mineralized sedimentary unit in the Jard-sur-Mer area. Numerous normal faults strike W-E to WNW-ESE (Fig. 6-S1). Their dip directions are homogeneously distributed between N and S directions and define dihedral patterns. Dip values range between 80° and 20° (Fig. 6-S1) and several fault planes present the arcuate shape of listric faults (Fig. 5-P5). Only a few of these faults cross-cut the Hercynian unconformity and affect the basement (see §4.1). The stress tensor we calculated for the Hettangian to Pliensbachian unit is characterized by a vertical σ_1 whereas the horizontal σ_2 and σ_3 are striking between N90 to N110 and N0 to N20, respectively (Fig. 6-S1).

On the coastal cliff of the *Pointe du Payré* and the foreshore of the *Anse St-Nicolas*, we could observe mineralized veins very well (Fig. 2). They are filled by barite, sulfides and quartz. The geometric relationships between mineral phases indicate that barite crystallized first, followed by sulfides and

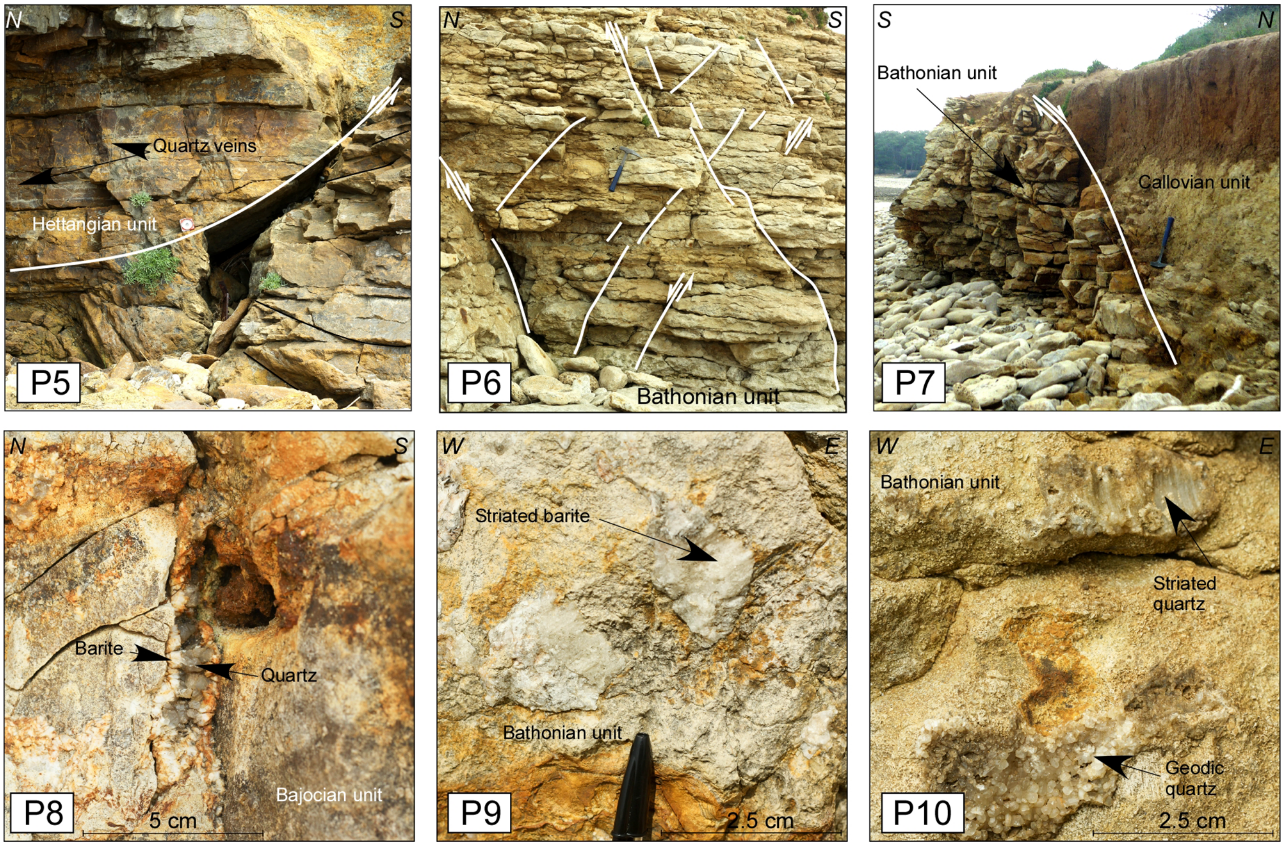

Fig. 5. Interpreted photographs of brittle structures in the Jard-sur-Mer area (Aquitaine Basin). P5: listric normal faults located near the discontinuity and crossing the Bathonian unit; P6: conjugated normal faults crossing the Bathonian unit; P7: high angle normal fault located forming the contact between Bathonian unit to the left and Callovian unit to the right; P8: barite and subsequent quartz fillings in a vertical vein in the Bajocian unit; P9 and P10: fault planes within the Bathonian unit. The geodic quartz and the striated quartz and barite suggest that faulting is coeval with mineral crystallization. See Figure 2 for the location of each picture.

then quartz (Fig. 4-P4). We can distinguish two groups of veins from their orientation and size. The first group consists of vertical veins striking between N90 to N120 affecting the whole Hettangian to Pliensbachian unit (Fig. 4-S2). Most of these veins contain barite and quartz, while thin layers of sulfides are sometimes located between these two minerals (Fig. 4-P4). Along the *Anse St-Nicolas* rocky foreshore where veins can be followed for more than 10 m, a very large amount of veins is concentrated within the heterogeneous few metres of the Hettangian to Pliensbachian unit composed of dolomitic limestones alternating with dolomitic clays and thin marl and sandy to conglomeratic levels (Fig. 3). The second group consists of nearly horizontal and bedding-parallel barite veins located in 2 to 3 m long for 0.5 m thick lenses where several veins are stacked (Fig. 4-P2). This group is only observed in the first few metres of the Hettangian to Pliensbachian unit and outcrops along the coastal cliff of the Pointe du Payré (Fig. 2 and Fig. 4-P1). When automorphic crystals are present, their growth directions are orthogonal to the vein boundaries (Fig. 5-P4).

Near the base of Hettangian to Pliensbachian unit in the neighborhood of the horizontal veins, we also noticed breccias locally following the bedding. They are composed of angular Hettangian dolomitic clasts suggesting an in situ formation. The cement is made of barite (Fig. 4-P3).

4.3 Brittle structures and mineralized veins within the Bajocian-Bathonian and the Callovian units

Brittle structures and mineralized veins are less abundant within the Bajocian-Bathonian and the Callovian units and they could not be observed within the marly Toarcian to Aalenian unit due to bad outcrop conditions. The strike directions of fault planes range from W-E to WNW-ESE and their dip directions between N and S (Fig. 5-P6 and Fig. 6). Striated elements related to these faults are made of Jurassic carbonate and mineralized deposits. Depending on their position along fault planes, these deposits often form automorphic to sub-automorphic crystals preserved in cavities. They can be striated in several places, and automorphic and striated crystal often coexists (Fig. 5-P9 and P10). The fault dips are greater in the Bajocian-Bathonian and Callovian units (Fig. 5-P6 and P7) than in the Hettangian to Pliensbachian unit (Fig. 5-P5). In addition, dip angles increase upward from the old to the younger sedimentary units (Fig. 6). The stress tensors we calculated for each station are consistent with one another: σ_1 is vertical while the

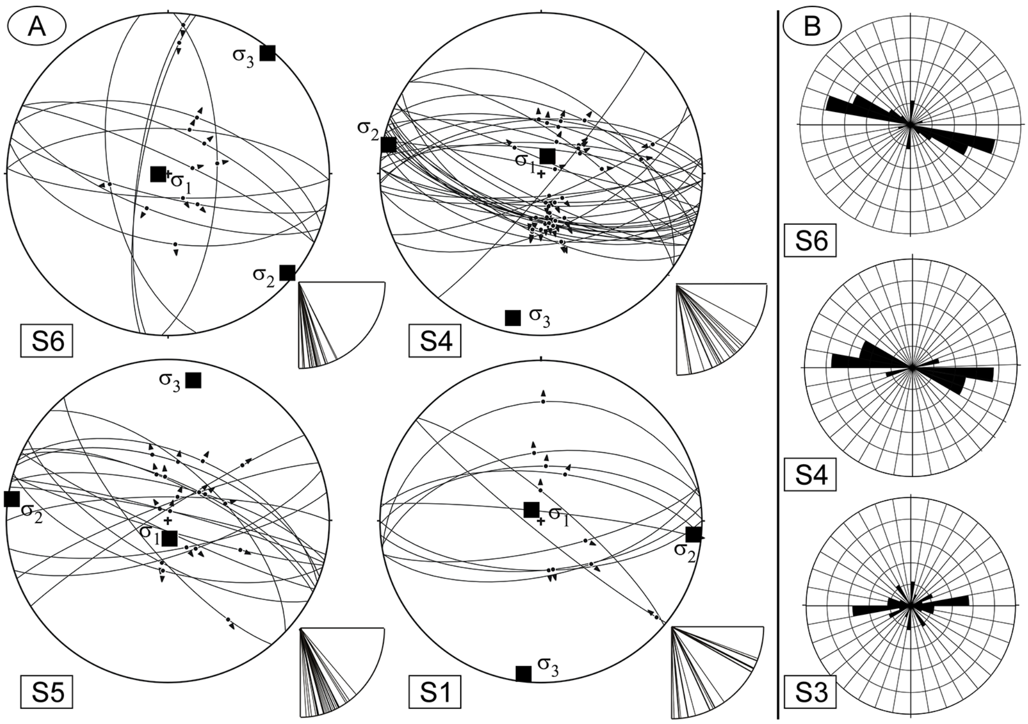

Fig. 6. Structural data of the Jard-sur-Mer sedimentary cover. A: Stereographic projection of faults and related stress tensors (full circles), and fault dips (quarter circles); B: Rose diagrams of vein strikes. See Figure 2 for the location of structural measurements in map and in the stratigraphic series.

horizontal σ_2 and σ_3 are striking between N90 to N110 and N0 to N20, respectively (Fig. 6). In addition, we mapped 183 lineaments on Google Earth© from aerial and satellite imagery and controlled their occurrence on the rocky foreshore during field work (Fig. 7). These lineaments can reach up to 1 km long because they are roughly parallel to the shoreline and not limited by the width of the rocky foreshore. These lineaments display consistent apparent directions: 80% of their strikes range between N100 and N130 (Fig. 7E). Our field observations indicate that these lineaments correspond to brittle structures, *i.e.* faults and mineralized veins. While their orientations seem relatively constant, there is a noticeable decrease in their density from the base of the Bajocian-Bathonian unit to the top of the Callovian one (Figs. 7A–7D). This upward decrease is validated by our field observations of the coastal cliff. Indeed, we carried out 36 measurements of striated fault planes at the base of the Bajocian-Bathonian unit (Fig. 2 and Fig. 6-S4), 18 measurements in its middle part (Fig. 6-S5) but we found only 12 striated planes on the 2500 m long shoreline east of the Jard-sur-Mer harbor (Fig. 6-S6).

Within the lower part of the well-exposed Bajocian-Bathonian unit immediately east of the *Anse St-Nicolas*, we observed mineralized veins that contain barite, sulfides and quartz crystals following the same crystallization sequence as in the previously detailed Hettangian to Pliensbachian unit (Fig. 5-P8; see Sect. 4.2). Going upward within the Bajocian-Bathonian and the Callovian units, the veins are mostly composed of calcite. However, calcite was not observed in direct association with other minerals and its timing of crystallization relative to barite, sulfides and quartz remains unconstrained.

5 Interpretation and discussion

5.1 The structural record of the late Jurassic N-S tectonic extension

Our observations and measurements of faults in the Jard-sur-Mer area are consistent within the Hettangian to Pliensbachian, Bajocian-Bathonian and Callovian units, including the pair that affects the basement. They indicate the preservation of a normal faulting event with a vertical σ_1 and horizontal σ_2 and σ_3 with striking direction ranging between N90° to N110 and between N0 to N20, respectively (Fig. 6-S1, S4, S5, S6). These results are coherent with the orientation of mineralized veins with strike directions ranging from N90 to N120 and nearly vertical dips (Fig. 6-S3, S4, S6), and with crystal growth directions orthogonal to vein boundaries. We interpret this good agreement between fault and vein orientations, together with the coexistence of automorphic and striated crystals of quartz and barite along fault planes (Fig. 5-P9 and P10) as evidence that the tectonic and fluid migration events are coeval.

The fluid event, that is assumed to be of regional importance (Fig. 1) was dated between 146 and 156 Ma (Kimmeridgian to Tithonian) in several places of the Poitou High (Cathelineau *et al.*, 2012). This lead us to propose a similar age for the fluid and brittle tectonic event in the Jard-sur-Mer area. In addition, very consistent NNE-SSW

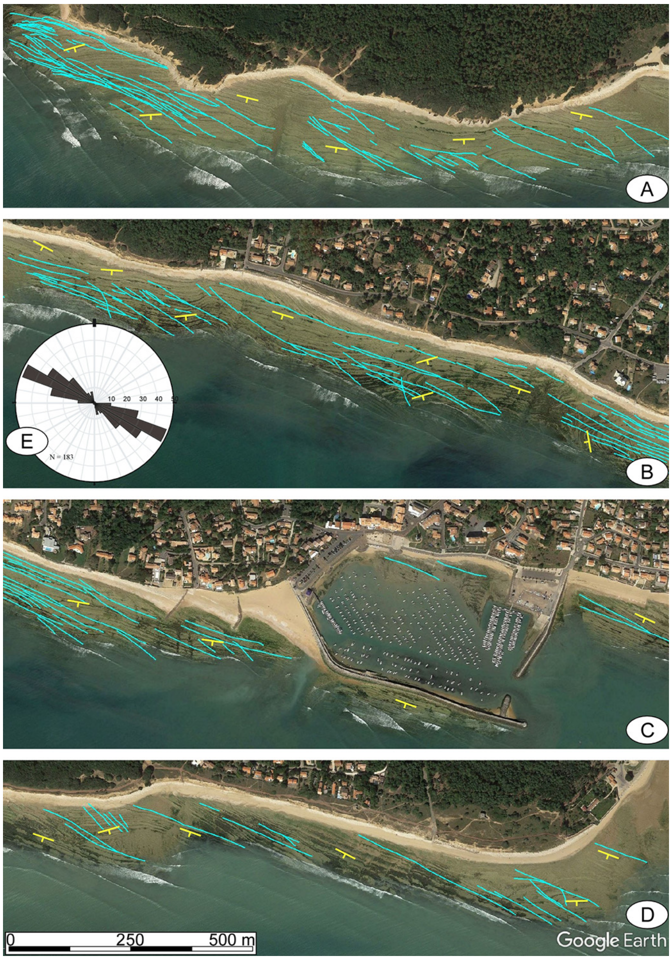

Fig. 7. A, B, C and D lineament maps of the Jard sur mer area plotted over Google Earth images (acquisition date: 03/09/2014) and E: rose diagram of the lineament strikes. See Figure 2 for location.

directions of extension dated from late Jurassic time are deduced i) from brittle structures analysis of the Poitou High area (Karnay *et al.*, 2004; Cariou *et al.*, 2006), ii) from a mineralized veins study of the western boundary of the French Massif Central (Munoz *et al.*, 2005) and iii) from regional thickness variations of Kimmeridgian deposits (Thomas *et al.*, 1996). These results suggest a Kimmeridgian-Tithonian tectonic event of regional importance (Fig. 1) and lead us to interpret i) the NNE-SSE extension faulting we observed as part of this event and ii) that fluids-related mineralization are coeval with it.

At the scale of the Aquitaine Basin, this event is interpreted as the onset of individualization of the sub-basins to extreme crustal thinning prior to the onset of oceanic accretion in the Bay of Biscay in latest Aptian-earliest Albian (Montadert *et al.*, 1979; Curnelle and Dubois, 1986; Jammes *et al.*, 2010; Tugend *et al.*, 2015; Nirrengarten *et al.*, 2018). Thus, our observations on the Jard-sur-Mer area, together with previous studies (Thomas *et al.*, 1996; Karnay *et al.*, 2004; Munoz *et al.*, 2005; Cariou *et al.*, 2006) suggest that the earliest stage of extension propagates far from the central part of the Aquitaine Basin and reaches its northern boundaries.

5.2 Geological evidences for fluid overpressure

In addition to coeval fluids circulations and brittle tectonics, our results show three main points regarding fluid overpressure within the Hettangian unit. First, we document for the first time the occurrence of breccias characterized by angular fragments of dolomitic limestones cemented by barite (Fig. 4-P3). These form a peculiar jigsaw puzzle pattern often interpreted as fluid-assisted brecciation in a context of fluid overpressure (Jebrak, 1997; Sibson 1986; Tartarotti and Pasquaré, 2003; Chi and Xue, 2011).

Second, we describe flat lying veins with crystals that grow orthogonally to vein borders (Fig. 4-P2 and P4). Following other studies in different basin areas, we propose that such horizontal veins and crystal growth indicate that fluid pressure has exceeded the lithostatic pressure and produced hydraulic fractures (Cobbold and Rodrigues, 2007; Chi and Xue, 2011; Cobbold *et al.*, 2013).

Third, we illustrate that normal fault dip angles decrease downward within the sedimentary cover to display listric pattern near the Hercynian unconformity (Fig. 5-P5). Such a decrease corresponds to a decrease of the internal friction angle of the faulted material near the base of the Mesozoic series that cannot be explained by lithological changes. We propose that the decrease of the internal friction angle was due to an increase of the fluid pressure and lead to the formation of a "décollement" level as observed in several other tectonic contexts (Davis *et al.*, 1983; Dahlen 1984; Mourgues and Cobbold, 2006; Collettini, 2011).

Because these structures are limited to the Hettangian to Pliensbachian unit, we propose that fluid overpressure is partly responsible for the rupture of the sedimentary cover in a state of stress compatible with the N-S to NNE-SSW direction of extension. Fluid overpressure might also explain mechanical decoupling at the base of the sedimentary cover.

5.3 Fluids and tectonics interaction in the Jard-sur-Mer area

Cathelineau *et al.* (2012) provided Th and salinities estimates on fluids related to mineralization of *the Anse St-Nicolas* and an area located 6 km north called Les Sards mine. These authors estimated Th and salinities ranging from 100 to 280 °C and from 4–7 to 20–21 wt.% eq. NaCl on quartz and geodic quartz within the Hettangian to Pliensbachian units (Fig. 8B). Within fractures of the Callovian unit, they obtained temperature and salinities ranging from 120 to 220 °C and from 2–3 to 3–5 wt.% eq. NaCl (Fig. 8B).

Assuming this and considering fluids mixing as already proposed on the northern part of Aquitaine basin (Boiron *et al.*, 2002; Fourcade *et al.*, 2002; Cathelineau *et al.*, 2012), we propose that the fluids of highest salinity values were probably present within the Hettangian to Pliensbachian units prior to faulting event, as this is not documented above in faults and veins affecting the Mesozoic series. Such fluids could represent the earliest sources of mineralization on our area and are related to sedimentary brines (Fig. 8B). Following this assumption, the decrease of salinity values together with the slight increase of Th within the Hettangian to Pliensbachian units could be related to the increase of the amount of low

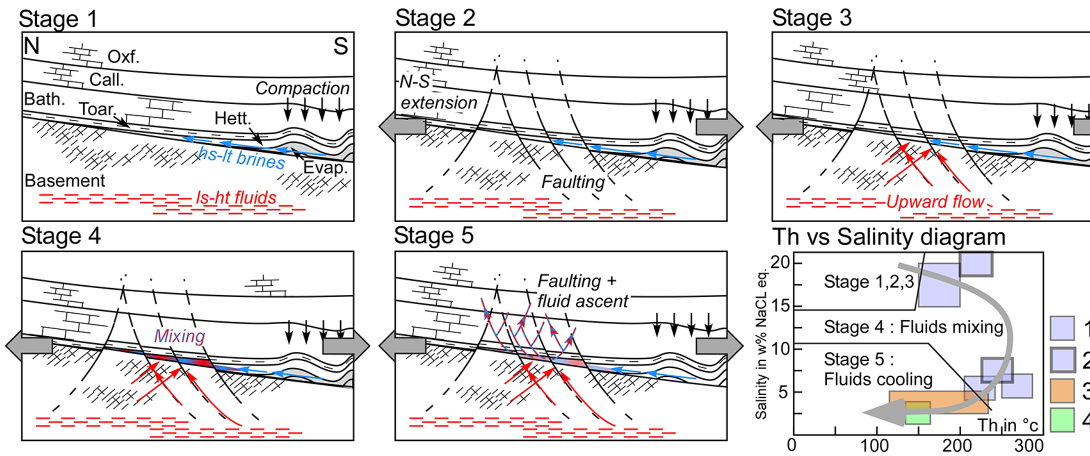

Fig. 8. A: a possible five-step fluid and tectonic evolution of the Aquitaine basin in the Jard-sur-Mer Area during the Jurassic (see text for explanations). B: Salinity and temperature evolution of fluids during stages 3 to 5 (modified after Cathelineau *et al.*, 2012). 1: anhedral quartz from Hettangian unit, 2: geodic quartz from Hettangian unit, 3: quartz within fault planes of the Bathonian unit, 4: geodic quartz following barite from the Hettangian unit.

salinity and high temperature hydrothermal water released from the Hercynian basement at the onset N-S extension. Graded color changes observed in the basement below the Hercynian unconformity of the Jard-sur-Mer area (Fig. 4-P1) have also been described in the Seuil du Poitou area (Cathelineau *et al.*, 2012) and interpreted as alteration related to fluids circulations. Similar observations around of basement fault planes lead us to propose that fluids related to baryte deposits have circulated within the inherited basement faults.

In the Jard-sur-Mer area, mixing fluids are also described in veins from the Callovian unit (Cathelineau *et al.*, 2012) suggesting that overpressure results from the inflow of low salinity and high temperature water within the Hettangian to Pliensbachian units (Fig. 8B). The wide range of Th with no significant salinity changes in veins present in the Callovian unit is explained by the cooling of mixed fluids as they flow through the sedimentary cover.

Therefore, we propose that an inflow of a low salinity water heated at depth as already described (Boiron *et al.*, 2002; Fourcade *et al.*, 2002; Cathelineau *et al.*, 2012) is responsible for fluids overpressure at the base of the Aquitaine Basin and the formation of brittle structures such as veins and normal faults in the overlying cover.

5.4 possible scenario for fluids and tectonic interaction (Fig. 8)

This scenario of fluids and tectonic structures interactions is summarized in a five-stage scenario (Fig. 8):

- *Stage 1* (Middle Jurassic): High salinity and low temperature (hs-lt) brines were expelled from Triassic to Lower Jurassic evaporites located in the central part of the Aquitaine Basin according to Boiron *et al.* (2002), Fourcade *et al.* (2002) and Cathelineau *et al.* (2012). Brines migrated along the sediment cover/basement and reached the Jard-sur-Mer area in a context of Mississipi Valley type deposit. Long lasting subsidence during the Jurassic (Brunet, 1994) suggests that such a process may have occurred prior to the tectonic event.
- *Stage 2* (Upper Jurassic): The Aquitaine Basin recorded an N-S extensional tectonic phase. This was responsible for the formation of several E-W normal fault affecting the basement and cover (Fig. 1B) while this change of stress constraints probably affected the preexisting fracture network, therefore inducing porosity changes. Deformation is dated from the upper Jurassic (Thomas *et al.*, 1996; Karnay *et al.*, 2004; Cariou *et al.*, 2006).
- *Stage 3* (Upper Jurassic): A second fluids consisting of Low salinity and high temperature hydrothermal water (ls-ht) was released from the Hercynian basement (Boiron *et al.*, 2002; Fourcade *et al.*, 2002; Cathelineau *et al.*, 2012). It migrated upward along inherited late Hercynian brittle structures and reached the discontinuity.
- *Stage 4* (Upper Jurassic): hs-lt brines and ascending ls-ht hydrothermal water mixed together and lead to the formation of the first mineral deposits. Mean salinity decreased whilst temperature increased up to 250 °C. Assuming a possible 30 to 50 °C geothermal gradient, such a temperature suggests that ascending ls-ht water were released several kilometers deep. As a consequence of the new influx at the base of the Aquitaine Basin, fluid overpressure started to increase within the Hettangian to Pliensbachian unit, and internal friction angle began to progressively decrease.
- *Stage 5* (Upper Jurassic): Under sufficiently overpressured conditions the sedimentary cover started to fracture, leading to the formation of E-W veins and normal faults filled with mineral deposits. Within the Hettangian to Pliensbachian units, the low internal friction angle was responsible for the formation of listric faults and fault dip angles became steeper in the overlying Bajocian-Bathonian and Callovian units.

Such a scenario is possibly unique in the northern part of the Aquitaine Basin as mineral deposits are limited to Hettangian to Pliensbachian units elsewhere (Boiron *et al.*, 2002; Fourcade *et al.*, 2002; Cathelineau *et al.*, 2012). In these locations, higher minimum salinity and lower maximum temperature suggests a smaller contribution of ascending ls-ht hydrothermal water than in the Jard-sur-Mer area. Thus fluids overpressure cannot be ruled out but it was probably not sufficient to initiate brittle structures.

In the southern part of the Aquitaine Basin, structures and mineral deposits related to fluid overpressure have also been described (Salardon *et al.*, 2017; Renard *et al.*, 2019). However, fluid circulations and fluid overpressure are suspected to have occurred during extreme crustal extension associated with the opening of the Bay of Biscay and to interact with exhumed mantle (Salardon *et al.*, 2017; Corre *et al.*, 2018, Renard *et al.*, 2019).

6 Conclusion

Structural analysis of brittle structures together with field observations of numerous mineralized deposits of the Jard-sur-Mer area (north of the Aquitaine Basin) highlight the record of a N-S to NNE-SSW extension phase dated from Kimmeridgian to Tithonian times representative of a regional state of stress. Major decoupling between basement and cover, horizontal veins and hydraulic breccias suggest that basement-trapped fluids and sedimentary brines interacted at the Hercynian unconformity and underwent overpressure. The fluid overpressure is proposed to have resulted from the ascent of low salinity water along inherited late Hercynian brittle structures and released at the onset of the N-S to NNE-SSW extension phase. Observed fluid temperatures are consistent with a fluid source several kilometre deep into the continental crust.

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