Are stylolites fluid-flow efficient features?

Bruna, Pierre Olivier; Lavenu, Arthur P.C.; Matonti, Christophe; Bertotti, Giovanni

DOI
10.1016/j.jsg.2018.05.018

Publication date
2019

Document Version
Accepted author manuscript

Published in
Journal of Structural Geology

Citation (APA)
Bruna, P. O., Lavenu, A. P. C., Matonti, C., & Bertotti, G. (2019). Are stylolites fluid-flow efficient features? *Journal of Structural Geology*, *125*, 270-277. https://doi.org/10.1016/j.jsg.2018.05.018

Are stylolites fluid-flow efficient features?

Pierre-Olivier BRUNA[(1)*], Arthur P.C. LAVENU[(2)], Christophe MATONTI[(3)] and Giovanni BERTOTTI[(1)]

(1) Department of Geoscience and Engineering, Delft University of Technology, Delft, the Netherlands
(2) ADNOC Offshore, PO Box 303, Abu Dhabi, U. A. E.
(3) Aix-Marseille Université, CNRS, IRD, CEREGE, Um 34, 3 Place Victor Hugo (Case 67), 13331 Marseille Cedex 03, France

* Corresponding author, p.b.r.bruna@tudelft.nl

Keywords: drains, barriers, stylolite life cycle, roughness, insoluble

Abstract

It sounds counter-intuitive to consider contraction features such as stylolites as potential conduits for flow. However, this idea has grown since 1980, with geoscientists finding many examples principally in carbonate reservoirs where stylolites can be considered as fluid-efficient features. Among others, these features can be reactivated stylolites, can generate positive porosity and permeability anomalies, can drive corrosive fluids or can remain open in an overpressured system. Conversely, stylolites can also be closed forever. These impermeable stylolites can generate permeability anisotropy that may impact fluid movements. Stylolites require particular attention to evaluate whether they act as drains or as barriers to flow (compartmentalisation). We review some of the key studies of the past thirty years with a special attention to the most recent ones. We end-up considering their mechanical origin, their nucleation and growth, their past and present impact on reservoir properties and performances as key factors influencing the flow efficiency differentiation of these features. This short review presents the latest theories and observations about stylolites

with respect to the key factors aforementioned. The authors support herein that a distinction should be made between processes occurring in the past and the present-day impact the stylolite had on reservoir properties.

Definition and morphology of a stylolite

Stylolites are common features found in a variety of geological contexts principally in carbonate rocks (Fig.1). Stylolites are planar structures that accommodate localised contractional strain (Fletcher and Pollard, 1981; Schultz and Fossen, 2008). In general, their 2-D profile is easily distinguishable and consists of rough lines displaying positive and negative peaks (teeth) of variable amplitudes (Fig. 1.A-C and G-I). These peaks develop parallel to the direction of the maximal principal stress σ_1 (Choukroune, 1969; Groshong, 1975), although the stylolite plane can be oblique compared to the displacement direction (e.g. slickolites, Gratier et al., 2005). Generally, during burial bedding parallel stylolites (BPS) or "sedimentary stylolites" are generated whereas during reverse, strike slip or normal tectonic regimes "tectonic stylolites" may be generated (David, 2016).

Stylolites form and grow through the process of pressure-solution occurring initially at the micron scale (grains – crystals interface). It implies localised physical stress-induced compaction of grains along fluid-filled interface and the chemical dissolution of authigenic material of the rock (Ebner et al., 2009; Vandeginste and John, 2013). This process is at least partially controlled by the mineralogical heterogeneity of the rock because it provides the required contrast of solubility to start generating stylolite surfaces. The "proto-stylolite plane" can be initially seen as a sharp surface that will roughen on localised less-soluble heterogeneous material [i.e. pinning process, *sensu* Koehn et al., 2012)]. Following Alsharhan and Sadd (2000), Pressure solution seams (PSS) are characterised by laterally discontinuous undulating (peaks amplitude < 1cm) (Fig 1, A-B) and anastomosed surfaces. They contain thin (< 1mm thick) but evenly distributed insoluble material along their surfaces. Stylolites are laterally continuous rough (peaks amplitude > 1cm, fig. 1 B-C) and generally isolated surfaces. They contain variable thickness of insoluble material not evenly distributed along the surface. At the particle level “insoluble” minerals (e.g. quartz, phyllosilicates, oxides, organic matter – see fig. 1.D-F) affect physico-chemical processes as well as the growth of stylolite teeth. For instance, it was advanced by Koehn et al. (2007) that micas can enhance the process of pressure-solution but can also flatten the stylolite profile on a longer time scale. Vandeginste and John (2013) who worked on stylolite characterisation in IODP core sampling Eocene to Early Oligocene Limestones in the Canterbury Basin, mention that the amplitude of stylolite peaks is anti-correlated with the amount of insoluble minerals they contain. At the tens to hundreds of meter scale, sedimentary facies and general lithological changes constitute preferential zones of solubility contrast where stylolites may develop. It was sometimes suggested that stylolites develop on bedding plane but it appears that this assumption is complex to verify. Indeed the fine layering (varying from few centimetres to about 60 cm) observed in the Flamborough Chalk cliffs, UK (Ammeraal, 2017) is not due to stratification but to stylolitisation. This is supported by the relative homogeneity of the chalk succession where no major facies change would be able to explain this bedding succession. This raise an issue concerning the fractures observed in these chalk cliffs appearing bed-confined. However, in this case it seems that this “mechanical stratigraphy” is more a dissolution artefact (due to the presence of stylolites). Then, the horizontal bounding discontinuities need to be cautiously characterised to decipher if they behave as barriers compartmentalising fluid flow or as drains conducting fluids in both vertical (fractures) and horizontal directions (stylolites).

The process of pressure-solution is also controlled by the diagenesis the rock experience. Alsharhan and Sadd (2000) showed that pressure-solution occurs generally syn- or post initial diagenesis phases. This is mainly because lithification reduces the grain rotation/rearrangement and allows for contraction and dissolution to start (Bathurst, 1987; Sheppard, 2002). Concomitantly, the porosity of the rock should remain important enough to receive products of dissolution – principally the main chemical components of the host rock. Following the experiments of Koehn et al. (2007), each pressure solution surface start with a slightly undulating profile that roughen with time – so we can consider that each PSS became a stylolite and that the present-day conservation of PSS results of a deactivation of stylolite. Along with the heterogeneity of the rock, Rustichelli et al., 2012) demonstrated that the amount of stress applied to the rock, the temperature of the system and the pore fluid chemistry are essential drivers and catalysers of the process of pressure-solution.

The 2-D lateral extension of stylolites varies from micrometres (Fabricius and Borre, 2007; Gratier et al., 2005; Park and Schot, 1968) to several kilometres (Laronne Ben-Itzhak et al., 2012). This range of scales makes stylolites easily observable at the scale the geologist is working: thin-sections, cores or outcrops (Bruna et al., 2013; Lavenu and Lamarche, 2017; Matonti et al., 2015 – see fig. 1). In 3-D, stylolite extension follows the same rules as fracture propagation. Theoretically, as stylolites are considered as anti-mode I fracture, they should tend towards infinite size in an isotropic media (e.g. without structural or sedimentological perturbations like fractures or erosion surfaces, Fletcher and Pollard, 1981). However, stylolites vary in length and have a characteristic shape whereby they are thicker in their central part (aperture, filled by insoluble material) and thin towards their tips. These characteristics make stylolites potentially connected each other (fig. 1 G, H and I). Unfortunately, only a limited amount of outcrops allow to investigate stylolites surfaces in 3-D (Laronne Ben-Itzhak et al., 2014 – mainly isolated features) and consequently their connectivity is a matter rarely addressed.

The life cycle of a stylolite

This section deals with the nucleation (initiation), growth (acquisition of roughness) and death (deactivation) of stylolites. To understand the stylolite initiation, the mechanical genetic process must be understood at small scale and ideally reproduced experimentally in the laboratory. So far, only Gratier et al. (2005) have been able to experimentally reproduce microstylolites (or/and proto-stylolite surfaces) at stressed grains contacts. This work constitutes a benchmark on how stylolites are initiated in Nature. These authors demonstrated that the early development of a stylolite is controlled by a competition between: i) a local stress-induced deflection of the grain-to-grain interface generating peaks – and consequently favouring the roughness – and ii) opposed to this roughening process, the strength of the grain-to-grain interface divided in surface energy at the micro-scale (resistance to compression) and the elastic energy at the stylolite interface scale (surface tension). The local deflexion of the grain-to-grain interface is materialised by dissolution pits. These dissolution pits occur at the location of heterogeneities (e.g. at the grain-to-grain boundary or at the bedding interface). Some of these dissolution pits predate the process of stylolitisation and act as stress-concentration spots that induce an amplification of the dissolution process. It was observed that stylolite peaks always grow opposite these dissolution pits. The process of stylolite nucleation also requires fluid in the interface to initiate and to develop. Then, the stylolite interface can be considered as a planar and continuous pore (Schmittbuhl et al., 2004).

The depth at which the stylolite initiation starts is still debated. Koehn et al. (2012) mention early stylolite formation at 90 m depth. This number is based observation of stylolite intensity and evaluation of the maximal burial depth of the host rock (neglecting temperature, pressure and time). Kroon (2017) used BPS sampled in outcrop analogues of the Potiguar Basin (Brazil) to determine the maximum value of vertical σ_1 and to deduct the associated burial depth. He showed that the depth at which σ_{1max} is vertical varies from less than 200m to 945m (4.7 and 22.2 MPa, respectively) for outcrops separated by 10 to 50 km only. However, the depth of formation of stylolites is also dependent on more parameters than the depth of burial exclusively. Vandeginste and John (2013) and Lavenu (2013) stated that texture, lithology (including the presence of phyllosilicates in the rock) and the host rock original porosity are the main drivers of stylolite initiation. While initial bed-parallel sedimentary heterogeneities/solubility contrast can be reasonably considered as the primary cause of stylolites spacing, the stress perturbations around stylolite planes cannot be ruled out. Indeed, such as other mechanical discontinuities (as fractures or faults) stylolites probably lead to the development of stress shadow-zone (Rabinovitch et al., 1999; Henrion, 2011; Bonneau et al., 2012) around and along stylolites axis, impeding the development of subsequent stylolites close to it. The question of the stylolite spacing remains subjected to controversial discussions in the scientific community. Ones argue that the spacing is self-organised (stress–induced instability in compacting rock creating heterogeneity, Merino et al., 1983) and the others mentioning that it is indistinguishable from random arrangement or that the roughly regular spacing is due to pre-existing heterogeneities (Railsback, 1998). The spacing of stylolites may depend on the strength of the rock. Bruna et al. (2013) and Martin-Martin et al. (2016) observed that bedding parallel stylolites spacing and abundance is different in mud-dominated facies compared to grain-dominated facies. In both cases, mud-dominated facies contains the larger amount of stylolites and the smaller spacing. Experiments conducted by Koehn et al. (2012) showed that the quenched noise (heterogeneity – resistive grains) initially present in the rock is required for pinning processes to occur (creation of stylolite teeth). Then it seems reasonable that the spacing of stylolite within interval of same lithologies follow a random organization influenced by pre-existing heterogeneity.

The next phase of the development of stylolite is their growth – or roughening (Fig. 1, A-C, G-I). The growth of a stylolite surface was qualified by Ebner et al. (2009) as a self-affine scaling invariant with a characteristic Hurst exponent or roughness exponent. Specifically, stylolite growth is characterised by two pseudo-linear growing regimes with two different roughness exponents. This behaviour is expressed by a slope break between the two regimes called the crossover length, which separate the surface-energy dominated regime and the elastic energy dominated regime. This author mention that this length is function of stress during stylolite growth and that a Fourier transform can be constituted along the stylolite profiles. The amount of stress implied during the formation of the stylolite is resolved by the relation linking crossover length and deformation stress. Then, stylolite can be used as a paleostress gauge. Following this definition, we can expect that stylolite peak amplitude (i.e. roughness) is comparable at each scale including the common outcrop scale where stylolites are easily observable.

Koehn et al. (2007) showed that stylolites roughen progressively following a power law distribution in time. After a certain time depending on the length of the stylolite, the growth tends to saturate and the stylolite morphology became constant (it acquire is present-day observed form). In their experiments, the critical saturation time was evaluated to 2500 years for a stylolite long of 0.4 mm and more than 8000 years for a stylolite of 40 cm long. This model seems to indicate that a stylolite growth involves a limited amount of time. However the model proposed by Koehn et al. (2007) is valid for one stylolite in an idealised model. We believe that for a large population of stylolites reaching this ideal situation at various moment of the geological history and in rocks where the initial heterogeneity might be very different from one place to another, then the stylolites history can be extended to a long geological time. Work of Laronne Ben-Itzhak et al. (2012) conducted on cliffs of La Blanche Formation in Israel displaying continuous large scale sedimentary stylolite exposures showed that below

50 cm, stylolites have the typical self-affine behaviour. However, above this threshold, the roughening exponent decreases to 0 indicating that the stylolite process was deactivated.

This last statement emphasises the death of the stylolites after their lateral propagation as a planar interface (anti mode-I fracture) due to stress concentration at the proto-stylolite tips (Beaudoin et al., 2016; Brouste et al., 2007; Katsman, 2010). The deactivation of the stylolite can be related to the nature of stylolite interface fluid and with the diagenetic history of the rock - the cessation of the stylolite process can occur during burial and do not require external triggering mechanism (e.g. change of tectonic regime). Concerning the type of fluid, Alsharhan and Sadd (2000), Esteban and Taberner (2003) and Paganoni et al. (2015), showed that hydrocarbon saturated fluid leads to the cessation of the stylolite activity because the mass transfer in oil is nil (Fig. 1, F). Concerning the diagenetic history, it determines the volume of sink sites available to receive the product of the dissolution process and the availability of nucleation sites for stylolites (Koepnick, 1986). The process of pressure-solution induces dissolution of host rock material and precipitation of this dissolved material elsewhere in the system (pore space). The fluid circulation in the rock makes this process happening. For instance, Paganoni et al. (2015) studied oil reservoir from onshore Abu Dhabi. They found kaolin cements filling micro-fractures oriented perpendicular to burial stylolites (contemporaneous) and pores in the matrix surrounding these fractures. They showed that insoluble kaolin are related to fluxes of aggressive organic acids waters. These waters dissolve mica and feldspars minerals and keep Si and Al in solution though organo-metallic chemical complexation. This process is effective during stylolitisation and induces the precipitation of kaolin in the open fractures and in pores surrounding them. Vandeginste and John (2013), indicates that during stylolitisation process, rock dissolution products migrate by diffusion to zones of lower pressure where they precipitate as cements. Devoid of available pore space fluids cannot reach stylolite interface and cannot disseminate the product of pressure-solution. The system is locked as observed by Bruna et al. (2013) in Lower Cretaceous limestone of the SE of France where the sedimentary series was buried at more than 1 km depth. At that depth, sedimentary formations with low cementation rate or with initial porosity preserved only were prone to the development of stylolites compared to early and intensely cemented ones that display very rare stylolites occurrences.

Time: an important parameter for stylolite fluid flow efficiency

All stylolites have been fluid conduits at least once in their life. The previous sections demonstrated that the presence of fluid and their movements are primordial in the early genesis of stylolites. Consequently, the principal question rose by this paper – are stylolites fluid flow efficient features? – is already answered. This question has been strongly debated since the early 1980s and the scientific community seems divided between researchers considering stylolites as fluid conduits and others considering them as fluid barriers. However, it seems relatively rare to find a clear discussion on when stylolites were active as fluid conduits and when they became – permanently or temporarily – barriers to fluid flow. We propose here to separate stylolites acting as fluid conduits in the past – after their formation and during their development until their deactivation – from those still playing a positive or negative flow role in currently exploited reservoirs (which may influence the performance of the reservoir).

Braithwaite (1988), was one of the first to discuss the potential for stylolites to be hydrocarbon conduits. He studied samples from Montana, USA and from Hadeland, Norway and observed that stylolites can be implicated in the process of hydrocarbon migration from source rock to reservoir. Overpressure in these systems help stylolites remains open and constitute super-permeability features allowing fluids to migrate at fast rates. This type of behaviour was later demonstrated by Peacock et al. (2017) and by Koehn et al. (2012) who interpreted stylolite interfaces as channels able to transit fluid freely within a reservoir system. Padmanabhan et al. (2015) used the thermal connectivity anomalies in carbonate samples from Turkey and Malaysia to emphasise that the diachronic role of stylolites (i.e. acting sometimes as fluid conduits or fluid barriers) in the migration of hydrocarbon can generate variation of maturity within the reservoir.

In another context, Martín-Martín et al. (2016) studied an Upper Cretaceous carbonate platform in Spain where stylolites are interpreted to be the main control of the distribution of stratabound dolomite bodies and also to be responsible for their later corrosion and perforation making them highly porous and permeable layers. In their case stylolites act initially as baffle zone. Mg-rich fluids are transported by faults until they reach a stylolite barrier that laterally drives the dolomitisation process. Later high-pressure hydrothermal fluids circulating again along faults induced a change in the function of the stylolite, whereby it became a fluid conduit and induced corrosion and hydraulic fracturing in the dolomite bodies [this process was also described by Gisquet et al. (2013) in the Etoile Massif in the SE of France] (Fig. 2 B-C). In this case, the change of tectonic regime flipping σ_1 from vertical to horizontal, or the induced fluid overpressure due to decompaction (inducing a disequilibrium of pore-fluid pressure) are suggested by the authors to explain the opening of stylolites.

Stylolites can also be responsible for their own deactivation by promoting cementation and consequently decreasing the initial or acquired porosity of the rock (Park and Schot, 1968). Sheppard (2002), showed that the stylolitisation process favours the petrophysical heterogeneity of the rock. Indeed, the pressure-solution mechanism is responsible for the creation of a diffusion gradient from porous zone conducting the fluid needed in the stylolitisation process to less porous zones where cementation occurred (Fig. 2 D-E). Then, with stylolite development, planar porous zones may be created in rocks. Matonti et al. (2012) in their work on the Castellas fault in the SE of France, suggested that stylolites, by increasing dissolution, are the main cause for pervasive and complete cementation of the pore network around faults affecting initially porous carbonates rocks during fault reactivation. Indeed, fault strike-slip reactivation is related to the development of dense/numerous tectonic stylolites, providing $CaCO_3$ enriched fluids that contributed to form a cementation gradient/fringe visible on a 10-40 m scale around the main fault plane. Bertotti et al. (2017), observed in the Jandaíra Formation, Brazil, that stylolite are the source of cement that fill open joints and impede further fluid circulation in the rock. Fabricius and Borre (2007) emphasised the influence of the rock texture in the degree of cementation coming from stylolite production. Large pores are generally quickly filled by cements coming from the stylolitisation process (the pressure differential between stylolite dissolution spot and the pore is higher with large pore and favour the cementation in these locus). They observed in the Ontong Plateau in Java and in the North Sea Gorm and Tyra chalk oil fields, that the wackestone textures are les porous than the mudstone textures which appears to be contradictory.

Influence of stylolite in present-day reservoir performance

As previously shown, stylolites can have a positive or negative impact on present day reservoir properties, which are partially linked to stylolites' geological history. The present section gives some examples and explanations on i) how stylolite may compartmentalise reservoirs acting as barriers to fluid flow and make them potentially difficult to exploit and ii) how stylolite can represent super-permeable drains and should potentially increase the productivity of the reservoir if they are rightly identified and used.

- **Stylolite playing a role of barrier**

The most common statement about stylolites is to consider them as barrier to fluid flow. For Koehn et al. (2016), stylolites with low roughness are generally good barriers (Fig. 3) because this makes them more continuous feature than stylolites with irregular profile. The nature of their filling material is also influencing their fluid flow behaviour (Fig. 1, D-F). Stylolites are good barrier if they are filled by non-permeable materials like clay, organic matter and/or oxides (Mehrabi et al., 2016; Vandeginste and John, 2013). In addition, for Heap et al. (2014), a stylolite can be considered as good barrier if its filling material is evenly distributed and continuous along the seam and if the insoluble material composition is globally homogeneous along it (Fig. 3). The Grignantes quarry in the SE France constitutes a key locality to discuss these relationships. Here, the Meyrargues Limestone Formation, Berriasian of age (see Bruna et al., 2013), includes alternating metre-scale beds containing isolated stylolites and centimetre thick bioturbated packstone interbeds with solution seams bands. Work of Bruna et al. (2013), Bruna (2013) and Matonti et al. (2015), evidenced the difference in shape and insoluble composition of stylolites included (i) in beds – isolated seams, variable roughness and clay-oxide insoluble filling – and the ones included in (ii) interbeds – over concentrated and connected seams, low roughness and heterogeneous filling composed of pyrite, quartz, clay, calcite with aperture up to 50 μm. They tested if these different types of stylolites and associated insoluble filling displayed a typical P-wave velocity (Vp) signature by measuring acoustic waves directly on outcrop and in the laboratory on plugs sample processed in both atmospheric and under confinement (40 MPa) conditions. Figure 4, shows the obtained results on outcrop demonstrating that stylolites in beds are mainly invisible for Vp but solution seams bands located on interbeds showed an important decrease of acoustic waves velocities. The authors interpreted this as underlining the importance of stylolite profile (low roughness), heterogeneous filling and aperture on their hydraulic property and geophysical signature. At the plug scale, Vp values, porosity and the occurrence of stylolites were statistically compared in and confirmed the observation conducted at the outcrop scale. It appears then that isolated and continuously filled stylolites are likely to display acoustic signature similar to their host rock making them less-to-no detectable, and when stylolites are open or discontinuously filled by insoluble material they have a distinctive acoustic signature. It is important to note here that these drastic contrasts in geophysical and hydraulic behaviour can occur below the metre scale, hence impacting heterogeneity distribution in reservoirs, below conventional seismic cross-section resolution.

However, stylolites acting as barriers can be important in reservoir as they may act as directional guide for fluid flow impeding vertical movements (when sedimentary stylolite only are developed) or restricting even more fluids spots - in the presence of both sedimentary and tectonic stylolites – (Alsharhan and Sadd, 2000; Bushara and Arab, 1998; Koepnick, 1986; Lavenu and Lamarche, 2017; Martín-Martín et al., 2016). Because the production of a compartmentalised reservoir is technically complex, one should carefully assess the presence of stylolites and evaluate their potential impact before starting any field development plans.

- **Stylolite playing a role of drain**

At a small scale, we previously discussed that stylolite filling continuity is a key to make them good barriers. Heap et al. (2014) conducted experiments on a series of 4 samples with different lithologies containing stylolites. In each of these samples, plugs where drilled in order to obtain 3 subsamples: i) without stylolites, ii) with stylolite oriented along the longitudinal axis of the subsample and iii) with stylolite oriented perpendicular to the long axis of the subsample. They showed that the porosity value in sample devoid of stylolites is systematically lower than in sample with stylolites. They also measured the permeability on the subsamples and demonstrated that the anisotropy of permeability is equivalent between samples without stylolites and samples with perpendicular to long axis stylolites (gas permeability ranging from 10^{-19} to 10^{-14} m^2 in both cases). They also observed that the permeability is enhanced when stylolites are oriented in the longitudinal axis of the subsample. This study shows that stylolites are here not a proper barrier and represent a zone of enhanced permeability that can flank the stylolite walls on the order of millimetres to few centimetres around the stylolites.

As previously discussed, the roughness is also a key parameter influencing the fluid flow behaviour of a stylolite. The work of Koehn et al. (2016) highlighted the fact that the roughness profile of a stylolite is directly linked with its petrophysical behaviour by making the stylolite potentially discontinuous. For instance in the case of the “rectangular layer stylolite”, insoluble material is concentrated in the horizontal part of the stylolite teeth, the vertical edges of the stylolite teeth having a completely different behaviour. During stylolite growth these vertical parts are parallel to the principal stress direction, and behave like tension gashes that can remain open if subsurface conditions are favourable (e.g. overpressure, Fig. 5). The authors showed that if the conditions are not favourable, fluids could remain trapped in the teeth and locally accelerate the dissolution leading to the creation of secondary vuggy porosity (Fig. 5 C). This latter process was also observed by Nader et al. (2016), and can be enhanced by the nature of fluids remaining trapped in the system (Martín-Martín et al., 2016; Paganoni et al., 2015).

Stylolites also appear as weak interfaces (Bjørlykke and Høeg, 1997; Vajdova et al., 2012) prone to break due to external mechanisms. Bruna et al. (2013) demonstrated that stylolites could be locally reopened due to short and intense episodes of uplift. Shearing can also be evocated as a potential reopening mechanism for stylolite, where it appears that the roughness could be a limiting factor for reactivation. However, if stylolite seams are flat enough, the reactivation seems mechanically possible as demonstrated in Barton and Bandis (1980).

It appears that the main parameters making stylolites a positive or negative fluid flow features is linked with their shape (rough stylolites are not continuous high density layers), their filling material, the nature of the fluid transiting trough them and the global geological history (e.g. highly corrosive fluids circulating along faults and using stylolite to invade the host rock). Indirectly, stylolites can also act as barrier by cementing locally part of the reservoir (if the dissolved calcite is transferred locally around the stylolite and fill the actual pore space). Heap et al., 2014 mention that mineral coating (e.g. stylolites formed before oil charge may be significant barriers to fluid flow because they are entirely cemented compared to stylolites formed after the oil entrapment that impede the cementation and consequently the closure of stylolites), low fluid fluxes, low partial pressure of CO_2, high pH and high temperature may also favor this process.

Concluding remarks

This paper proposes a short review of selected recent works conducted on stylolites. We covered the origin and the evolution of stylolites in terms of triggering mechanisms involved. We investigated how the stylolitisation process should impact reservoir properties and we discussed how stylolites can have a negative or positive control on present-day reservoir fluid flow and storage. In the present section, the authors wanted to raise some questions that do not seems to be answered yet.

The origin and life cycle of a stylolite has been the focus of numerous high quality studies that increased strongly the community's understanding of how a stylolite occurs, grow and die. However, an important part these articles focus on results obtained from numerical modelling or/and conducted at small scale sometimes compared to natural experimental examples. The rare studies focusing on larger scale stylolites (Laronne Ben-Itzhak et al., 2014; Laronne Ben-Itzhak et al., 2012) opened a new perspective, showing in particular the process of deactivation of stylolites. This can probably constitute a basis to date when the stylolite stopped to grow. Because the cementation of the reservoir may be linked to the stylolite deactivation, understanding the relative timing of these processes will be a strong asset to reconstruct the evolution of a petroleum system (migration, charge, fluid flow). An approach based on dating and provenance evaluation (isotopic studies) of the different cements can be advanced as a research axis for the future.

Since the beginning of 1980s, it is understood that stylolites can laterally propagate almost towards infinity in 3-D. However, the dimension of a single stylolite or the dimension of a population of interconnected stylolites has not yet been investigated in detail. Bruna (2013) and Bruna et al. (2015) observed springs flowing out from solution seem bands. Tracing the spring waters in this area will be a way to evaluate the connectivity of these porous units. Another methodology will be to apply fluid flow modelling workflow conducted on fracture network to horizontal interface. These kinds of models can be calibrated from outcrop analogues where the different populations of stylolites, their intrinsic characteristic and their potential degree of connectivity can almost fully characterised in pseudo-3-dimension and with a high degree of confidence (observable).

The potential of stylolites to be drain or barriers seems to follow a binary response. In fact stylolites can be drains AND barriers to fluid flow. Depending on facies variation, on diagenesis, on the heterogeneity of the reservoir itself, multiple types of stylolites can be generated and consequently their impact on fluid flow could be very different. Accordingly, the impact of stylolite is not only black or white but can be viewed as shades of grey. Rather than mentioning the presence of stylolites in reservoir intervals and stating that they will have a negative impact on reserve and flow, efforts need to be consented on describing the roughness of stylolite and the nature/thickness of insoluble filling. The understanding of regional stress state and tectonic history of the area where the targeted reservoir is located need also to be considered to take into account a potential reopening of these structures. As it has been recognized for fractures several decades ago, stylolites properties and hydraulic behaviour should now be considered as the final result of multifactorial (sedimentary, burial, chemical, tectonic) and polyphased processes. Experiments of Heap et al. (2014) constitute a benchmark to change the classical vision of stylolites as a simple barrier. Systematic testing of various types of stylolite roughness and of different type of insoluble to decipher the impact of these parameters on petrophysical properties would be an interesting axis of research for the future. Obtained results could be compared to the modelling results obtained by Koehn et al. (2016). Finally, conducting a series of experiments on full size core at subsurface condition will help to get rid of artefacts/biases caused by surface decompaction that can occur to natural samples.

Acknowledgements

Barry Reno is acknowledged for his great help improving English in this paper. Antonio Benedicto and the second anonymous reviewer, are also warmly thanked for their constructive remarks.

Figure Captions

Figure 1: Insoluble, shape and connectivity are some of the principal parameters characterizing stylolites. For each column, a photograph is shown to illustrate these parameters. The evolution of a stylolite goes through a variety of shapes, from almost flat – or wispy seam (A – Grignantes Quarry, SE France), passing by the stage of solution seam (B1

Grignantes Quarry, SE France) to more mature with visible picks (B2) up to the advanced stage of columnar - or rectangular - stylolite (C, Offshore Abu Dhabi). D-E presentation of some of the most common insoluble types: D) oxidised material (thin-section, Western Australia), E) clay (Grignantes Quarry, SE France), F) organic matter and bitumen filled stylolites (Maiella, Italy). Stylolite connectivity is at play when dealing with potential flow. In case of isolated features (G, Grignantes Quarry, SE France), stylolites contribution to flow is limited. If stylolites are connected (H, Abu Dhabi), a path is created and can enhance fluid flow. In the case of multiple tectonic phases, isolated horizontal stylolites (I1 Grignantes Quarry, SE France) can connect tectonic stylolites (I2, oblique to perpendicular) and improve their connectivity.

Figure 2: Time evolution of stylolite behaviour (drain or barriers). The stylolite initiation (A) is common for both of the presented example. At grain to grain contact, proto-stylolitisation occur implying the transport of dissolution product in the seam interface (A') and the roughening initiation (A", SEM picture from Gratier et al., 2005). B – C example of evolution: ancient behaviour of stylolites acting initially as (B – B' photograph from Martín-Martín et al., 2016) baffle zones driving stratabound dolomitisation process and C – C') later as conduits driving highly corrosive hydrothermal fluids responsible of natural hydro fracturing and secondary porosity creation. Modified from Martín-Martín et al., 2016. D – E example of evolution: the roughening of the stylolite increase (D') with time and the product of dissolution start to fill available pores in the surrounding matrix. When the roughening tend towards its maximum (columnar shape), the available pore space in the matrix is likely to be filled by the product of dissolution and stylolites became inactive.

Figure 3: Stylolite system acting as potential barrier to fluid flow. A) sketch of stylolites population where some (green) are potential fluid flow barriers. This sketch present the principal parameters that condition this behaviour. B) outcrop example (Flamborough Chalk, UK, modified from Ammeraal, 2017) where fractures appear confined by two stylolite surfaces. C) block diagram showing the potential 3D fluid flow pathways through this kind of configuration. The reservoir is compartmentalised and fracture-controlled flow units can potentially be disconnected each other.

Figure 4: Relationship between microscale properties of stylolites and their contrasted hydraulic behaviour/geophysical signatures. A: Panorama of the Grignantes Quarry outcrop, composed Berriasian micritic carbonates, and showing alternating bed/interbed (in purple) organisation (modified from Bruna et al. 2013). B: Map of interpolated Vp values measured along a meter scale outcrop showing extremely low values located across the solution seam interbeds (see. Matonti et al., 2015 for methodology). C: Close-up on interbred structures composed of hundreds of anastomosing stylolites. D-E: Schemes illustrating the strong decreasing effect of open stylolites on Vp values (stylolite aperture in blue on E), compared to the “transparent” closed and filled stylolites (oxide/clay filling in brown on D).

Figure 5: Stylolite system acting as potential to fluid flow. A) sketch of stylolites population where some (green) are potential fluid flow barriers and where the connectivity between stylolite of tectonic and sedimentary origin is marked by green dots. This sketch present the principal parameters that condition this behaviour. B) block diagram showing the potential 3D fluid flow pathways through this kind of configuration. Exchanges trough stylolite interface are then possible. In addition, stylolites with well-developed peaks concentrate insoluble material on the top/bottom of the teeth. The side of the teeth remain potential pathways for

fluids. In the case of partial filling of the teeth sides, this configuration can generate secondary porosity within the teeth area where corrosive fluid can be trapped and can generate localised secondary porosity (modified from Koehn et al., 2016). Picture C (Oman, courtesy of Juliette Lamarche) show a real example of stylolite-localised secondary porosity.

References

Alsharhan, A.S., Sadd, J.L., 2000. Stylolites in Lower Cretaceous carbonate reservoirs, U.A.E. . SEPM Special Publication 69, Middle East Models of Jurassic/Cretaceous Carbonate Systems, 23.

Ammeraal, D., 2017. Fracture stratigraphy in the Flamborough Chalk, Civil Engineering and Geoscience. Delft University of Technology, p. 105.

Barton, N., Bandis, S., 1980. Some effects of scale on the shear strength of joints. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, 17, 5.

Bathurst, R.G.C., 1987. Diagenetically enhanced bedding in argillaceous platform limestones: stratified cementation and selective compaction. Sedimentology 34, 30.

Beaudoin, N., Koehn, D., Lacombe, O., Lecouty, A., Billi, A., Aharonov, E., Parlangeau, C., 2016. Fingerprinting stress: Stylolite and calcite twinning paleopiezometry revealing the complexity of progressive stress patterns during folding—The case of the Monte Nero anticline in the Apennines, Italy. Tectonics 35, 1687-1712.

Bertotti, G., de Graaf, S., Bisdom, K., Oskam, B., Vonhof, H.B., Bezerra, F.H.R., Reijmer, J.J.G., Cazarin, C.L., 2017. Fracturing and fluid-flow during post-rift subsidence in carbonates of the Jandaira Formation,Potiguar Basin,NE Brazil. Basin Research 29, 18.

Bjørlykke, K., Høeg, K., 1997. Effects of burial diagenesis on stresses, compaction and fluid flow in sedimentary basins. Marine and Petroleum Geology 14, 267-276.

Braithwaite, C.J.R., 1988. Stylolites as open fluid conduits. Marine and Petroleum Geology 6, 4.

Brouste, A., Renard, F., Gratier, J.-P., Schmittbuhl, J., 2007. Variety of stylolites' morphologies and statistical characterization of the amount of heterogeneities in the rock. Journal of Structural Geology 29, 422-434.

Bruna, P.-O., 2013. Tight Carbonates Reservoir Properties Evolution: A case study of Lower Cretaceous hemipelagic limestone from the Northern Provence region, CEREGE. Aix-Marseille Universite, p. 235.

Bruna, P.-O., Guglielmi, Y., Lamarche, J., Floquet, M., Fournier, F., Sizun, J.-P., Gallois, A., Marié, L., Bertrand, C., Hollender, F., 2013. Porosity gain and loss in unconventional reservoirs: Example of rock typing in Lower Cretaceous hemipelagic limestones, SE France (Provence). Marine and Petroleum Geology 48, 186-205.

Bruna, P.-O., Guglielmi, Y., Viseur, S., Lamarche, J., Bildstein, O., 2015. Coupling fracture facies with in-situ permeability measurements to generate stochastic simulations of tight carbonate aquifer properties: Example from the Lower Cretaceous aquifer, Northern Provence, SE France. Journal of Hydrology 529, Part 3, 737-753.

Bushara, M.N., Arab, H.M., 1998. Fracture/stylolite characterization using stochastic modeling in zone-II reservoir, offshore Abu Dhabi, 8th SPE Abu Dhabi International Petroleum Exhibition and Conference, Abu Dhabi.

Choukroune, P., 1969. An example of mesoscopic analysis of concentric folding in limestone series. Techtonophysics 7, 14.

David, M.-E., 2016. Evaluation de la compaction chimique et des paléo-enfouissements des carbonates par l'étude des stylolites sédimentaires - Cas du Bassin de Paris. University pierre et Marie Curie, Paris, p. 42.

Ebner, M., Koehn, D., Toussaint, R., Renard, F., 2009. The influence of rock heterogeneity on the scaling properties of simulated and natural stylolites. Journal of Structural Geology 31, 72-82.

Esteban, M., Taberner, C., 2003. Secondary porosity development during late burial in carbonate reservoirs as a result of mixing and/or cooling of brines. Journal of Geochemical Exploration 78-79, 355-359.

Fabricius, I.L., Borre, M.K., 2007. Stylolites, porosity, depositional texture, and silicates in chalk facies sediments. Ontong Java Plateau – Gorm and Tyra fields, North Sea. Sedimentology 54, 183-205.

Fletcher, R.C., Pollard, D.D., 1981. Anticrack model for pressure solution surfaces. Geology 9, 419-424.

Gisquet, F., Lamarche, J., Floquet, M., Borgomano, J., Masse, J.-P., Caline, B., 2013. Three-dimensional structural model of composite dolomite bodies in folded area (Upper Jurassic of the Etoile massif, southeastern France). AAPG Bulletin 97, 26.

Gratier, J.P., Muquet, L., Hassani, R., Renard, F., 2005. Experimental microstylolites in quartz and modeled application to natural stylolitic structures. Journal of Structural Geology 27, 89-100.

Groshong, R.H.J., 1975. Strain, fractures, and pressure solution in natural single-layer folds. Geological Society of America Bulletin 86, 14.

Heap, M.J., Baud, P., Reuschlé, T., Meredith, P.G., 2014. Stylolites in limestones: Barriers to fluid flow? Geology 42, 4.

Katsman, R., 2010. Extensional veins induced by self-similar dissolution at stylolites: analytical modeling. Earth and Planetary Science Letters 299, 33-41.

Koehn, D., Ebner, M., Renard, F., Toussaint, R., Passchier, C.W., 2012. Modelling of stylolite geometries and stress scaling. Earth and Planetary Science Letters 341-344, 104-113.

Koehn, D., Renard, F., Toussaint, R., Passchier, C.W., 2007. Growth of stylolite teeth patterns depending on normal stress and finite compaction. Earth and Planetary Science Letters 257, 582-595.

Koehn, D., Rood, M.P., Beaudoin, N., Chung, P., Bons, P.D., Gomez-Rivas, E., 2016. A new stylolite classification scheme to estimate compaction and local permeability variations. Sedimentary Geology 346, 60-71.

Koepnick, R.B., 1986. Distribution and permeability of stylolite-bearing horizons within a Lower Cretaceous carbonate reservoir in the Middle East, SPE Annual Technical Conference and Exhibition Las Vegas.

Kroon, L.J., 2017. Multi-scale state of stress analysis of the Potiguar Basin NE Brazil, Civil Engineering and Geoscience. Delft University of Technology, Delft, p. 46.

Laronne Ben-Itzhak, L., Aharonov, E., Karcz, Z., Kaduri, M., Toussaint, R., 2014. Sedimentary stylolite networks and connectivity in limestone: Large-scale field observations and implications for structure evolution. Journal of Structural Geology 63, 106-123.

Laronne Ben-Itzhak, L., Aharonov, E., Toussaint, R., Sagy, A., 2012. Upper bound on stylolite roughness as indicator for amount of dissolution. Earth and Planetary Science Letters 337-338, 186-196.
Lavenu, A.P.C., 2013. Relationships between fracture pattern and geodynamics in carbonates. Role of depositional facies, diagenesis and rock mechanical properties., CEREGE. Aix-Marseille Universite, p. 198.
Lavenu, A.P.C., Lamarche, J., 2017. What controls diffuse fractures in platform carbonates? Insights from Provence (France) and Apulia (Italy). Journal of Structural Geology.
Martín-Martín, J.D., Gomez-Rivas, E., Gómez-Gras, D., Travé, A., Ameneiro, R., Koehn, D., Bons, P.D., 2016. Activation of stylolites as conduits for overpressured fluid flow in dolomitized platform carbonates. Geological Society of London Special Publication.
Matonti, C., Guglielmi, Y., Viseur, S., Bruna, P.O., Borgomano, J., Dahl, C., Marié, L., 2015. Heterogeneities and diagenetic control on the spatial distribution of carbonate rocks acoustic properties at the outcrop scale. Tectonophysics 638, 94-111.
Matonti, C., Lamarche, J., Guglielmi, Y., Marié, L., 2012. Structural and petrophysical characterization of mixed conduit/seal fault zones in carbonates: Example from the Castellas fault (SE France). Journal of Structural Geology 39, 103-121.
Mehrabi, H., Mansouri, M., Rahimpour-Bonab, H., Tavakoli, V., Hassanzadeh, M., 2016. Chemical compaction features as potential barriers in the Permian-Triassic reservoirs of Southern Iran. Journal of Petroleum Science and Engineering 145, 95-113.
Nader, F.H., Champenois, F., Barbier, M., Adelinet, M., Rosenberg, E., Houel, P., Delmas, J., Swennen, R., 2016. Diagenetic effects of compaction on reservoir properties: The case of early callovian "Dalle Nacrée" formation (Paris basin, France). Journal of Geodynamics 101, 5-29.
Padmanabhan, E., Sivapriya, B., Huang, K.H., Askury, A.K., Chow, W.S., 2015. The impact of stylolites and fractures in defining critical petrophysical and geomechanical properties of some carbonate rocks. Geomechanics and Geophysics for Geo-Energy and Geo-Resources 1, 13.
Paganoni, M., Al Harethi, A., Morad, D., Morad, S., Ceriani, A., Mansurbeg, H., Al Suwaidi, A., Al-Aasm, I.S., Ehrenberg, S.N., Sirat, M., 2015. Impact of stylolitization on diagenesis and reservoir quality: A case study from an Early Cretaceous reservoir in a giant oilfield, Abu Dhabi, United Arab Emirates, SPE Abu Dhabi International Petroleum Exhibition and Conference, Abu Dhabi.
Park, W.C., Schot, E.H., 1968. Stylolites: their nature and origin. Journal of sedimentary petrology 38, 17.
Peacock, D.C.P., Korneva, I., Nixon, C.W., Rotevatn, A., 2017. Changes of scaling relationships in an evolving population: The example of "sedimentary" stylolites. Journal of Structural Geology 96, 118-133.
Rustichelli, A., Tondi, E., Agosta, F., Cilona, A., Giorgioni, M., 2012. Development and distribution of bed-parallel compaction bands and pressure solution seams in carbonates (Bolognano Formation, Majella Mountain, Italy). Journal of Structural Geology 37, 181-199.
Schmittbuhl, J., Renard, F., Gratier, J.P., Toussaint, R., 2004. Roughness of stylolites: implications of 3D high resolution topography measurements. Physical Review Letters 93.
Schultz, R.A., Fossen, H., 2008. Terminology for structural discontinuities. AAPG Bulletin 92, 15.

Sheppard, T.H., 2002. Stylolite development at sites of primary and diagenetic fabric contrast within the Sutton Stone (Lower Lias), Ogmore-by-Sea, Glamorgan, UK. Proceeding of the Geologists' Association 113, 13.

Vajdova, V., Baud, P., Wu, L., Wong, T.-f., 2012. Micromechanics of inelastic compaction in two allochemical limestones. Journal of Structural Geology 43, 100-117.

Vandeginste, V., John, C.M., 2013. Diagenetic implications of stylolitization in pelagic carbonates, Canterbury Basin, offshore New Zealand. Journal of Sedimentary Research 83, 226-240.