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# Are stylolites fluid-flow efficient features?

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## 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

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

32

### 33 **Definition and morphology of a stylolite**

34 Stylolites are common features found in a variety of geological contexts principally in  
35 carbonate rocks (Fig.1). Stylolites are planar structures that accommodate localised  
36 contractional strain (Fletcher and Pollard, 1981; Schultz and Fossen, 2008). In general, their  
37 2-D profile is easily distinguishable and consists of rough lines displaying positive and  
38 negative peaks (teeth) of variable amplitudes (Fig. 1.A-C and G-I). These peaks develop  
39 parallel to the direction of the maximal principal stress  $\sigma_1$  (Choukroune, 1969; Groshong,  
40 1975), although the stylolite plane can be oblique compared to the displacement direction (e.g.  
41 slickolites, Gratier et al., 2005). Generally, during burial bedding parallel stylolites (BPS) or  
42 “sedimentary stylolites” are generated whereas during reverse, strike slip or normal tectonic  
43 regimes “tectonic stylolites” may be generated (David, 2016).

44 Stylolites form and grow through the process of pressure-solution occurring initially at the  
45 micron scale (grains – crystals interface). It implies localised physical stress-induced  
46 compaction of grains along fluid-filled interface and the chemical dissolution of authigenic  
47 material of the rock (Ebner et al., 2009; Vandeginste and John, 2013). This process is at least  
48 partially controlled by the mineralogical heterogeneity of the rock because it provides the  
49 required contrast of solubility to start generating stylolite surfaces. The “proto-stylolite plane”  
50 can be initially seen as a sharp surface that will roughen on localised less-soluble  
51 heterogeneous material [i.e. pinning process, *sensu* Koehn et al., 2012)]. Following Alsharhan  
52 and Sadd (2000), Pressure solution seams (PSS) are characterised by laterally discontinuous  
53 undulating (peaks amplitude < 1cm) (Fig 1, A-B) and anastomosed surfaces. They contain

54 thin (< 1mm thick) but evenly distributed insoluble material along their surfaces. Stylolites  
55 are laterally continuous rough (peaks amplitude > 1cm, fig. 1 B-C) and generally isolated  
56 surfaces. They contain variable thickness of insoluble material not evenly distributed along  
57 the surface. At the particle level “insoluble” minerals (e.g. quartz, phyllosilicates, oxides,  
58 organic matter – see fig. 1.D-F) affect physico-chemical processes as well as the growth of  
59 stylolite teeth. For instance, it was advanced by Koehn et al. (2007) that micas can enhance  
60 the process of pressure-solution but can also flatten the stylolite profile on a longer time scale.  
61 Vandeginste and John (2013) who worked on stylolite characterisation in IODP core sampling  
62 Eocene to Early Oligocene Limestones in the Canterbury Basin, mention that the amplitude of  
63 stylolite peaks is anti-correlated with the amount of insoluble minerals they contain. At the  
64 tens to hundreds of meter scale, sedimentary facies and general lithological changes constitute  
65 preferential zones of solubility contrast where stylolites may develop. It was sometimes  
66 suggested that stylolites develop on bedding plane but it appears that this assumption is  
67 complex to verify. Indeed the fine layering (varying from few centimetres to about 60 cm)  
68 observed in the Flamborough Chalk cliffs, UK (Ammeraal, 2017) is not due to stratification  
69 but to stylolitisation. This is supported by the relative homogeneity of the chalk succession  
70 where no major facies change would be able to explain this bedding succession. This raise an  
71 issue concerning the fractures observed in these chalk cliffs appearing bed-confined.  
72 However, in this case it seems that this “mechanical stratigraphy” is more a dissolution  
73 artefact (due to the presence of stylolites). Then, the horizontal bounding discontinuities need  
74 to be cautiously characterised to decipher if they behave as barriers compartmentalising fluid  
75 flow or as drains conducting fluids in both vertical (fractures ) and horizontal directions  
76 (stylolites).

77 The process of pressure-solution is also controlled by the diagenesis the rock experience.  
78 Alsharhan and Sadd (2000) showed that pressure-solution occurs generally syn- or post initial

79 diagenesis phases. This is mainly because lithification reduces the grain  
80 rotation/rearrangement and allows for contraction and dissolution to start (Bathurst, 1987;  
81 Sheppard, 2002). Concomitantly, the porosity of the rock should remain important enough to  
82 receive products of dissolution – principally the main chemical components of the host rock.  
83 Following the experiments of Koehn et al. (2007), each pressure solution surface start with a  
84 slightly undulating profile that roughen with time – so we can consider that each PSS became  
85 a stylolite and that the present-day conservation of PSS results of a deactivation of stylolite.  
86 Along with the heterogeneity of the rock, Rustichelli et al., 2012) demonstrated that the  
87 amount of stress applied to the rock, the temperature of the system and the pore fluid  
88 chemistry are essential drivers and catalysers of the process of pressure-solution.  
89 The 2-D lateral extension of stylolites varies from micrometres (Fabricius and Borre, 2007;  
90 Gratier et al., 2005; Park and Schot, 1968) to several kilometres (Laronne Ben-Itzhak et al.,  
91 2012). This range of scales makes stylolites easily observable at the scale the geologist is  
92 working: thin-sections, cores or outcrops (Bruna et al., 2013; Lavenu and Lamarche, 2017;  
93 Matonti et al., 2015 – see fig. 1). In 3-D, stylolite extension follows the same rules as fracture  
94 propagation. Theoretically, as stylolites are considered as anti-mode I fracture, they should  
95 tend towards infinite size in an isotropic media (e.g. without structural or sedimentological  
96 perturbations like fractures or erosion surfaces, Fletcher and Pollard, 1981). However,  
97 stylolites vary in length and have a characteristic shape whereby they are thicker in their  
98 central part (aperture, filled by insoluble material) and thin towards their tips. These  
99 characteristics make stylolites potentially connected each other (fig. 1 G, H and I).  
100 Unfortunately, only a limited amount of outcrops allow to investigate stylolites surfaces in 3-  
101 D (Laronne Ben-Itzhak et al., 2014 – mainly isolated features) and consequently their  
102 connectivity is a matter rarely addressed.

103

## 104 **The life cycle of a stylolite**

105 This section deals with the nucleation (initiation), growth (acquisition of roughness) and death  
106 (deactivation) of stylolites. To understand the stylolite initiation, the mechanical genetic  
107 process must be understood at small scale and ideally reproduced experimentally in the  
108 laboratory. So far, only Gratier et al. (2005) have been able to experimentally reproduce  
109 microstylolites (or/and proto-stylolite surfaces) at stressed grains contacts. This work  
110 constitutes a benchmark on how stylolites are initiated in Nature. These authors demonstrated  
111 that the early development of a stylolite is controlled by a competition between: i) a local  
112 stress-induced deflection of the grain-to-grain interface generating peaks – and consequently  
113 favouring the roughness – and ii) opposed to this roughening process, the strength of the  
114 grain-to-grain interface divided in surface energy at the micro-scale (resistance to  
115 compression) and the elastic energy at the stylolite interface scale (surface tension). The local  
116 deflexion of the grain-to-grain interface is materialised by dissolution pits. These dissolution  
117 pits occur at the location of heterogeneities (e.g. at the grain-to-grain boundary or at the  
118 bedding interface). Some of these dissolution pits predate the process of stylolitisation and act  
119 as stress-concentration spots that induce an amplification of the dissolution process. It was  
120 observed that stylolite peaks always grow opposite these dissolution pits. The process of  
121 stylolite nucleation also requires fluid in the interface to initiate and to develop. Then, the  
122 stylolite interface can be considered as a planar and continuous pore (Schmittbuhl et al.,  
123 2004).

124 The depth at which the stylolite initiation starts is still debated. Koehn et al. (2012) mention  
125 early stylolite formation at 90 m depth. This number is based observation of stylolite intensity  
126 and evaluation of the maximal burial depth of the host rock (neglecting temperature, pressure  
127 and time). Kroon (2017) used BPS sampled in outcrop analogues of the Potiguar Basin  
128 (Brazil) to determine the maximum value of vertical  $\sigma_1$  and to deduct the associated burial

129 depth. He showed that the depth at which  $\sigma_{1\max}$  is vertical varies from less than 200m to 945m  
130 (4.7 and 22.2 MPa, respectively) for outcrops separated by 10 to 50 km only. However, the  
131 depth of formation of stylolites is also dependent on more parameters than the depth of burial  
132 exclusively. Vandeginste and John (2013) and Lavenu (2013) stated that texture, lithology  
133 (including the presence of phyllosilicates in the rock) and the host rock original porosity are  
134 the main drivers of stylolite initiation. While initial bed-parallel sedimentary  
135 heterogeneities/solubility contrast can be reasonably considered as the primary cause of  
136 stylolites spacing, the stress perturbations around stylolite planes cannot be ruled out. Indeed,  
137 such as other mechanical discontinuities (as fractures or faults) stylolites probably lead to the  
138 development of stress shadow-zone (Rabinovitch et al., 1999; Henrion, 2011; Bonneau et al.,  
139 2012) around and along stylolites axis, impeding the development of subsequent stylolites  
140 close to it. The question of the stylolite spacing remains subjected to controversial discussions  
141 in the scientific community. Ones argue that the spacing is self-organised (stress-induced  
142 instability in compacting rock creating heterogeneity, Merino et al., 1983) and the others  
143 mentioning that it is indistinguishable from random arrangement or that the roughly regular  
144 spacing is due to pre-existing heterogeneities (Railsback, 1998). The spacing of stylolites may  
145 depend on the strength of the rock. Bruna et al. (2013) and Martin-Martin et al. (2016)  
146 observed that bedding parallel stylolites spacing and abundance is different in mud-dominated  
147 facies compared to grain-dominated facies. In both cases, mud-dominated facies contains the  
148 larger amount of stylolites and the smaller spacing. Experiments conducted by Koehn et al.  
149 (2012) showed that the quenched noise (heterogeneity – resistive grains) initially present in  
150 the rock is required for pinning processes to occur (creation of stylolite teeth). Then it seems  
151 reasonable that the spacing of stylolite within interval of same lithologies follow a random  
152 organization influenced by pre-existing heterogeneity.

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

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



178 50 cm, stylolites have the typical self-affine behaviour. However, above this threshold, the  
179 roughening exponent decreases to 0 indicating that the stylolite process was deactivated.  
180 This last statement emphasises the death of the stylolites after their lateral propagation as a  
181 planar interface (anti mode-I fracture) due to stress concentration at the proto-stylolite tips  
182 (Beaudoin et al., 2016; Brouste et al., 2007; Katsman, 2010). The deactivation of the stylolite  
183 can be related to the nature of stylolite interface fluid and with the diagenetic history of the  
184 rock - the cessation of the stylolite process can occur during burial and do not require external  
185 triggering mechanism (e.g. change of tectonic regime). Concerning the type of fluid,  
186 Alsharhan and Sadd (2000), Esteban and Taberner (2003) and Paganoni et al. (2015), showed  
187 that hydrocarbon saturated fluid leads to the cessation of the stylolite activity because the  
188 mass transfer in oil is nil (Fig. 1, F). Concerning the diagenetic history, it determines the  
189 volume of sink sites available to receive the product of the dissolution process and the  
190 availability of nucleation sites for stylolites (Koepnick, 1986). The process of pressure-  
191 solution induces dissolution of host rock material and precipitation of this dissolved material  
192 elsewhere in the system (pore space). The fluid circulation in the rock makes this process  
193 happening. For instance, Paganoni et al. (2015) studied oil reservoir from onshore Abu Dhabi.  
194 They found kaolin cements filling micro-fractures oriented perpendicular to burial stylolites  
195 (contemporaneous) and pores in the matrix surrounding these fractures. They showed that  
196 insoluble kaolin are related to fluxes of aggressive organic acids waters. These waters  
197 dissolve mica and feldspars minerals and keep Si and Al in solution through organo-metallic  
198 chemical complexation. This process is effective during stylolitisation and induces the  
199 precipitation of kaolin in the open fractures and in pores surrounding them. Vandeginste and  
200 John (2013), indicates that during stylolitisation process, rock dissolution products migrate by  
201 diffusion to zones of lower pressure where they precipitate as cements. Devoid of available  
202 pore space fluids cannot reach stylolite interface and cannot disseminate the product of

203 pressure-solution. The system is locked as observed by Bruna et al. (2013) in Lower  
204 Cretaceous limestone of the SE of France where the sedimentary series was buried at more  
205 than 1 km depth. At that depth, sedimentary formations with low cementation rate or with  
206 initial porosity preserved only were prone to the development of stylolites compared to early  
207 and intensely cemented ones that display very rare stylolites occurrences.

208

### 209 **Time: an important parameter for stylolite fluid flow efficiency**

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

222 Braithwaite (1988), was one of the first to discuss the potential for stylolites to be  
223 hydrocarbon conduits. He studied samples from Montana, USA and from Hadeland, Norway  
224 and observed that stylolites can be implicated in the process of hydrocarbon migration from  
225 source rock to reservoir. Overpressure in these systems help stylolites remains open and  
226 constitute super-permeability features allowing fluids to migrate at fast rates. This type of  
227 behaviour was later demonstrated by Peacock et al. (2017) and by Koehn et al. (2012) who

228 interpreted stylolite interfaces as channels able to transit fluid freely within a reservoir system.  
229 Padmanabhan et al. (2015) used the thermal connectivity anomalies in carbonate samples  
230 from Turkey and Malaysia to emphasise that the diachronic role of stylolites (i.e. acting  
231 sometimes as fluid conduits or fluid barriers) in the migration of hydrocarbon can generate  
232 variation of maturity within the reservoir.

233 In another context, Martín-Martín et al. (2016) studied an Upper Cretaceous carbonate  
234 platform in Spain where stylolites are interpreted to be the main control of the distribution of  
235 stratabound dolomite bodies and also to be responsible for their later corrosion and  
236 perforation making them highly porous and permeable layers. In their case stylolites act  
237 initially as baffle zone. Mg-rich fluids are transported by faults until they reach a stylolite  
238 barrier that laterally drives the dolomitisation process. Later high-pressure hydrothermal  
239 fluids circulating again along faults induced a change in the function of the stylolite, whereby  
240 it became a fluid conduit and induced corrosion and hydraulic fracturing in the dolomite  
241 bodies [this process was also described by Gisquet et al. (2013) in the Etoile Massif in the SE  
242 of France] (Fig. 2 B-C). In this case, the change of tectonic regime flipping  $\sigma_1$  from vertical to  
243 horizontal, or the induced fluid overpressure due to decompaction (inducing a disequilibrium  
244 of pore-fluid pressure) are suggested by the authors to explain the opening of stylolites.

245 Stylolites can also be responsible for their own deactivation by promoting cementation and  
246 consequently decreasing the initial or acquired porosity of the rock (Park and Schot, 1968).  
247 Sheppard (2002), showed that the stylolitisation process favours the petrophysical  
248 heterogeneity of the rock. Indeed, the pressure-solution mechanism is responsible for the  
249 creation of a diffusion gradient from porous zone conducting the fluid needed in the  
250 stylolitisation process to less porous zones where cementation occurred (Fig. 2 D-E). Then,  
251 with stylolite development, planar porous zones may be created in rocks. Matonti et al. (2012)  
252 in their work on the Castellans fault in the SE of France, suggested that stylolites, by increasing

253 dissolution, are the main cause for pervasive and complete cementation of the pore network  
254 around faults affecting initially porous carbonates rocks during fault reactivation. Indeed,  
255 fault strike-slip reactivation is related to the development of dense/numerous tectonic  
256 stylolites, providing CaCO<sub>3</sub> enriched fluids that contributed to form a cementation  
257 gradient/fringe visible on a 10-40 m scale around the main fault plane. Bertotti et al. (2017),  
258 observed in the Jandaíra Formation, Brazil, that stylolite are the source of cement that fill  
259 open joints and impede further fluid circulation in the rock. Fabricius and Borre (2007)  
260 emphasised the influence of the rock texture in the degree of cementation coming from  
261 stylolite production. Large pores are generally quickly filled by cements coming from the  
262 stylolitisation process (the pressure differential between stylolite dissolution spot and the pore  
263 is higher with large pore and favour the cementation in these locus). They observed in the  
264 Ontong Plateau in Java and in the North Sea Gorm and Tyra chalk oil fields, that the  
265 wackestone textures are less porous than the mudstone textures which appears to be  
266 contradictory.

267

### 268 **Influence of stylolite in present-day reservoir performance**

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

275

#### 276 • **Stylolite playing a role of barrier**

277 The most common statement about stylolites is to consider them as barrier to fluid flow. For  
278 Koehn et al. (2016), stylolites with low roughness are generally good barriers (Fig. 3) because  
279 this makes them more continuous feature than stylolites with irregular profile. The nature of  
280 their filling material is also influencing their fluid flow behaviour (Fig. 1, D-F). Stylolites are  
281 good barrier if they are filled by non-permeable materials like clay, organic matter and/or  
282 oxides (Mehrabi et al., 2016; Vandeginste and John, 2013). In addition, for Heap et al. (2014),  
283 a stylolite can be considered as good barrier if its filling material is evenly distributed and  
284 continuous along the seam and if the insoluble material composition is globally homogeneous  
285 along it (Fig. 3). The Grignantes quarry in the SE France constitutes a key locality to discuss  
286 these relationships. Here, the Meyrargues Limestone Formation, Berriasian of age (see Bruna  
287 et al., 2013), includes alternating metre-scale beds containing isolated stylolites and  
288 centimetre thick bioturbated packstone interbeds with solution seams bands. Work of Bruna et  
289 al. (2013), Bruna (2013) and Matonti et al. (2015), evidenced the difference in shape and  
290 insoluble composition of stylolites included (i) in beds – isolated seams, variable roughness  
291 and clay-oxide insoluble filling – and the ones included in (ii) interbeds – over concentrated  
292 and connected seams, low roughness and heterogeneous filling composed of pyrite, quartz,  
293 clay, calcite with aperture up to 50  $\mu\text{m}$ . They tested if these different types of stylolites and  
294 associated insoluble filling displayed a typical P-wave velocity ( $V_p$ ) signature by measuring  
295 acoustic waves directly on outcrop and in the laboratory on plugs sample processed in both  
296 atmospheric and under confinement (40 MPa) conditions. Figure 4, shows the obtained results  
297 on outcrop demonstrating that stylolites in beds are mainly invisible for  $V_p$  but solution seams  
298 bands located on interbeds showed an important decrease of acoustic waves velocities. The  
299 authors interpreted this as underlining the importance of stylolite profile (low roughness),  
300 heterogeneous filling and aperture on their hydraulic property and geophysical signature. At  
301 the plug scale,  $V_p$  values, porosity and the occurrence of stylolites were statistically compared

302 in and confirmed the observation conducted at the outcrop scale. It appears then that isolated  
303 and continuously filled stylolites are likely to display acoustic signature similar to their host  
304 rock making them less-to-no detectable, and when stylolites are open or discontinuously filled  
305 by insoluble material they have a distinctive acoustic signature. It is important to note here  
306 that these drastic contrasts in geophysical and hydraulic behaviour can occur below the metre  
307 scale, hence impacting heterogeneity distribution in reservoirs, below conventional seismic  
308 cross-section resolution.

309 However, stylolites acting as barriers can be important in reservoir as they may act as  
310 directional guide for fluid flow impeding vertical movements (when sedimentary stylolite  
311 only are developed) or restricting even more fluids spots - in the presence of both sedimentary  
312 and tectonic stylolites – (Alsharhan and Sadd, 2000; Bushara and Arab, 1998; Koepnick,  
313 1986; Lavenu and Lamarche, 2017; Martín-Martín et al., 2016). Because the production of a  
314 compartmentalised reservoir is technically complex, one should carefully assess the presence  
315 of stylolites and evaluate their potential impact before starting any field development plans.

316

### 317 • **Stylolite playing a role of drain**

318 At a small scale, we previously discussed that stylolite filling continuity is a key to make  
319 them good barriers. Heap et al. (2014) conducted experiments on a series of 4 samples with  
320 different lithologies containing stylolites. In each of these samples, plugs were drilled in  
321 order to obtain 3 subsamples: i) without stylolites, ii) with stylolite oriented along the  
322 longitudinal axis of the subsample and iii) with stylolite oriented perpendicular to the long  
323 axis of the subsample. They showed that the porosity value in sample devoid of stylolites is  
324 systematically lower than in sample with stylolites. They also measured the permeability on  
325 the subsamples and demonstrated that the anisotropy of permeability is equivalent between  
326 samples without stylolites and samples with perpendicular to long axis stylolites (gas

327 permeability ranging from  $10^{-19}$  to  $10^{-14}$  m<sup>2</sup> in both cases). They also observed that the  
328 permeability is enhanced when stylolites are oriented in the longitudinal axis of the  
329 subsample. This study shows that stylolites are here not a proper barrier and represent a zone  
330 of enhanced permeability that can flank the stylolite walls on the order of millimetres to few  
331 centimetres around the stylolites.

332 As previously discussed, the roughness is also a key parameter influencing the fluid flow  
333 behaviour of a stylolite. The work of Koehn et al. (2016) highlighted the fact that the  
334 roughness profile of a stylolite is directly linked with its petrophysical behaviour by making  
335 the stylolite potentially discontinuous. For instance in the case of the “rectangular layer  
336 stylolite”, insoluble material is concentrated in the horizontal part of the stylolite teeth, the  
337 vertical edges of the stylolite teeth having a completely different behaviour. During stylolite  
338 growth these vertical parts are parallel to the principal stress direction, and behave like  
339 tension gashes that can remain open if subsurface conditions are favourable (e.g.  
340 overpressure, Fig. 5). The authors showed that if the conditions are not favourable, fluids  
341 could remain trapped in the teeth and locally accelerate the dissolution leading to the creation  
342 of secondary vuggy porosity (Fig. 5 C). This latter process was also observed by Nader et al.  
343 (2016), and can be enhanced by the nature of fluids remaining trapped in the system (Martín-  
344 Martín et al., 2016; Paganoni et al., 2015).

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

351

352 It appears that the main parameters making stylolites a positive or negative fluid flow features  
353 is linked with their shape (rough stylolites are not continuous high density layers), their  
354 filling material, the nature of the fluid transiting through them and the global geological history  
355 (e.g. highly corrosive fluids circulating along faults and using stylolite to invade the host  
356 rock). Indirectly, stylolites can also act as barrier by cementing locally part of the reservoir (if  
357 the dissolved calcite is transferred locally around the stylolite and fill the actual pore space).  
358 Heap et al., 2014 mention that mineral coating (e.g. stylolites formed before oil charge may  
359 be significant barriers to fluid flow because they are entirely cemented compared to stylolites  
360 formed after the oil entrapment that impede the cementation and consequently the closure of  
361 stylolites), low fluid fluxes, low partial pressure of CO<sub>2</sub>, high pH and high temperature may  
362 also favor this process.

363

## 364 **Concluding remarks**

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

371

372 The origin and life cycle of a stylolite has been the focus of numerous high quality studies  
373 that increased strongly the community's understanding of how a stylolite occurs, grows and  
374 dies. However, an important part of these articles focus on results obtained from numerical  
375 modelling or/and conducted at small scale sometimes compared to natural experimental  
376 examples. The rare studies focusing on larger scale stylolites (Laronne Ben-Itzhak et al.,



377 2014; Laronne Ben-Itzhak et al., 2012) opened a new perspective, showing in particular the  
378 process of deactivation of stylolites. This can probably constitute a basis to date when the  
379 stylolite stopped to grow. Because the cementation of the reservoir may be linked to the  
380 stylolite deactivation, understanding the relative timing of these processes will be a strong  
381 asset to reconstruct the evolution of a petroleum system (migration, charge, fluid flow). An  
382 approach based on dating and provenance evaluation (isotopic studies) of the different  
383 cements can be advanced as a research axis for the future.

384

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

395

396 The potential of stylolites to be drain or barriers seems to follow a binary response. In fact  
397 stylolites can be drains AND barriers to fluid flow. Depending on facies variation, on  
398 diagenesis, on the heterogeneity of the reservoir itself, multiple types of stylolites can be  
399 generated and consequently their impact on fluid flow could be very different. Accordingly,  
400 the impact of stylolite is not only black or white but can be viewed as shades of grey. Rather  
401 than mentioning the presence of stylolites in reservoir intervals and stating that they will have

402 a negative impact on reserve and flow, efforts need to be consented on describing the  
403 roughness of stylolite and the nature/thickness of insoluble filling. The understanding of  
404 regional stress state and tectonic history of the area where the targeted reservoir is located  
405 need also to be considered to take into account a potential reopening of these structures. As it  
406 has been recognized for fractures several decades ago, stylolites properties and hydraulic  
407 behaviour should now be considered as the final result of multifactorial (sedimentary, burial,  
408 chemical, tectonic) and polyphased processes. Experiments of Heap et al. (2014) constitute a  
409 benchmark to change the classical vision of stylolites as a simple barrier. Systematic testing  
410 of various types of stylolite roughness and of different type of insoluble to decipher the  
411 impact of these parameters on petrophysical properties would be an interesting axis of  
412 research for the future. Obtained results could be compared to the modelling results obtained  
413 by Koehn et al. (2016). Finally, conducting a series of experiments on full size core at  
414 subsurface condition will help to get rid of artefacts/biases caused by surface decompaction  
415 that can occur to natural samples.

416

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421

## 422 **Figure Captions**

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

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

437

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

450

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

458

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

468

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

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

480

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