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1 Bedding-parallel stylolites as a tool to unravel maximum burial depth in sedimentary basins:
2 application to Middle Jurassic carbonate reservoirs in the Paris basin

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15 Abstract

16 In recent years stylolites, which are rough dissolution surfaces commonly found in carbonates, have
17 been used for paleopiezometry estimates. The Stylolite Roughness Inversion Technique (SRIT) applied
18 on sedimentary bedding-parallel stylolites (BPS) grants access to the maximum principal vertical stress
19 experienced by the host carbonates and thus to their maximum burial paleo-depth. This study reports
20 the results of SRIT applied to a BPS stylolite population hosted in carbonate platform reservoirs of the
21 Paris basin sub-surface (France). Middle Jurassic carbonates from two well cores from the depocenter
22 and margin of the basin, for which the burial and thermal history are known, based on a thermally
23 calibrated 3D basin model, were analysed. By defining a consistency criterion and using two signal
24 treatment methods, we propose a new approach to select which BPS can be reliably used to
25 reconstruct the maximum vertical stress undergone by the host carbonates, which then can be
26 converted into maximum burial depth. The study of a BPS population shows that there is a control
27 operated by the host rock texture and the stylolite morphology on the burial depth recorded.
28 Especially suture and sharp peak BPS are better suited to estimate the real maximum depth, whereas
29 seismogram pinning BPS record preferentially intermediate depths. Median values of maximum depth
30 derived from our dataset (1.3 and 1.7 km for the margin and depocenter cores, respectively) are in
31 line with maximum burial estimates provided by conventional basin modelling (1450 and 1800 m,

32 respectively), thus showing that SRIT is a standalone robust depth gauge in sedimentary basins,
33 provided sample selection and data treatment are carried out in a rigorous and thoughtful manner.

34 1. Introduction

35 Stylolites are localized rough dissolution surfaces that are encountered in all sedimentary rock types
36 (Alvarez et al., 1978; Koehn et al., 2007) and are particularly common in carbonates, which represent
37 significant host rocks of natural resources (water, oil, gas, ores) worldwide. The chemical compaction
38 process occurring during burial and/or tectonic loading significantly affects the physical properties of
39 carbonate reservoirs by reducing porosity (Raynaud and Carrio-Schaffhauser, 1992; Ehrenberg, 2006).
40 The occurrence of sedimentary stylolites, usually oriented parallel to bedding (bedding-parallel
41 stylolites or BPS) impacts fluid flows, by forming either barriers or drains in reservoir rocks (Koepnick,
42 1987; Ehrenberg et al., 2006; Hassan, 2007; Heap et al., 2013; Baud et al., 2016; Koehn et al., 2016;
43 Bruna et al., 2018; Martín-Martín et al., 2018, Toussaint et al., 2018). The characteristic teeth of
44 stylolites, oriented oblique or normal to the dissolution surface, are related to the distribution of
45 insoluble elements in the host rock, leading to local pinning under an oriented applied stress (Fletcher
46 and Pollard, 1981; Merino et al., 1983; Koehn et al., 2007). Various genetic models were proposed to
47 account for the initial localization of dissolution along a surface and the lateral propagation of BPS.
48 The pressure-solution model (Merino et al., 1983) considers that stylolites are related to local
49 dissolution under an applied stress field and that the lateral propagation is controlled by the stress
50 concentration at stylolite's tips (anticrack model, Fletcher and Pollard (1981)). This model was
51 questioned by Aharonov and Katsman (2009) because stress concentrations at the tips of a stylolite
52 are relaxed once the stylolite itself supports the applied stress. The clay-enhanced dissolution model
53 (Bjorkum, 1996; Oelkers et al., 1996; Walderhaug et al., 2006), originally developed for quartz-mica
54 interfaces, considers that stylolites develop on a clay-rich interface related to an electrochemical
55 potential at the contact between the host rock and the clay. The clay-enhanced model can explain the
56 localisation of dissolution at a surface and also the lateral propagation of stylolite planes (Aharonov
57 and Katsman, 2009) along clay-rich areas. Both the pressure-solution and the clay-enhanced models
58 can be combined where clay particles, that accumulated during the host rock dissolution under
59 applied stress, enhance the dissolution kinetics (Renard et al., 2001). Since stylolites are features that
60 form during chemical compaction, which is a function of the sediment overburden and since the tooth
61 flanks are parallel to maximum the principal compressive stress, the stress clearly plays a key role in
62 the formation of these features. In carbonates, the type of facies (chiefly dependent on depositional
63 texture, primary mineralogy and abundance of allochems, mud and pores), the morphology (Andrews
64 and Railsback, 1997), the presence of clays and organic matter, as well as the vertical heterogeneity
65 of the strata and the applied stress are the main parameters that govern stylolitization (Shinn and

66 Robbin, 1983; Bathurst, 1987, 1991; Aharonov and Katsman, 2009; Koehn et al., 2012; Vandeginste
67 and John, 2013; Koehn et al., 2016). Today still, assessing the mechanisms that govern BPS
68 development as well as the quantification of the stress experienced by the stylolite host rock are key
69 points to understand sedimentary basin evolution aiming at improving geological simulations at both
70 the basin and the reservoir scales (Braithwaite, 1988; Andrade Ramos, 2000; Gratier et al., 2005;
71 Peacock and Azzam, 2006; Baron and Parnell, 2007; Benedicto and Schultz, 2010; Angheluta et al.,
72 2012; Koehn et al., 2012; Heap et al., 2013; Khair et al., 2013, 2015; Baud et al., 2016; Bertotti et al.,
73 2017).

74 In addition to being used to estimate chemical compaction during burial diagenesis (Peacock and
75 Azzam, 2006; Angheluta et al., 2012; Koehn et al., 2016) and to refine deformation history of strata
76 (Benedicto and Schultz, 2010; Tavani et al., 2006, 2015), stylolites have been used to access the
77 magnitude of applied stress. The Stylolite Roughness Inversion Technique (SRIT, Schmittbuhl et al.,
78 2004) is based on a signal analysis of the stylolite's roughness. Successive studies (Renard, 2004;
79 Schmittbuhl et al., 2004; Brouste et al., 2007; Ebner et al., 2009a; Ebner et al., 2009b; Croizé et al.,
80 2010; Ebner et al., 2010a; Rolland et al., 2012, Koehn et al., 2012) established SRIT as a novel
81 paleopiezometric technique, independent from dissolution kinetics, temperature and fluid pressure,
82 that quantifies (1) the maximum vertical stress at the time the dissolution along the stylolite plane
83 stops, and thus the corresponding burial depth, if the method is applied to sedimentary stylolites
84 (Brouste et al., 2007; Ebner et al., 2009b 2010a, 2010b; Rolland et al., 2014; Beaudoin et al., 2016;
85 Bertotti et al., 2017), and (2) the complete stress tensor, by applying SRIT on coeval sedimentary and
86 tectonic stylolites (Ebner et al., 2010a; Rolland et al., 2014; Beaudoin et al., 2016). SRIT relies on the
87 self-affine properties of the stylolite plane roughness to access the magnitude of the stress oriented
88 normal to the stylolite plane (considering a 2D signal, Schmittbuhl et al., 2004) or of both the stresses
89 oriented normal and parallel to the stylolite plane (considering a 3D signal, Ebner et al., 2010b). Even
90 if SRIT was successfully applied to BPS in natural samples and the method reproduced applied external
91 stresses in numerical simulations (Koehn et al., 2012), the magnitudes of the vertical stress
92 reconstructed in published studies show a variability, leading authors to either use averaged values
93 (Bertotti et al., 2017), or to discuss what this variability can mean. Indeed, variable SRIT results were
94 accounted for by considering elastic parameters of the host rock (Rolland et al., 2014), morphological
95 sensitivity of the roughness (Brouste et al., 2007), polyphase burial history or methodological
96 limitations (Beaudoin et al., 2016).

97 This contribution proposes a statistical appraisal of SRIT applied to a natural BPS population in a weakly
98 tectonized sedimentary basin. Our approach aims at inverting BPS from two cores of the Paris basin
99 sub-surface (Fig. 1) where Middle Jurassic carbonates suffered different maximum burial depth. We

100 use established signal treatment methods (Simonsen et al., 1998; Renard et al., 2004; Ebner et al.,
101 2009b), Fourier Power Spectrum (FPS) and Average Wavelet Coefficient (AWC), to reconstruct the
102 maximum vertical stress recorded by BPS, and hence the maximum burial depth undergone by the
103 host carbonates. The SRIT is conducted regarding the stylolite morphology, following the recent
104 classification proposed in Koehn et al., (2016), and regarding the depositional texture of the host-rock.
105 On the basis of the direct comparison between the inversion results and the known maximum burial
106 depth independently provided by 3D basin modeling (Fig. 2), we develop a data treatment workflow
107 for BPS populations that show how to use SRIT to access to the maximum burial depth experienced
108 by strata as a reliable paleopiezometer in future studies.

109 2. Stylolite Roughness Inversion Technique (SRIT)

110 a. Principles of the technique

111 SRIT assumes that the stylolite roughness results from a competition between (1) a destabilizing
112 (roughening) force due to pinning particles on the stylolite surface, that resists dissolution in specific
113 locations, locally increasing the Helmholtz free energy and producing peaks and teeth; and (2) two
114 stabilizing (smoothing) forces, long-range elastic forces and local surface tension, that tend to
115 reduce the Helmholtz free energy of the solid, leading to flattening of the surface by localizing
116 dissolution on areas of local roughness (Schmittbuhl et al., 2004; Koehn et al., 2007, Rolland et al.,
117 2012). The stylolite roughness displays self-affine properties, i.e., a geometry that is invariant across
118 a range of scales typically with a different scaling in x than in y so that the surface becomes rougher
119 towards smaller scales. The two stabilizing forces are efficient at different spatial scales so that two
120 regimes can be defined: an elastic energy-dominated regime at a large-scale (above mm, typically),
121 and a surface energy-dominated regime at a small-scale (below mm, Schmittbuhl et al., 2004). Each
122 of the stabilizing forces is characterized by a specific roughness coefficient (called Hurst coefficient)
123 that can be determined by conducting a Fast Fourier Transform, Wavelet Analysis or applying a
124 Correlation Function on the roughness profile along a stylolite. This Hurst coefficient has been
125 extensively documented in natural stylolites (Brouste et al., 2007), and the transition from one
126 stabilizing force spatial scale domain to the other is called the crossover length (L_c). L_c is related to
127 both the mean stress and differential stress the rocks sustained during stylolite growth according to
128 Schmittbuhl et al. (2004)

$$129 \quad L_c = \frac{\gamma E}{\beta \sigma_m \sigma_d}, \quad (1)$$

130 where the cross-over length L_c (mm) is linked to the Young's modulus E (Pa), to the solid-fluid
131 interfacial energy γ ($\text{J}\cdot\text{m}^{-2}$), to the dimensionless constant $\beta = \nu(1 - 2\nu)/\pi$ with ν being the Poisson's
132 ratio, and to the mean and differential stress, σ_m and σ_d , respectively. It is noteworthy that this

133 equation is valid considering that the stylolite localized along a water-rock interface, and that the
134 mechanical properties of the dissolved rock remain constant during dissolution. Provided the rock
135 properties are known, SRIT therefore grants access to the stress acting normal to the BPS plane.

136

137 b. Measurement methodology

138 The roughness signal was studied following the approach described in Schmittbuhl et al. (2004) and
139 Ebner et al. (2009b). Surfaces of core samples, cut perpendicular to the stylolite planes, were hand-
140 polished using abrasive grinding papers from coarse (250 μm) to extra fine (2.5 μm) allowing gentle
141 polishing in order to prevent any alteration of the material. Once the stylolite track visually contrasts
142 with the host rock, the surface is scanned in 2D at a resolution of 12800 dpi. Stylolite tracks were hand-
143 drawn using a drawing software (GIMP) with a 5 pt. thick line. We then used scripts presented in Ebner
144 et al. (2009b) to rotate the stylolite plane back to horizontal. The resulting 1D signal was analyzed
145 using the Fourier Power Spectrum (FPS; Renard et al., 2004) and the Average Wavelet Coefficient
146 (AWC) methods with Daubechies D4 wavelets (Simonsen et al., 1998; Ebner et al., 2009b). Both
147 methods have been applied to roughness 1-D profiles, and returned similar results (Simonsen et al.,
148 1998; Candela et al., 2009; Ebner et al., 2009b). The general signal analysis revolves around the self-
149 affine properties of the stylolite roughness, defined as the height difference Δh between two points
150 of the rough surface separated by a distance Δx . A self-affine signal is characterized by $\Delta h \approx \Delta x^H$, where
151 H is the Hurst coefficient. In the case of a FPS analysis, in which the signal is considered as a sum of
152 periodic sinuses and cosinuses, the wave number k (mm^{-1}) and the squared Fourier transform modulus
153 $P(k)$ are related as $P(k) = k^{2H+1}$. In the case of an AWC analysis, in which the signal is reconstructed
154 in a sum of different wavelets, starting with a mother function (Simonsen et al., 1998), the scale a
155 (mm) and the averaged wavelet coefficient $W(a)$ are related as $W(a) = a^{H+0.5}$. For each method, it
156 is possible to access the H coefficient based on the slope that links the data, picked following a binning
157 interval, on a log-log plot, and using the relations reported above. In an ideal case, two straight lines
158 should be traceable on log-log plots, a steep line at the lower scale values, characterized by a H of 1
159 (corresponding to surface energy), and a gentle slope line at the higher scale values, characterized by
160 a H of 0.5 (corresponding to elastic energy). The observation scale (k for FPS, a for AWC) at which the
161 two slopes intersect is the crossover length L_c that is related to the vertical stress for sedimentary
162 stylolites. In order to reduce uncertainty on L_c , we fit the line that goes through the maximum of
163 binned data points and use slopes that satisfy the theoretical H coefficients. To estimate the error on
164 the L_c value obtained, we consider a domain of transition between the two regimes using the scale at
165 which there is a clear separation of the two slopes on each side of the intersection (log-log plots of
166 Fig. 6). This domain represents an error graphically evaluated from $\pm 4\%$ to $\pm 10\%$ of the L_c , depending

167 on where the L_c sits on the log-log plot. It is noteworthy that the SRIT is independent of the dissolution
168 kinetics, the surrounding fluid pressure and the amount of dissolution. Thus, the amount of chemical
169 compaction accommodated by the stylolites is beyond the scope of this study.

170

171 c. BPS inversion for vertical stress and depth assessment

172 For BPS, we can assume a zero horizontal displacement in the stylolite plane, corresponding to a
173 perfect isotropy of the horizontal principal stress, such as $\sigma_v > \sigma_H = \sigma_h$ (σ_H and σ_h are the notation for the
174 maximum and minimum horizontal principal stress, respectively), leading to the simplification of the
175 equation (1) as:

$$176 \quad \sigma_v^2 = \frac{\gamma E}{\kappa L_c}, \quad (2)$$

177 with $\kappa = \frac{\nu}{3\pi} \times \left(\frac{(1-2\nu)^2(1+\nu)}{(1-\nu)^2} \right)$ (Koehn et al., 2012). Finally, the depth h is obtained using $\sigma_v = \rho gh$, with
178 ρ the rock density and g the gravitational field acceleration. In our study, we use the classic solid-fluid
179 interfacial energy value for calcite ($\nu=0.27$ J.m⁻²), the averaged mechanical parameters obtained from
180 mechanical testing conducted on the Comblanchien carbonate formations (Bemer and Lombar, 2010):
181 a Poisson's ratio of 0.22, a Young's modulus of 34 GPa, and a density for carbonates of 2700 g.cm⁻³.
182 Considering the error on the L_c values, and the range of the mechanical parameters ($E = [31 - 36]$ GPa,
183 Poisson's ratio [0.21-0.23]), the uncertainty on the inversion results is $\pm 10\%$.

184

185 3. Case study of the Middle Jurassic carbonates of the Paris basin

186 a. Geological and thermal history

187 The Paris basin is a Meso-Cenozoic intracratonic basin which initiated in late Carboniferous and
188 Permo-Triassic times in response to the extensional collapse of the thickened Variscan lithosphere and
189 reactivation of inherited Variscan structures (Perrodon and Zabek, 1990; Guillocheau et al., 2000; Le
190 Solleuz et al., 2004; Averbuch and Piromallo, 2012). It is mainly filled by Mesozoic sediments lying
191 unconformably on a Paleozoic basement (Fig. 1), with the whole sedimentary column (from Triassic
192 to Tertiary) reaching about 3000m of thickness in the central part of the basin (Fig. 1). During Mesozoic
193 times the Paris basin experienced a simple burial history, punctuated by periods of rapid subsidence
194 in the Jurassic and Late Cretaceous and of minor uplifts. A major tectonic inversion occurred at the
195 Mesozoic-Cenozoic boundary, which led to the main uplift phase causing the exposure of the entire
196 basin (Brunet and Le Pichon, 1982; Guillocheau et al., 2000; Barbarand et al., 2013). At the southern
197 and eastern basin margins evidence for three Cenozoic tectonic events were recorded: the Pyrenean
198 orogeny (N-S compression; Eocene), the opening of the Bresse and Rhine grabens related to the West
199 European Rifting (E-W to WNW-ESE extension; late Eocene – Oligocene) and the Alpine orogeny

200 (WNW-ESE compression; Miocene-Pliocene) (Lacombe et al., 1990, 1993, 1994; Guillocheau et al.,
201 2000; Andre et al., 2010). The sedimentary succession has been extensively explored for oil and gas
202 resources (Espitalié et al., 1988; Delmas et al., 2002, 2010), which migrated mostly in Late Cretaceous
203 time into reservoir rocks from different stratigraphic intervals (mainly Upper Triassic, Middle Jurassic
204 and Lower Cretaceous; Wendebourg and Lamiroux, 2002; Delmas et al., 2002, 2010).

205

206 In this study, a 3D basin model for the Paris basin was used to extract the burial and thermal history
207 of the studied cores. The original geometric model was constructed with the TemisFlow software for
208 basin modeling, (Teles et al., 2014) and was recently improved by considering a lithospheric model for
209 heat transfer, and by reconstructing paleobathymetry maps and eroded thicknesses through time
210 (Torelli, 2018) (Fig. 2). Thermal calibration was accomplished with present-day bottom hole
211 temperatures (BHT) and conventional organic thermometers, like vitrinite reflectance and Rock-Eval
212 pyrolysis data (Torelli, 2018). Further constraints were also made available from absolute thermo-
213 chronometry of carbonate cements from the same stratigraphic unit studied here (Mangenot et al.,
214 2017; Mangenot et al., 2018).

215

216 b. Studied sedimentary cores

217 This study focuses on the sedimentary, bedding-parallel stylolite (BPS) population hosted in two
218 exploration well cores, one from the depocenter (Rigny-la-Nonneuse; hereafter referred as Rigny) and
219 one from the southern margin (Parly) of the basin (Fig. 1). The stratigraphic interval studied consists
220 of the Upper Bathonian – Lower Callovian platform carbonates corresponding to the *Comblanchien*
221 and *Dalle Nacrée* Fms., separated by a major transgressive surface (Guillocheau, 1991; Guillocheau et
222 al., 2000) and differentiated based on their biostratigraphic content (Garcia, 1993; Garcia and Sambet,
223 1994). This corresponds to a large isolated platform, recording no detrital input from the continent.
224 The two cores exhibit a different thermal and burial history (Fig. 2). Currently, the studied interval is
225 buried at a depth of 1537-1574 m in the basin depocenter (Rigny) and at a depth of 640-663 m on the
226 basin southern margin (Parly). The 3D model further predicts that at peak burial conditions the Middle
227 Jurassic carbonates experienced depths of 1800 m and 1450 m and temperatures of 92 and 80 °C in
228 the Rigny and Parly cores, respectively (Fig. 2). Figure 2 also illustrates that the carbonates experienced
229 a simple burial history characterized by a nearly continuous burial until Late Cretaceous, followed by
230 a main uplift event. Thus, the rocks mainly underwent normal overburden pressure (inducing
231 development of BPS) and escaped major tectonic deformations.

232 The Upper Bathonian – Lower Callovian stratigraphic interval investigated is 37 and 23 m thick in the
233 Rigny and Parly cores, respectively. Sedimentary logging and macro-facies analysis were accomplished

234 at the 1:100 scale and sampling for thin section preparation and petrographic micro-facies analysis
235 was performed on average every 1 m of core and specifically in close vicinity of the BPS selected for
236 SRIT analysis (Fig. 3a). Gas and water porosimetry on this stratigraphic interval at basin scale revealed
237 a wide range of porosities from 0 to 22%, with average and mode values that are 5.5% and 3-4%,
238 respectively (Delmas et al., 2010). However, 2D point counting estimates on thin sections from the
239 studied cores point towards porosity mostly below 5% (Mangenot et al., 2018).

240 Macro- and micro-facies analyses and comparison with previously published works (Gaumet, 1994,
241 1997; Granier, 1995; Gaumet et al., 1996) allowed us to distinguish a total of 23 carbonate facies from
242 the two studied cores. Based on sedimentary structures, depositional textures, as well as type and
243 proportion of allochems, mud and primary pores, the 23 facies were ascribed to 6 depositional
244 environments (Fig. 4): (1) Intertidal deposits are mainly composed of packstone and grainstone
245 dominated by intraclasts (1-10 mm) and reworked oncoids (0.5-1.5 cm) with oblique lamination and
246 fenestral pores, typical of high energy sediments subjected to periodic emersions; (2) Sub-tidal lagoon
247 deposits are mainly composed by wackstone to packstone dominated by oncoids, locally reaching 2
248 cm in diameter (floatstone), and peloids, associated with planar microbial mats, suggesting a low to
249 medium energy environment; (3) Deep lagoon deposits are mainly composed of mudstone and
250 wackstone containing small (<1 mm) oncoids, locally associated with lenses of organic-rich sediments,
251 indicating a very low energy environment; (4) Back-shoal to shoal deposits. The former are mainly
252 composed of the lagoonal facies containing spill-over deposits derived from the shoal. The latter
253 include high energy grainstone and packstone composed of ooids (<2mm), coated grains (1-2 mm),
254 peloids (<0.5 mm), bioclast fragments (crinoids, corals, bryozoans, brachiopods, bivalves) locally with
255 cross-stratification and rare evidences of emersion associated with geopetal features and fenestral
256 pores; (5) Fore-shoal deposits include mud-, wack-, pack- and grainstone with dominant peloids (<0.5
257 mm) and bioclast fragments (mainly crinoids, brachiopods and bivalves) and encrusting serpulids; (6)
258 Off-shore deposits include wackstone with wavy bedding containing few crinoid fragments (<0.5 mm),
259 commonly recrystallized and locally associated with dark lenses of clay-size particles (organics or
260 siliciclastics), deposited in a low energy setting.

261 Petrographic analysis did not identify phyllosilicates like micas in any of the 23 sedimentary facies.
262 Minor clay-size particles, likely siliciclastic, were identified only in the off-shore environment and are
263 possibly linked to upwelling from distal plains, whereas clay-size particles, likely organic, were
264 identified in the deep lagoon environment where anoxic conditions could have favoured their
265 preservation.

266 For the scope of this survey the 23 facies identified were gathered into 4 main groups based on the
267 dominant carbonate textures (*sensu* Dunham, 1962) irrespective of the depositional environment of
268 provenance: (1) Mudstone to wackstone (locally with clay-size siliciclastic and organic particles) with
269 minor oncoids, peloids and bioclast fragments (<0.5 mm); (2) Wackstone to floatstone mainly with
270 oncoids, peloids and locally intraclasts (<2 mm); (3) Floatstone to packstone with oncoids, intraclasts
271 and locally peloids (1.5 cm); (4) Packstone to grainstone with ooids, coated grains, intraclasts, bioclasts
272 (mainly brachiopods and crinoids) and locally oncoids (up to 2 cm). These groups will be further used
273 to assess the role of the carbonate depositional texture on the results of SRIT analysis.

274 c. Stylolite populations

275 Stylolite populations in the cores consist exclusively of bedding-parallel stylolites (BPS) that formed in
276 response to vertical stress during burial (Fig. 3b), in a setting where the horizontal stress is likely to
277 remain isotropic. All peaks are observed normal to the stylolite planes, indicating that the governing
278 stress direction was vertical (Koehn et al., 2012), and that no horizontal displacement occurred along
279 the stylolite plane. The investigated core samples were typically 15-20 cm long (Fig. 3b). Twenty-five
280 (25) samples (core slabs) containing single-trace stylolites were considered for the SRIT, and forty-
281 eight (48) stylolites were selected with lengths ranging from 1.5 cm to 7.4 cm. Sampling covers
282 different depositional facies and corresponding environments in both cores (Fig. 3a), comprising 14
283 samples (32 stylolites) from the Parly core (covering the 643-663 m depth interval) and 11 samples
284 (16 stylolites) from the Rigny core (covering the 1542-1559 m depth interval), respectively. Stylolites
285 were characterized regarding their morphologies, following the classification proposed by Koehn et
286 al. (2016). This classification comprises 4 classes of stylolites based on the shape of the roughness,
287 which itself is related to the stylolite growth (Fig. 5). In the following description the stylolite
288 morphology is split into a baseline corresponding to above-mm scale morphology and peaks referring
289 to below-mm scale morphology. Class 1 stylolites (rectangular layer) consist of a large rectangular
290 baseline with small peaks on the rectangle flat top. Class 2 stylolites (seismogram) are characterized
291 on the large scale by the occurrence of narrow top-hat like rectangles, with small-scale peaks. Class 3
292 (suture and sharp peak) includes all stylolites that have a flat or wavy base line with locally tall peaks.
293 Finally, Class 4 stylolites (simple wave) display a wavy base line and sparse small peaks. Numerous
294 core samples comprise stylolites with various morphologies, indicating that the morphology is
295 independent from the depositional textures/facies and corresponding environments. A rough
296 minimum estimate of the vertical displacement (compaction) that the studied stylolites
297 accommodated can be obtained by measuring the maximum amplitude of the teeth along the 2D
298 profile (Koehn et al., 2016, Toussaint et al., 2018). These amplitude values are reported in the Table
299 1, showing stylolites accommodated a minimum of 1.14 mm to 8.4 mm vertical displacement.

300 Superposition of stylolite teeth also suggests a complex polyphase development of pressure-solution
301 in the strata, and the anastomosed pattern results from complex interactions between stylolite planes
302 that likely destroyed the original roughness (Sinha-Roy, 2002; Laronne Ben-Itzhak et al., 2014).
303 Consequently, we discarded overprinted or fused stylolites from our study so that SRIT analysis
304 focussed on single, isolated stylolites only.

305 4. SRIT results

306 The roughness of forty-eight (48) stylolites was studied using both the FPS and AWC methods (Table
307 1). Figure 6 shows representative examples of the obtained treatment. By calculating the values of the
308 Hurst coefficient for each stylolite, we can divide the population into three categories: (1) stylolites of
309 which both small-scale and large-scale Hurst coefficients correspond to 1 ± 0.1 and to 0.5 ± 0.1 ,
310 respectively. These values are the theoretical ones expected from the growth model (Schmittbuhl et
311 al., 2004), and we consider an uncertainty of ± 0.1 to account for user-related sources of error (stylolite
312 drawing and value reading mainly, Fig. 6a). Thirty-five and twenty-six stylolites satisfy this criterion
313 when analysed using AWC and FPS, respectively; (2) stylolites of which either one or both small-scale
314 and large-scale Hurst coefficients do not correspond to the theoretical values (Fig. 6b). Eight and
315 thirteen stylolites belong to this category, when analysed using AWC and FPS respectively; (3) stylolites
316 where roughness analysis does not show two growth regimes, hence no cross-over length (Fig. 6c).
317 Five and eight stylolites belong to this category, when analysed using AWC and FPS, respectively. The
318 fact that both small-scale and large-scale Hurst coefficients reconstructed satisfy the theory is the key
319 factor to select the stylolites among the population that are the best suited to be used as
320 paleopiezometers. This characteristic is hereafter referred to as the consistency.

321 In order to characterize the stylolites that are the best suited to be used for SRIT, we studied the
322 statistical distribution of the population considering the consistency with the growth model, the
323 stylolite morphology and the host rock texture. Vertical stress and corresponding burial depth
324 distribution modes (first and third quartiles and median) of the population were compared to the
325 depth predicted by the burial-thermal modelling. This approach enables us to establish the most
326 efficient way to use SRIT to access the maximum depth experienced by the strata on one hand, and to
327 assess the impact of the stylolite morphology or of the host rock texture on the other hand. It is worth
328 noting that the results from SRIT analysis are more consistent with the modelled depths when
329 analyzed using the AWC method rather than the FPS method.

330 To account for the difference in the depth estimates depending on the signal analysis method used,
331 we considered FPS and AWC averaged depth values for the stylolites that are referred to as consistent,
332 i.e. those with Hurst coefficients consistent with Schmittbuhl et al. (2004). More than 80% of the

333 stylolites satisfy the consistency criterion in our sample population, considering either results from
334 AWS, or from FPS or from both, the latter case encompassing 50% of the whole population. The depth
335 median value obtained from the average between FPS and AWC inversion for these stylolites is very
336 close to the maximum burial depth predicted by the burial-thermal model (Figs. 2 and 7). Indeed, SRIT
337 returns maximum depths of 1300 ± 100 m for the Parly core and 1650 ± 100 m from the Rigny core,
338 while maximum depths estimated by the basin model are 1450 m in Parly and 1800 m in Rigny. This
339 shows that the depth median value derived from a stylolite population can be used to reliably access
340 the maximum burial depth, provided stylolites satisfy the consistency criterion previously defined in
341 this study.

342 5. Discussion

343 a. Impact of the stylolite morphology on SRIT reliability

344 Sedimentary rocks host stylolites of various morphologies, which can be described based on teeth
345 frequency, wavelength and amplitude at different observation scales (Andrews and Railsback, 1997).
346 Stylolite morphology affects estimates of the chemical compaction and the efficiency of fluid flow
347 along the dissolution planes (Braithwaite, 1988; Meredith et al., 2011; Heap et al., 2013; Koehn et al.,
348 2016). Morphology is likely to be controlled by both the growth regime (Koehn et al., 2016) and the
349 host rock heterogeneity distribution such as porosity (Andrews and Railsback, 1997) or pinning
350 particles (Koehn et al., 2007; 2012). Both these parameters deeply affect the ability of a stylolite to
351 record two-scales of growth regimes, hence reliable stress magnitudes (Renard, 2004; Ebner et al.,
352 2009b; Ebner et al., 2010a; Ebner et al., 2010b; Rolland et al., 2014). The case study of the Middle
353 Jurassic carbonates from the Paris basin subsurface enables us to discuss how reliable the SRIT is with
354 respect to the stylolite morphology. We studied stylolites clearly related to the vertical stress applied,
355 with teeth oriented vertical and perpendicular to the dissolution plane, and formed in rocks containing
356 very few clays and no micas. In order to assess whether morphology plays a noticeable role on the
357 SRIT results, we reported a statistical analysis of the BPS populations as box-and-whisker plots as a
358 function of the morphology (Fig. 8a). It is worth noting that provided that the stylolite 2D profile is
359 long enough for both the roughness Hurst exponents to be found (>1.5 cm, Table 1), our dataset shows
360 that SRIT returns a L_c independent from the stylolite length and from the amount of vertical
361 displacement it accommodated. Also no correlation can be found between 2D profile length and the
362 validation of the consistency criterion.

363 SRIT results vary depending on the stylolite morphology (classes 2, 3 and 4, Fig. 8a): stylolites from
364 class 2 are systematically underestimating the maximum burial depth, with median values ranging
365 between 1000 and 1150 m, and up to 65% of the population satisfying the consistency criterion.

366 Stylolites from class 3 return a depth in line with the estimated maximum burial depth (1350 m – 1600
367 m) and up to 80% of the population is consistent with the depths derived from burial-thermal model
368 (Fig. 2). Stylolites from class 4 show the most scattered distribution, with no systematic behaviour
369 regarding the depth, suggesting they are not the best suited to obtain a reliable depth estimate,
370 despite 75% of them satisfying the consistency criterion. Stylolites belonging to class 3 seem to be the
371 best suited to calculate the maximum burial depth, while class 2 stylolites are better indicators of
372 intermediate depths. We suggest avoiding the simple wave-like stylolites (class 4), which will not
373 return a reliable depth, probably because of the lack of teeth, most of the signal then relying in a small-
374 scale roughness which is difficult to digitize and so to analyse.

375 b. Impact of the host rock depositional texture on SRIT reliability

376 The texture of the host also seems to affect the inversion results (Fig. 8b), with consistent results for
377 the 4 textures documented. Texture 1 (mudstone to wackstone) returns the most scattered depth
378 distribution, with 75% consistency, and a clear difference in the median value for FPS (1100m) or for
379 AWC (1700m). Texture 2 (wackstone to floatstone) hosts stylolites that return a narrow depth
380 distribution (1400 to 1650m) in the range of the depths expected from the burial-thermal model
381 considering both cores, and 100% consistency. Textures 3 (floatstone to packstone) and 4 (packstone
382 to grainstone) host stylolites of which quartile distribution is narrow (1000 to 1400 m), with median
383 values slightly underestimating the maximum burial depth modelled with a consistency of 90% for
384 texture 3 and of 50% for texture 4. From this statistical representation, it returns that wackstone,
385 floatstone and packstone are the better suited host rock textures to assess the maximum burial depth,
386 grainstone hosting more than half of the inconsistent stylolites, and mudstone being the less suited
387 texture to assess a burial depth, should it be maximum or intermediate.

388 c. Limitations of SRIT and application beyond the case of sedimentary basins

389 The application of SRIT requires a good estimate of mechanical parameters (young modulus and
390 poisson ratio) and of the solid-fluid interfacial energy. If the latter is strictly related to the host lithology
391 and does not vary much with the conditions of deformation (compaction, temperature, pressure),
392 mechanical parameters are likely to evolve as the host undergoes shortening or compaction, as
393 emphasized in Rolland et al. (2012). The Young's modulus E is the most critical parameter to assess,
394 and determining it at the time of the deformation is not trivial. One solution was proposed by Ebner
395 et al. (2009b), that uses the SRIT results carried on several BPS hosted in the same rock to assess the
396 value of E prevailing at the time stylolites formed. The method inverts equation (2), using the
397 difference in vertical stress from BPS separated by a measured distance to access E . In cases where
398 the studied succession is not long enough to apply this approach (i.e. <10 m), a minimum requirement

399 to carry out SRIT is to know the value of E from mechanical tests (e.g. this paper). It is important to be
400 aware of these limitations when assessing vertical stress in deep conditions of deformation, or in
401 different lithologies. In addition, the SRIT presented in this paper is tied to the assumption that the
402 stress in the plane of the stylolite is isotropic. It is very likely that the horizontal stress remained
403 isotropic in settings with very limited shortening or extension like the subsidence phase of the Paris
404 Basin, however in other settings where SRIT was successfully applied such as foreland basins this
405 isotropy may not be valid (Beaudoin et al., 2016; Bertotti et al., 2017; Beaudoin and Lacombe, 2018).
406 In such settings, it appears important to check that the horizontal stress remained isotropic for a given
407 BPS, (1) by ensuring the teeth are perpendicular to the dissolution plane (so that the surface contains
408 no shear component) and (2) testing a sample with SRIT applied to a stylolite in three cuts at 60
409 degrees to each other that should return identical values for L_c , as anisotropy in stress creates an
410 anisotropy of the L_c values (Ebner et al., 2010b). Otherwise, alternative approaches exist for
411 anisotropic stresses along the stylolite plane, which typically occurs for tectonic stylolites (Ebner et al.,
412 2010b; Beaudoin et al., 2016).

413 Formational fluids involved in the pressure-solution process have a strong impact on stylolite
414 development (Toussaint et al., 2018, and reference therein). In order to test the impact of fluids onto
415 SRIT, we consider the paleo-fluids circulating within the Middle Jurassic reservoirs of the Paris basin,
416 assessed on several cores from the basin depocenter and margin (including Rigny core, Mangenot et
417 al., 2017, 2018; Dassié et al., 2018). The studied interval in the Rigny core consists in a highly saline-
418 dominated fluid system during the whole burial time (Cretaceous), yet various vertical stresses were
419 reconstructed by applying SRIT on this interval. Consequently, it suggests that the pore fluid chemistry
420 is not affecting the SRIT results. Also, the study of both Parly and Rigny cores illustrates that the
421 occurrence of oil migration at maximum burial, observed in Rigny but absent from Parly, does not
422 impact the SRIT result in spite of being able to affect stylolite development. This highlights that the
423 external parameters such as fluid chemistry or environment temperature affect stylolite development
424 (reviewed in Toussaint et al., 2018) but are not involved in SRIT equations and do not affect the SRIT
425 results.

426 d. Lessons learnt on sedimentary stylolite development

427 The study from the Middle Jurassic carbonates of the Paris basin highlights that 80% of the stylolite
428 population is consistent with the growth model, hence that they are suitable for SRIT. 20% of the
429 population of stylolites fails to return consistent Hurst coefficients with both methods. This failure
430 takes two shapes: (1) a single growth regime, always related to the surface energy scale, in which case
431 it is safe to assume that the 2D portion is too small to encompass where the L_c sits, emphasizing that

432 the 2D stylolite used for SRIT must be longer than the L_c by at least two orders of magnitude, or (2) 2
433 growth regimes, but the Hurst exponent being different from what the model predicts. In that case,
434 the roughness may have been altered during chemical compaction either by excessive pinning, an
435 effect that is especially visible in morphology classes 1 and 2 (Koehn et al., 2007; Ebner et al., 2009a),
436 or by a transient stop in the dissolution history, altering the roughness and Hurst exponent of the
437 large-scale elastic energy (Larone Ben-Itzhak et al., 2014).

438 Half of the stylolites that show consistency with the growth model stopped developing at an
439 intermediate depth, returning an intermediate vertical stress value. The results of SRIT suggest two
440 possible scenarios to account for the development of stylolites that do not finish their growth at the
441 same depth: (1) all stylolites start dissolution at the same time, some stopping before others. (2)
442 stylolites start dissolution in sequence, class 2 forming and stopping, then class 3 forming and
443 stopping. The depth distribution shown in Figure 8a seems to support the latter case. However, such
444 a scenario requires that there is enough space in between dissolving stylolites to localize new ones.
445 As the dissolution increases during burial, the spacing between stylolites tends to decrease, because
446 of the physical effect of dissolution on the one hand, and because of the effect of increasing vertical
447 stress coupled to an increase in local fluid pressure (Kelka et al., 2017) due to a decrease in local
448 permeability around the stylolite (Koehn et al., 2016). Thus, it is physically unlikely that sedimentary
449 stylolites developed in sequence (class 2 then 3) and it is more sound to consider that all dissolution
450 planes start at the same time, with some stylolites stopping before others.

451 Our study shows that the seismogram pinning type morphology (class 2) statistically yields a fossil
452 stress signal that corresponds to an intermediate burial depth (Fig 9). Alternatively, the suture and
453 sharp peak type morphology (class 3), where pinning is distributed along the plane, tends to record
454 the maximum burial depth-related stress, suggesting that growth and so dissolution were active until
455 the maximum burial depth was reached (Fig. 9). This suggests that the strong localized pinning can kill
456 the roughness ability to record deep stress. The role of pinning may govern the impact of host texture
457 on SRIT results, i.e. that coarser grained texture returns intermediate values of vertical stress (Fig. 8).
458 Indeed, if we do not expect that heterogeneous grain size distribution in a sample would affect SRIT,
459 the range of grain sizes in a homogeneous sample will control the distribution of the pinning particles
460 (e.g. oxydes). In a rock with coarser grains like a grainstone, pinning particles will be further apart from
461 each other, and so the pinning will be localized in those points, leading to a shorter lifespan of the
462 stylolite. This idea corroborates the observations of Andrews and Railsback (1997), that reported that
463 more serrate stylolites (class 1 and 2 here) seem to predate less serrate stylolites (class 3). Authors
464 related this to the development of stylolites in sequence, affected by the evolution of the rock
465 lithology with burial, where destruction of porosity and decrease in amount of heterogeneities tends

466 to decrease the pinning effect. We propose that this observation rather reflects that most BPS initiated
467 at the same time, with the more serrate stylolites stopping their development earlier than the less
468 serrate stylolites because of the localized pinning, itself controlled by the distribution of pinning
469 particles in the rock (Koehn et al., 2012). Our study also reports that the minimum burial depth
470 recorded by a BPS at the time it stopped developing is 800 m, which suggests that dissolution started
471 at lower depth. That supports the studies reporting sedimentary stylolites developing at very shallow
472 depth (150m, e.g. Rolland et al., 2012), and contradicts the previous attempts to infer a minimum
473 burial depth needed for stylolite formation (from 800 m to 1000 m, Finkel and Wilkinson, 1990;
474 Railsback, 1993; Dunnington, 1967; Nicolaides and Wallace, 1997). Our study results suggest that a
475 combination of SRIT applied on classes 2 and 3 stylolites in carbonate rocks, considering each
476 stratigraphic unit as hosting a population, can be used to reconstruct a major part of the basin
477 subsidence history.

478

479 6. Conclusions

480 Using two cores from Middle Jurassic carbonate reservoirs of the Paris basin (France), of which the
481 burial-thermal history is well constrained, this contribution presents a first statistical appraisal of the
482 Stylolite Roughness Inversion Technique (SRIT) applied to sedimentary, bedding-parallel stylolites
483 (BPS) aiming to access maximum paleo-depth experienced by their host rocks. By direct comparison
484 between inversion results and modelled maximum burial depths, we define a mathematical
485 consistency criterion, fulfilled if stylolite roughness analysed with either the Fourier Power Spectrum
486 (FPS) or the Average Wavelet Coefficient (AWC) methods returns 2 growth regimes with Hurst
487 coefficient of 1 ± 0.1 for the surface energy (typically encountered at a scale below 1 mm) and 0.5 ± 0.1
488 for the elastic energy (above 1 mm). Then, the median values of the depth considering the stylolites
489 consistent with the growth model approach the maximum burial depths giving $1300\text{m} \pm 130\text{ m}$ for the
490 southern margin core and $1650\text{m} \pm 160\text{m}$ for the depocenter core. These values are close to (within
491 10%) those independently deduced from a thermally calibrated basin model, yielding maximum paleo-
492 depths for the studied carbonates of 1450 and 1800 m, respectively.

493 From a distribution analysis, we assess the impact of stylolite morphology and host rock depositional
494 texture on the reliability of SRIT, and we propose that suture and sharp peak stylolite types are the
495 best suited to access the maximum paleo-depth, while the seismogram pinning type provides
496 intermediate depth values. This survey encourages future basin studies to use SRIT since a moderate
497 number of stylolites (<5) is needed to consistently return the maximum burial depth, or an
498 intermediate burial depth, provided that a selection of the stylolites based on their morphology is

499 properly made and that the Hurst coefficient consistency is respected. In cases where such selection
500 proves to be hard, we suggest that future studies should avoid using the simple wave-like stylolites
501 and the mudstone host rock textures, since both show the largest variability on SRIT results. We also
502 suggest to work on a population of a minimum of 15 stylolites to obtain a reliable estimate of the
503 maximum depth.

504 Beyond presenting a workflow to assess the maximum burial depth from BPS population, our study
505 points out that nearly 100% of the sedimentary, bedding-parallel stylolites developed in accordance
506 to the stress-driven growth theory that links the stylolite roughening to the applied stress. 80% of the
507 studied population retain this relationship intact. We propose that BPS development starts from the
508 same depth (≤ 800 m), with localized strong pinning tending to stop the dissolution at intermediate
509 depths during burial. Thus only the stylolites where pinning is distributed along the plane can yield the
510 maximum vertical stress magnitude.

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516

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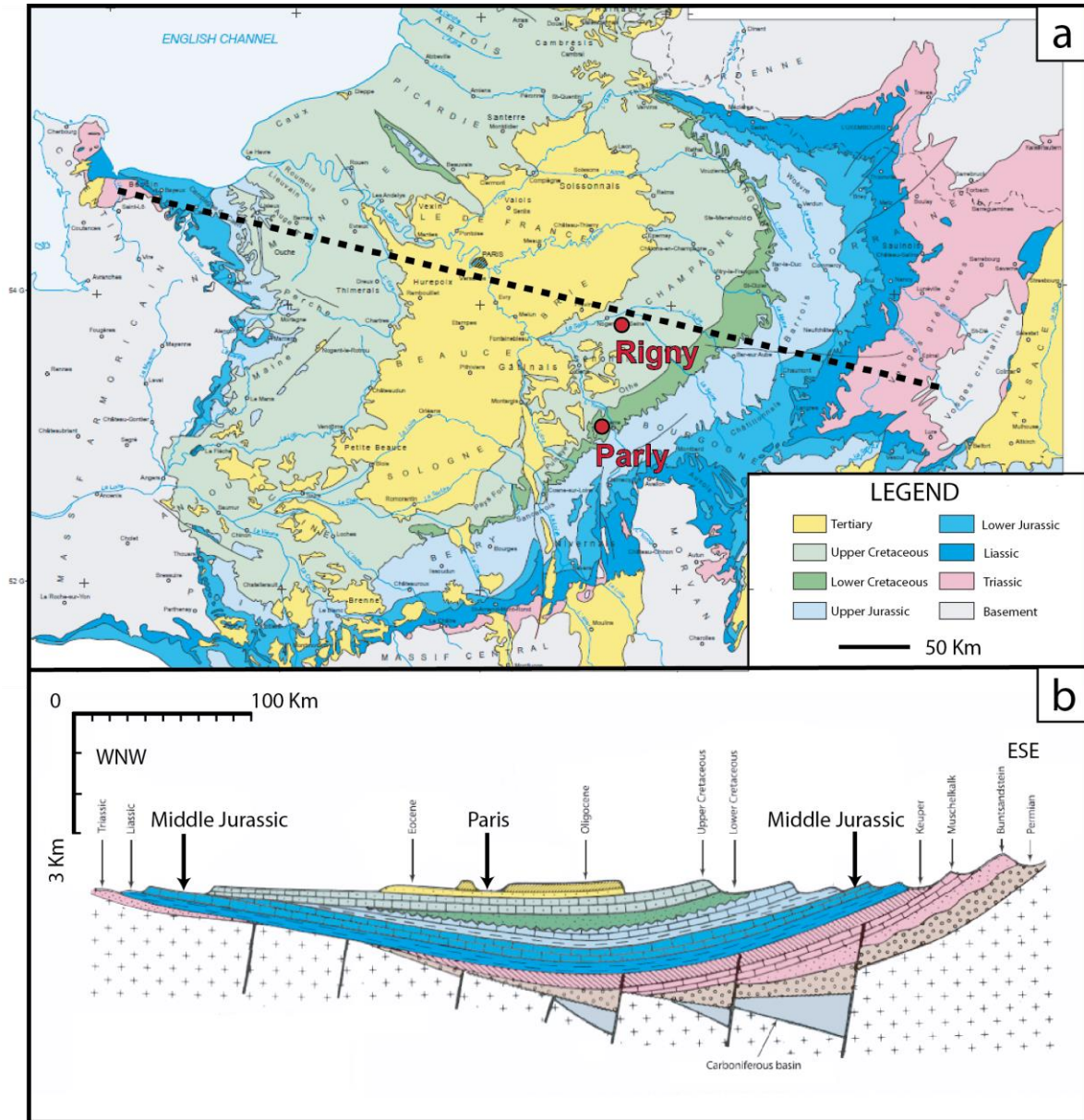
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- 770

771 Table 1 – Results of the Stylolite Roughness Inversion Technique (SRIT).

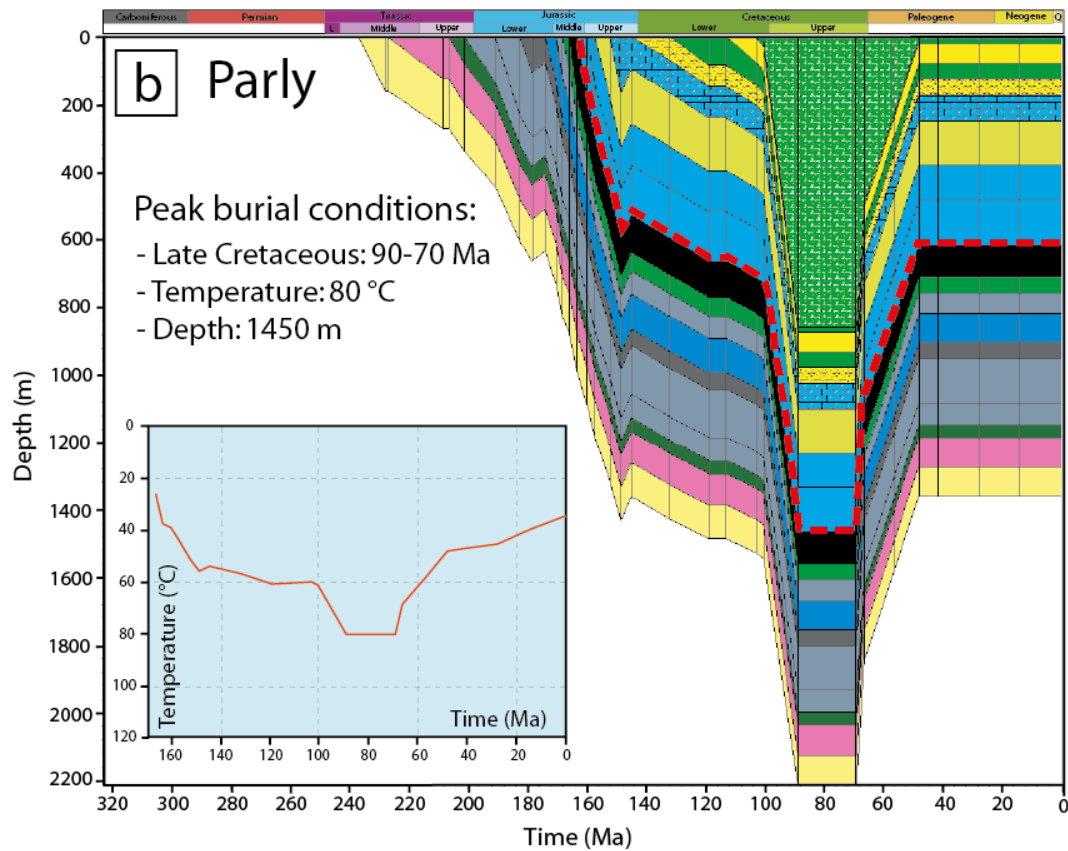
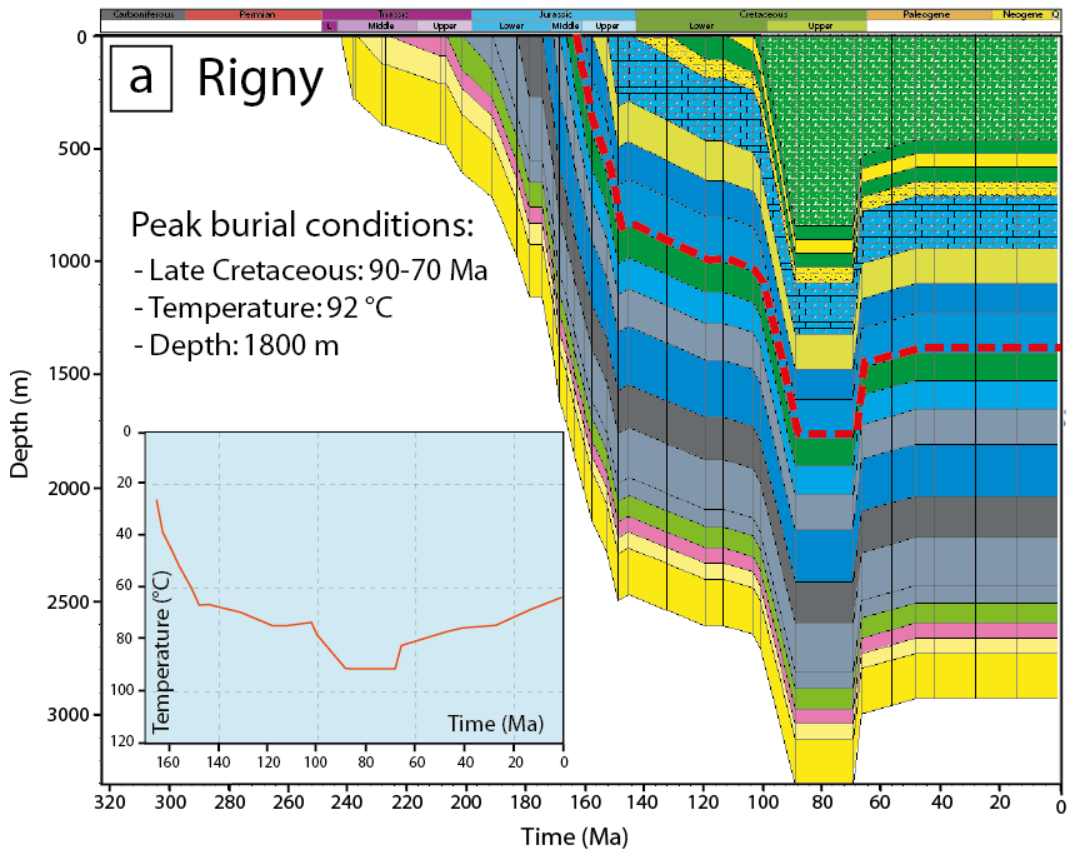
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773 Figures captions



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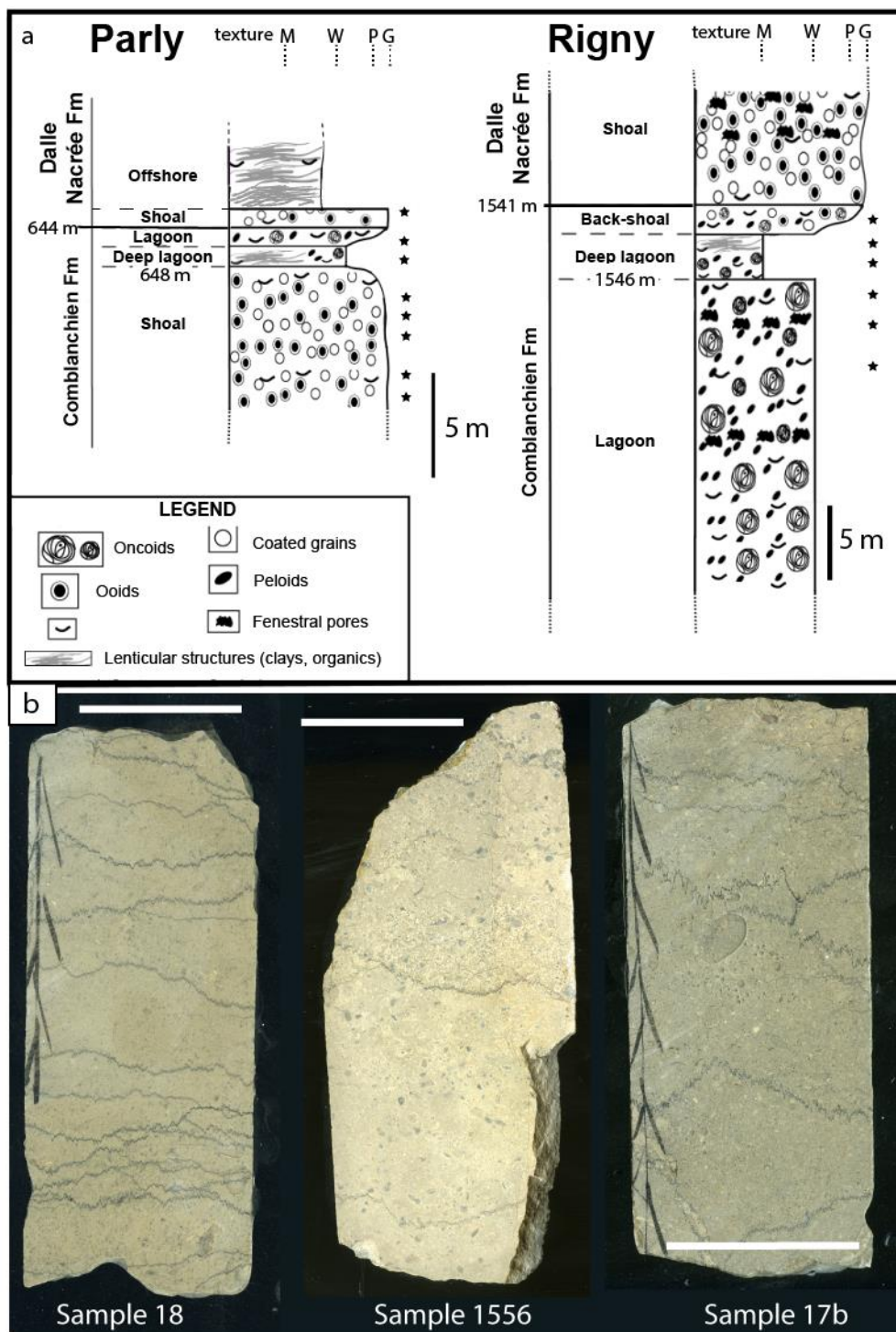
775 Figure 1 – a) Geological map of the Paris basin with the location of the studied cores (Rigny and Parly,
776 from depocenter and southern margin, respectively), and the WNW-ESE cross-section displayed below
777 in b). Modified after Perrodon and Zabeck (1991) and Delmas et al. (2002).



778

779 Figure 2 – 1D burial curves extracted from the Paris basin 3D basin model for the two studied wells,
 780 which describe the evolution of depth with time for the different stratigraphic intervals. The red

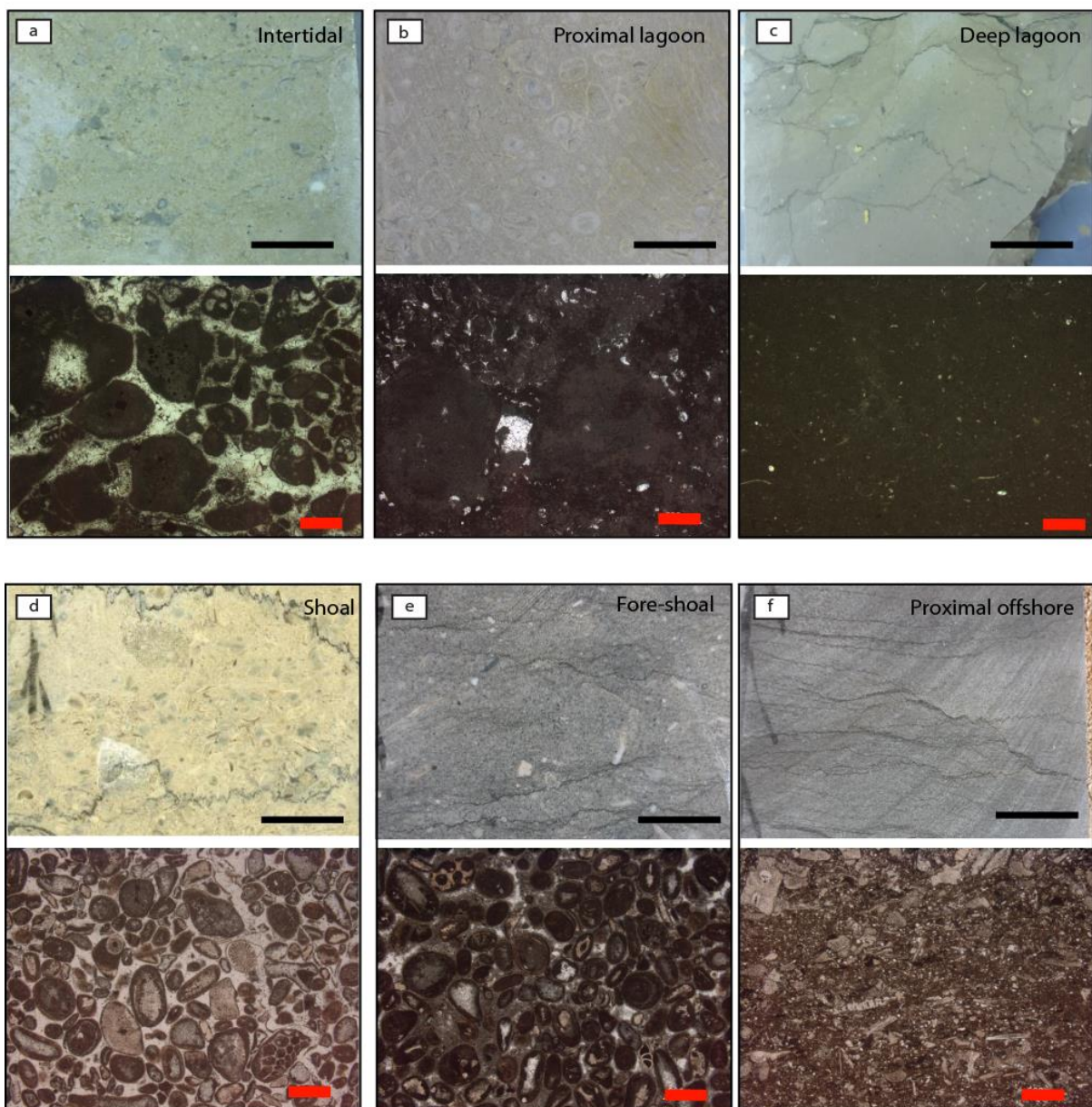
781 dotted lines indicate the location of the studied Middle Jurassic (Upper Bathonian – Lower Callovian)
 782 interval. The temperature evolution with time of these rocks is reported in the graphs. a) Rigny
 783 (depocentre) ; b) Parly (southern margin).



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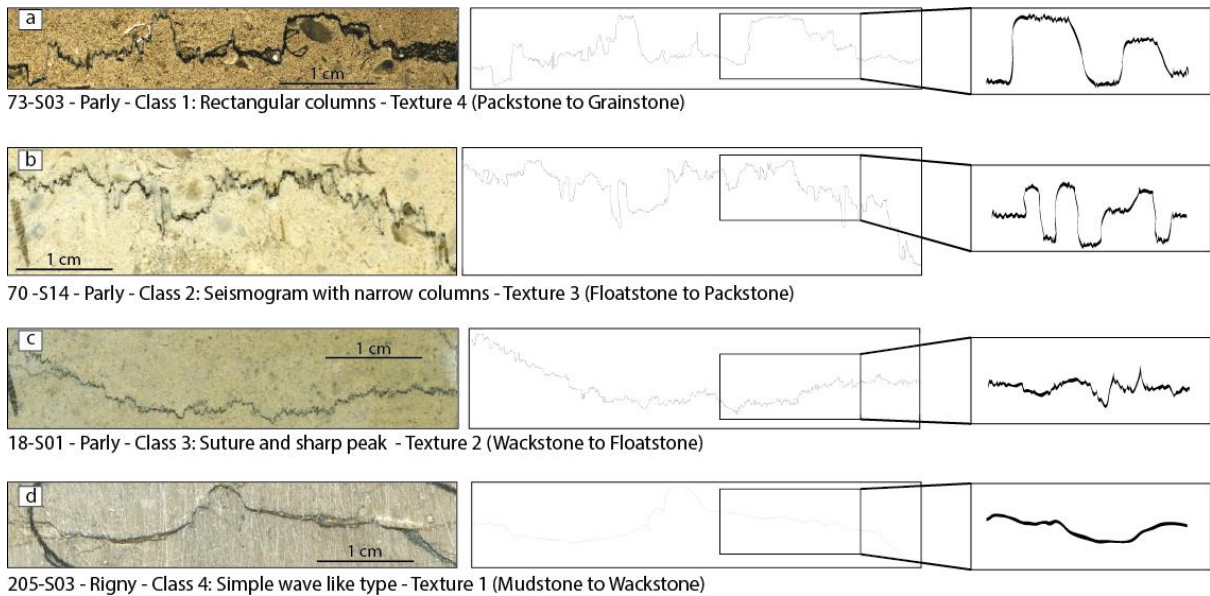
785 Figure 3 - a) Simplified stratigraphic columns for the Rigny and Parly core sections investigated, with
 786 the depositional environments reconstructed by macro- and micro-facies analysis. Horizontal

787 thickness of the column indicates the carbonate dominant texture of the different depositional
 788 environments also illustrated in Figure 4. The texture code is as follow: M: Mudstone, W:Wackstone;
 789 P: Packstone; G: Grainstone. Asterisks locate the samples used in this study. b) examples of core
 790 samples investigated, exhibiting various density and morphology of stylolites. White scale bars
 791 represent 5 cm.



792
 793 Fig. 4 - Example of macro-facies (top, scanned hand-sample) and micro-facies (bottom, optical
 794 microphotograph) and corresponding depositional environments. a) Grainstone with oncoids in a

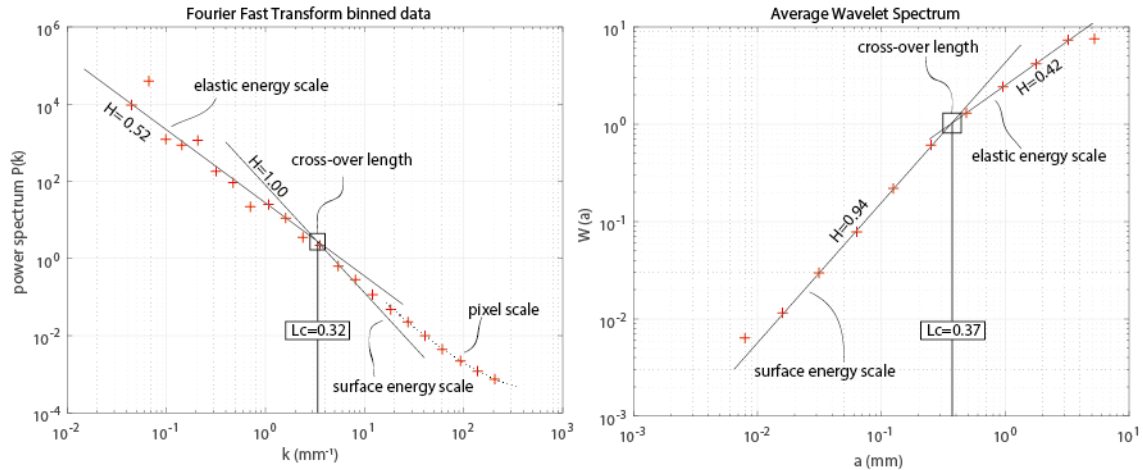
795 groundmass of fine intraclasts and fenestral pores cemented by calcite (intertidal). b) Floatstone with
 796 large oncoids (proximal lagoon). c) Highly bioturbated mudstone (deep lagoon). d) Grainstone with
 797 coated grains, bioclasts and ooids (shoal). e) Packstone with ooids and large crinoid fragments (fore-
 798 shoal). f) Fine packstone to wackstone alternated with marly layers containing crinoid and brachiopod
 799 fragments (proximal off-shore). Red and black scale bars are 2 cm.



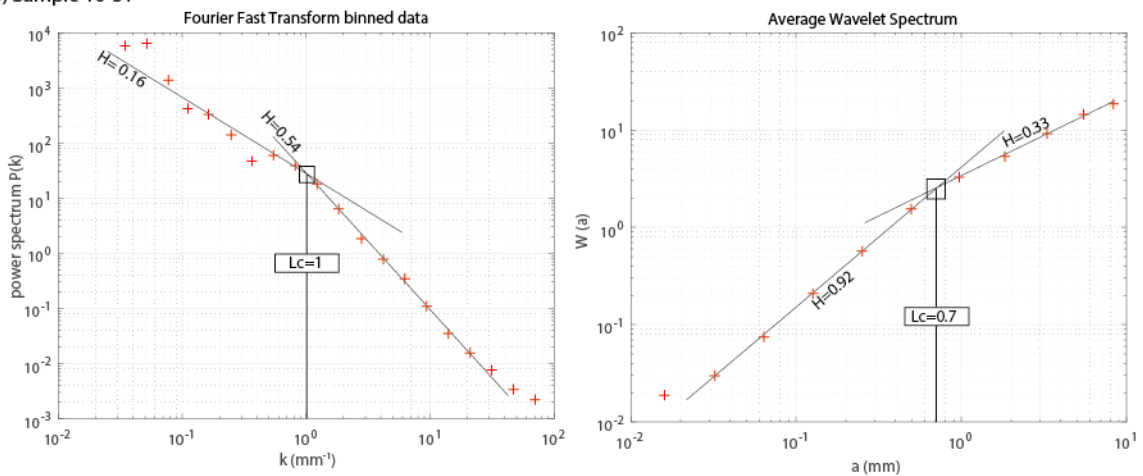
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801 Figure 5 – a-d) Examples of stylolite classes based on morphology as proposed by Koehn et al. (2016),
 802 with high resolution scan (left-hand side), stylolite track drawn for SRIT (middle) and sketch showing
 803 general morphology class characteristics (right-hand side).

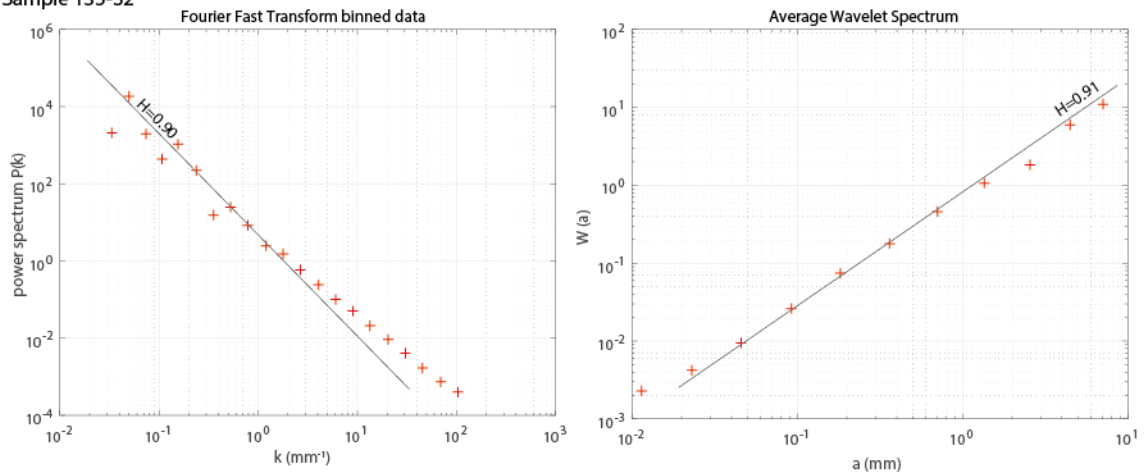
a) Sample 146-S2



b) Sample 10-S1

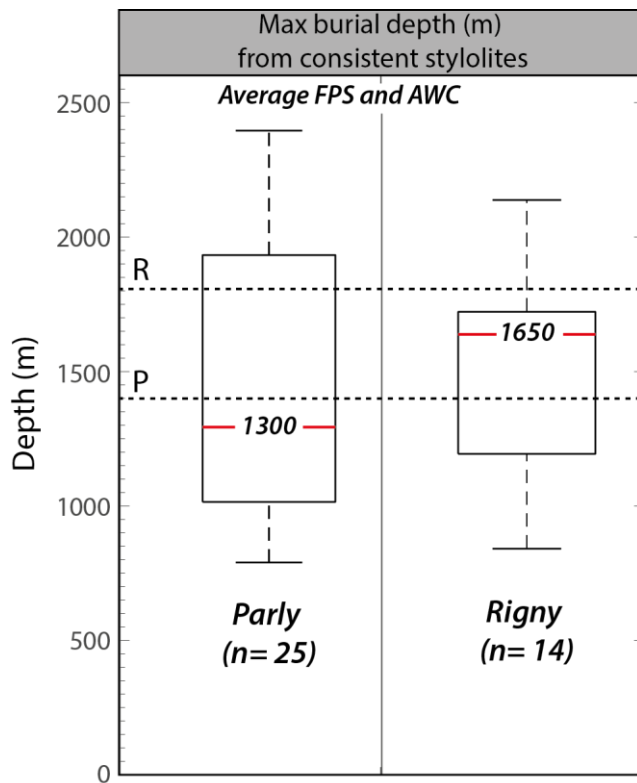


c) Sample 135-S2



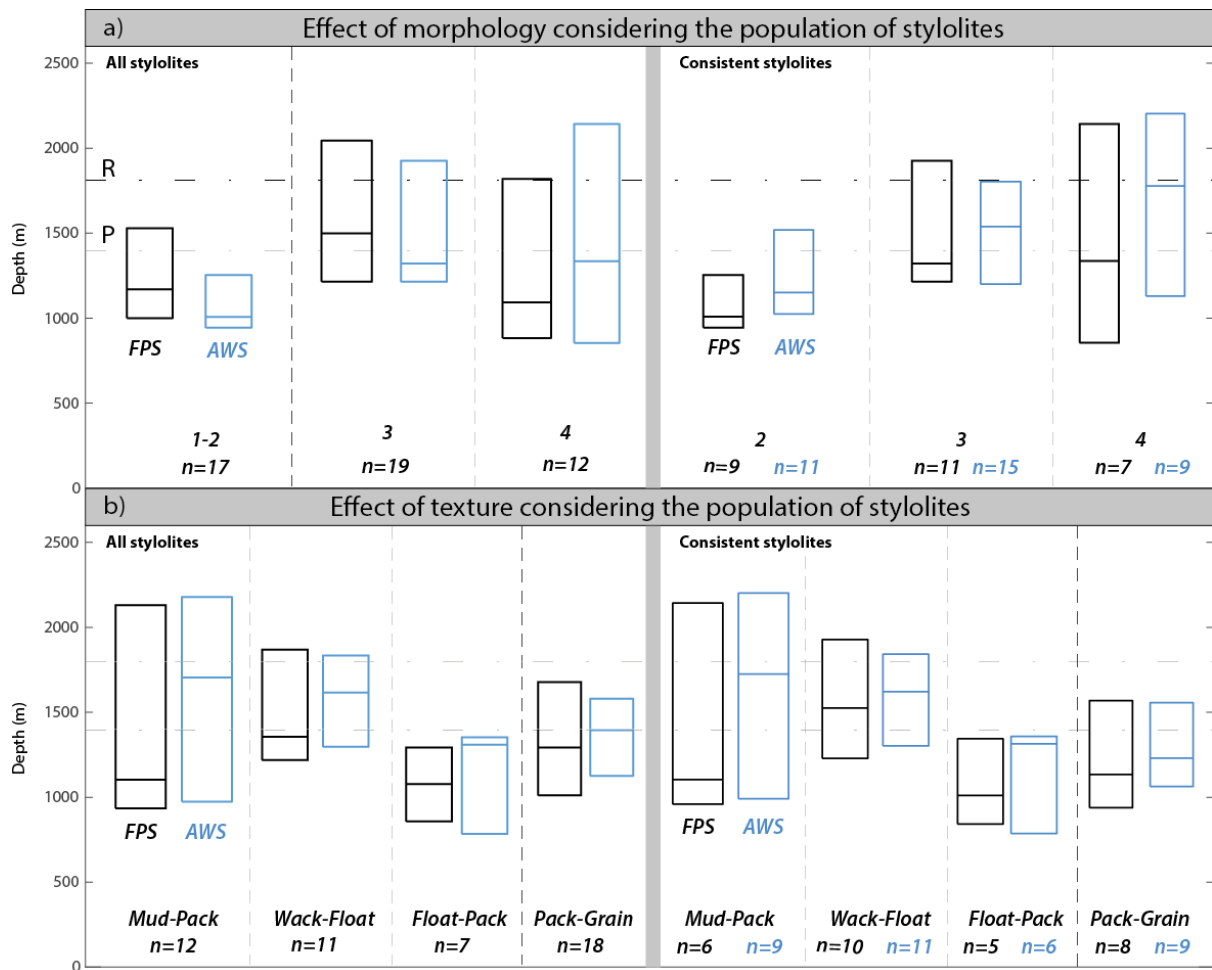
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805 Figure 6 – Fourier Power Spectrum (left-hand side) and Average Wavelet Coefficient (right-hand side)
 806 log-log plot obtained from 3 different BPS tracks. Data are represented as red crosses. Straight lines
 807 representing growth regimes are reported in black with corresponding Hurst coefficient values (H)
 808 calculated, and cross-over values (Lc) obtained from intersection (if any) between both lines are
 809 reported in mm in the black frame.



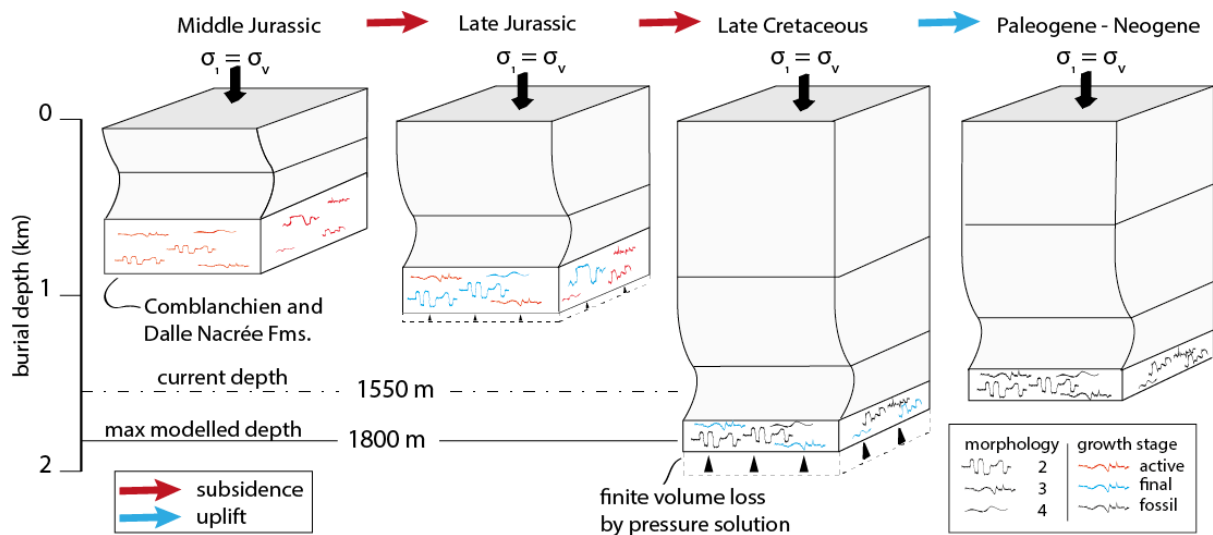
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811 Figure 7 – Box-and-whisker plots of the burial depth derived from magnitude of vertical stress
 812 obtained from SRIT for each core, considering only the BPS that are consistent (see text for details).
 813 Distribution is reported as horizontal lines from bottom to top: the minimum value in the population,
 814 the first quartile, the median value (red line), the third quartile, and the maximum value of the
 815 population. Values of the medians (red line) are reported on the plot. Dotted lines represent the
 816 maximum burial depths predicted independently from basin modeling for the two cores (P: Parly, R:
 817 Rigny).



818

819 Figure 8 – Box-and-whisker plots reporting the magnitude of the vertical stress obtained from SRIT
 820 applied to the population of BPS considering both cores as one, reporting as horizontal lines from
 821 bottom to top: the first quartile, the median value, and the third quartile. Black box plots (left-hand
 822 side of each plot) result from Fourier Power Spectrum (FPS) analysis, whereas blue box plots (right-
 823 hand side of each plot) result from Average Wavelet Coefficient (AWS) method. Dotted lines represent
 824 the maximum burial depth predicted independently from basin modelling for the two cores (P: Parly,
 825 R: Rigny). a) Population divided regarding the stylolite morphology (2: Seismogram, 3: Suture and
 826 sharp peak, 4: Simple wave), considering the whole population (left-hand side) and only the consistent
 827 data (right-hand side). b) Population divided regarding the carbonate texture (1: Mudstone to
 828 wackstone, 2: Wackstone to floatstone, 3: Floatstone to Packstone, 4: Packstone to grainstone),
 829 considering the whole population (left-hand side) and only the stylolite giving consistent Hurst
 830 exponent (right-hand side).



832 Figure 9 – Schematic representation of the bedding-parallel stylolite (BPS) growth at different steps of
 833 the host rock burial history, based on the findings from the Paris basin depocentre (Rigny core).
 834 Stylolites of different morphology classes are represented only in the studied Middle Jurassic interval
 835 (white stratum). Sediments successively piled up are represented by the grey strata. Stylolites of
 836 classes 2, 3 and 4 are pictured in colours depending if the growth is active (red), final (blue), or fossil
 837 (black). Current burial depth and maximum burial depth are derived respectively from the well drilling
 838 report and the burial-thermal modelling for the Rigny core. Final stage of BPS growth (in blue) is
 839 represented in accordance with the results of the roughness inversion reported on Figure 8.

840