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Geomorphic variability of submarine channelized systems along continental margins: comparison with fluvial meandering channels

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Highlights

- New geomorphic classification applied worldwide to modern submarine channelized systems
- Flow conduit geometry changes according to their location along continental margins
- Submarine unit leveed channels are the most analogous to alluvial meandering rivers
- Submarine leveed channel width and area correlate with slope similarly to rivers
- Increasing aspect ratio down-slope is likely related to flow deconfinement

23 **Abstract**

24 Understanding submarine sediment conduits is a challenging yet rewarding task given its applications in
25 offshore industries and source-to-sink studies. Despite flow structure dissimilarities, sinuous submarine
26 sediment conduits display morphologies similar to alluvial meandering rivers. An extensive quantification of
27 degrees of (dis)similarity is however lacking. This study combines (i) a new geomorphic classification of
28 submarine sediment conduits relying on cross-sectional data only, complemented by (ii) measurements of
29 planform (sinuosity, wavelength, amplitude) and cross-sectional (bankfull width, depth, section area)
30 parameters to compare alluvial meandering and submarine systems. We apply the methods to a worldwide
31 dataset including 254 measurements from 35 modern systems. We identify four types of submarine
32 sediment conduits including composite (i.e., canyon and valley) and unit (i.e., incised or leveed channel)
33 types. The following findings arise. (i) Submarine sediment conduit geomorphology is strongly controlled by
34 slope, mostly depending on location along the continental margin. Composite and erosive submarine
35 sediment conduits are located on the continental slope and unit and constructive channels extend down to
36 the basin floor. (ii) Submarine unit leveed channels form a consistent group of constructive, higher-order,
37 smaller-size and more laterally mobile submarine sediment conduits. (iii) Submarine unit leveed channels
38 are the most analogous to alluvial meandering rivers. (iv) Without discharge contribution from tributaries,
39 the width and the area of long-running submarine sediment conduits increase as they migrate towards the
40 abyssal plains. Such behavior is similar to rivers, although it is better explained for submarine sediment
41 conduits by progressive flow deconfinement, and decreasing bank cohesion and friction angle.

42

43 **Keywords**

44 Submarine systems; Channel morphometrics; Geomorphology; Turbidity flow; Meandering process

45

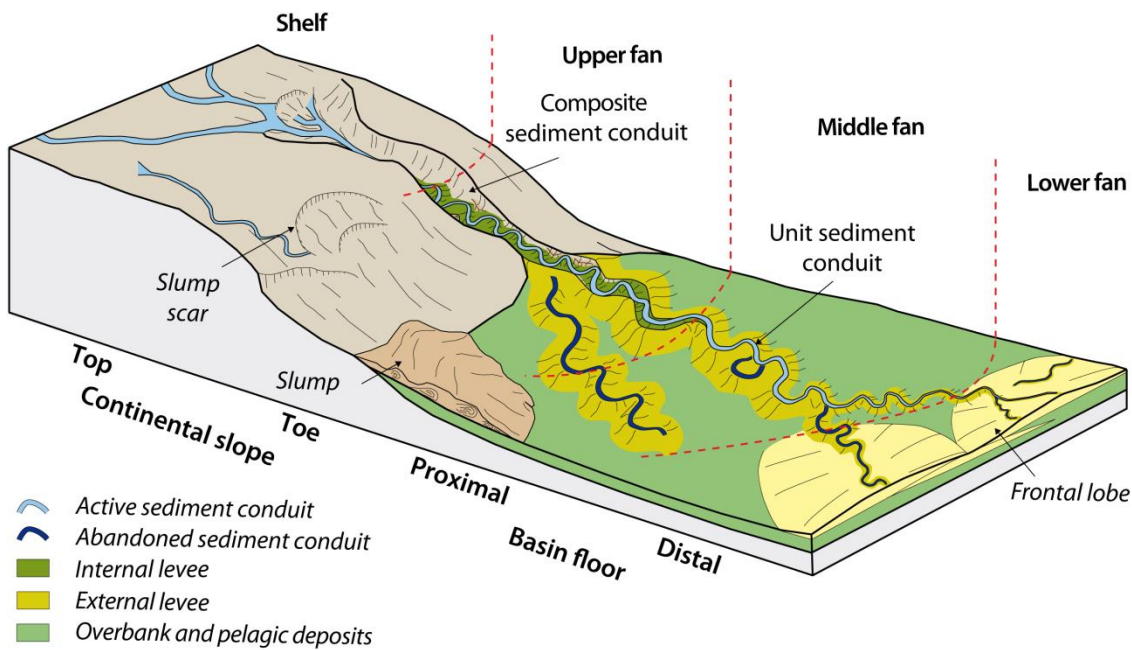
46

47 **1. Introduction**

48 Submarine channelized systems are the final links of the source-to-sink sediment transfer chain
49 (Allen, 2017), which extend over the entire submarine environment from the shelf to the abyssal plain
50 (Figure 1 – Deptuck et al., 2007; Wynn et al., 2007). The interest in these channelized systems is constantly
51 growing because they transfer sediment, organic carbon, nutrients and contaminants to the deep sea (Galy
52 et al., 2007; Hugues et al., 2015; Kane and Clare, 2019), create large hydrocarbon reservoirs (Weimer and
53 Slatt, 2004), and may impact offshore facilities such as hydrocarbon production platforms, pipelines,
54 telecommunication cables, wind power plants, or –in the near future– deep water mining apparatuses
55 (Baker et al., 2016). One aim is therefore to understand the dynamics of these systems to improve their
56 modeling.

57 Despite recent progress on in-situ flow measurements (Paull et al., 2018), our understanding of the
58 long-term (10^2 - 10^4 yr) evolution of submarine sediment conduits and associated deposits is still incomplete
59 (Mulder and Alexander, 2001; de Leeuw et al., 2018; Ono and Plink-Björklund, 2018). Due to the difficulty of
60 monitoring submarine sediment conduit evolution, a common approach is to formulate theories based on
61 those describing fluvial channel morphodynamic processes. Physical processes at play at the scale of the
62 full turbidity current profile are incontestably different from that of rivers (Wynn et al., 2007 and
63 references therein), for example owing to the role of sediments as flow driver (Parker et al. 1986; Konsoer
64 et al., 2013; Traer et al., 2018), flow stratification (Dorrell et al., 2014; Luchi et al., 2018), friction at flow
65 upper interface (Konsoer et al., 2013), water entrainment (Ellison and Turner, 1959; Pirmez and Imran,
66 2003; Traer et al., 2018), flow overspill and stripping (Peakall et al., 2000; Traer et al., 2018), or variations in
67 secondary currents (Azpiroz-Zabala et al., 2017; Dorrell et al., 2018). However, similarities of planform
68 morphology and other geomorphic features (Peakall et al., 2000; Wynn et al. 2007 and references therein;
69 Konsoer et al., 2013) suggest that concepts that apply to rivers, such as styles of channel migration and
70 channel-forming flows, apply to submarine channels too. Indeed, both fluvial and submarine sediment
71 conduits display braid bars (Hesse et al., 2001; O’Cofaigh et al., 2006; Foreman et al., 2015), lateral

72 accretion packages (Abreu et al., 2003), bend cutoffs, levees or crevasse splays (Figure 1 – Posamentier,
 73 2003; Wynn et al., 2007). Applying fluvial theories to submarine systems allows to better understand the
 74 processes at play in the latter –e.g., the larger size of submarine sediment conduits compared to river
 75 channels due to the lower density contrast between the current and the ambient fluid (Konsoer et al.,
 76 2013; Limaye et al., 2018; Shumaker et al., 2018), the braiding-sinuuous threshold (Foreman et al., 2015) or
 77 the channel mobility number (Jobe et al., 2016).



78

79 *Figure 1: Channelized submarine systems with the submarine environment subdivision used in this study.*

80 In fluvial systems, seminal studies showed that channel planform morphology (sinuosity,
 81 wavelength, amplitude) and cross-sectional geometry (bankfull width, depth, area) parameters (Jefferson,
 82 1902; Friedkin, 1945; Leopold and Wolman, 1960; Williams, 1986; Bridge and Mackey, 1993) are correlated
 83 to each other and to channel slope and river dynamics (e.g., flow or sediment discharge) according to
 84 power laws (Table 2; Leopold and Maddock 1953; Leopold and Wolman, 1957; Williams, 1986; Held, 2011).
 85 The derived equations are valuable in many practical applications such as hydraulic engineering and
 86 restoration projects (e.g., Kondolf, 2016 and references therein), paleo-hydrologic studies (Williams, 1978,
 87 1986; Bridge, 2003 and references therein; Held, 2011), or reservoir modeling (Bridge and Mackey, 1993;
 88 Heller and Paola, 1996; Tye, 2004; Lopez et al., 2008; Pyrcz et al., 2015; Parquer et al., 2017). Establishing

89 similar relationships for submarine channelized systems would be equally promising and could generate
90 insight into the (dis-)similarities with fluvial channels in terms of processes. Accurately comparing rivers and
91 submarine sediment conduits is however still a challenge for three reasons: (i) existing datasets of
92 submarine sediment conduits are based on a limited number of systems compared to riverine datasets, (ii)
93 the measurement methodology used for submarine sediment conduits slightly varies from the one used for
94 rivers (Pirmez and Imran, 2003; Clark and Pickering, 1996; Konsoer et al., 2013) and finally (iii) current
95 submarine nomenclatures do not take into account the downstream evolution of the formative processes
96 and the shape of submarine sediment conduits (Figure 1 – Babonneau et al., 2002). The accuracy of the
97 comparisons between submarine sediment conduits and rivers is therefore affected by these issues (Clark
98 and Pickering, 1996; Pirmez and Imran, 2003; Wynn et al., 2007; Konsoer et al., 2013).

99 In this study, we introduce a new geomorphic classification of modern submarine sediment
100 conduits. We then make a comparison between the different submarine sediment conduits types and
101 alluvial sinuous channels based on geometric parameters. This methodology is applied to a worldwide
102 dataset of the morphology of submarine sediment conduits based on published data, which is the most
103 extensive to our knowledge. We show that the location along the continental margin has a first-order
104 control on the flow conduit morphometry. Based on the geometric parameters, we find that submarine
105 leveed channels are very similar to alluvial meandering rivers in terms of parameter scaling, which allows us
106 to infer submarine flow processes.

107 **2. Material and methods**

108 **2.1. Submarine sediment conduit geomorphic classification**

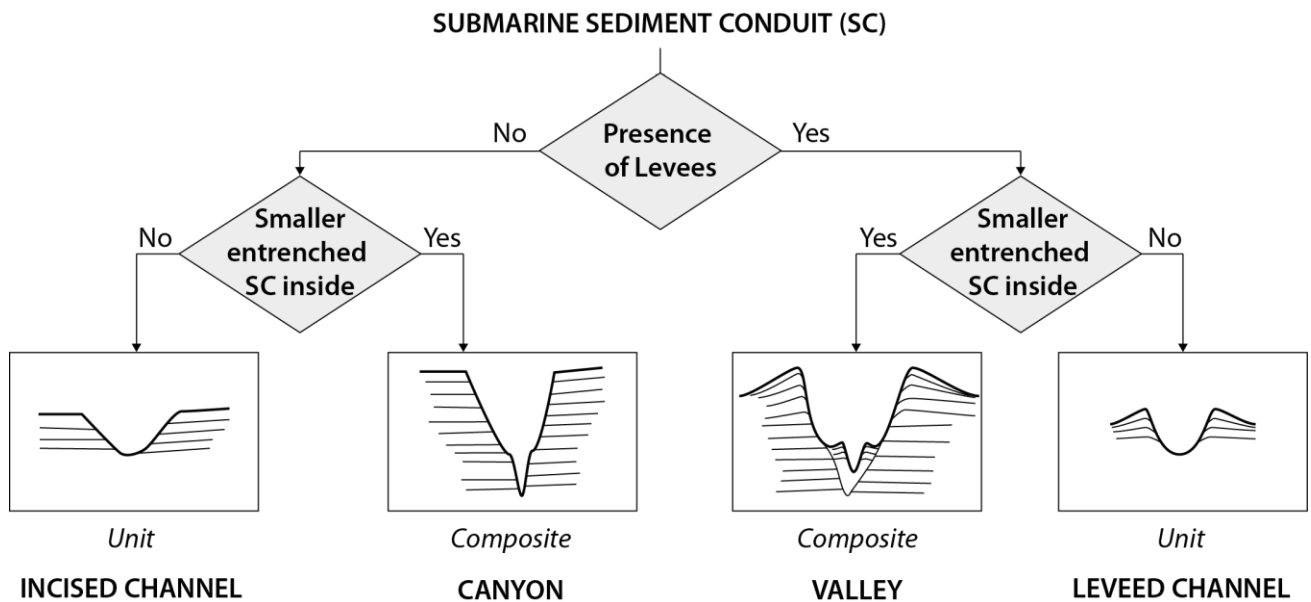
109 Existing submarine sediment conduit nomenclatures vary according to the field of study –i.e.
110 geomorphology, stratigraphy, process sedimentology– and authors (Clark and Pickering, 1996; Wynn et al.,
111 2007). This makes the dialogue between communities sometimes difficult. For example, the term

112 “sediment conduit” is employed as a generic term (e.g., Graham and Bachman, 1983; Carter and Carter,
113 1987; Clark and Pickering, 1996; Deptuck et al., 2007; Wiles et al., 2017; Harishidayat et al., 2018; Traer et
114 al., 2018), but many authors interchangeably used “canyon” (Heezen et al., 1959; Huvenne et al., 2014),
115 “valley” (e.g., Shepard, 1965; Normark et al., 1993; Curray et al., 2003), or “channel” (Normark et al., 1993;
116 Pirmez and Imran, 2003; Wynn et al., 2007; Konsoer et al., 2013). Modern conduits can primarily be
117 classified on the basis of their location of occurrence in the system (i.e., canyons connecting the shelf to the
118 continental slope, valleys on the toe of the continental slope, and channels downstream in the basin;
119 Shepard, 1965; Normark et al., 1993; Babonneau et al., 2002). Such distinction is however somewhat
120 incomplete as it does not consider local adjustment to, for example, slope and/or lithological change along
121 continental margins. Other features are thus used –and must be combined– to identify precisely sediment
122 conduit types. Canyons consist in deeply erosive V-shapes with steep walls, steep gradient, and showing a
123 limited development of external levees (Shepard, 1965; Normark et al., 1993; Wynn et al., 2007; Hansen et
124 al., 2015; Harishidayat et al., 2018). Valleys and channels are smaller than canyons, located on more gentle
125 slopes, associated with external and/or internal levees or terraces, and have a sinuous thalweg (Normark et
126 al., 1993; Babonneau et al., 2002; Wynn et al., 2007; Hansen et al., 2017). In stratigraphic studies, large
127 valleys (also called channel complexes or channel-belts) are differentiated from higher-order and smaller
128 channels or channel fill deposits (Mayall et al., 2006; Deptuck et al., 2007; Hodgson et al., 2011; Janocko et
129 al., 2013b; Covault et al., 2016). Process-oriented studies consider that submarine channels are created
130 from flow processes somehow analogous to those of continental rivers (Peakall et al., 2000; Kneller, 2003;
131 Pirmez and Imran, 2003; Konsoer et al., 2013), while valleys are shaped by supplementary processes
132 including channel entrenchment, lateral migration and aggradation (Babonneau et al., 2004; Deptuck et al.,
133 2007).

134 In the following, we propose to use two simple geomorphic criteria to classify submarine sediment
135 conduits allowing for a clear and objective definition of canyons, valleys and channels (Figure 2). The first
136 criterion is the occurrence or absence of levees flanking the submarine sediment conduit (along one or
137 both sides). Levees are constructional wedges that thin away from the sediment conduit (Skene et al.,

138 2002; Kane and Hodgson, 2011). The second criterion is the presence or absence of terraces and/or internal
 139 levees (Kane and Hodgson, 2011) within the considered conduit delimiting an "entrenched submarine
 140 sediment conduit" –i.e., of smaller size (Figures 2 and 3a). When these internal features are present the
 141 sediment conduit is termed *composite*, otherwise it is termed *unit*. Note that the entrenched conduit in a
 142 composite sediment conduit is often unit but not necessarily.

143 The two criteria described above enable the identification of two common composite submarine
 144 sediment conduits (here termed constructive valleys –i.e., with flanking external levees– and incising
 145 canyons –i.e., no external levees), and two unit submarine sediment conduits (leveed and incised channels
 146 – Figure 2). Note that these criteria apply locally, hence a given submarine sediment conduit may change in
 147 type along its course. For instance, in the Congo fan (Babonneau et al., 2002) it may be a canyon on the
 148 continental slope, split into several valleys downstream when external levees appear, and finally transition
 149 into unit leveed channels on the basin floor when internal levees and/or terraces disappear (Figure 1).



150

151 *Figure 2: Classification of the submarine sediment conduits based on the presence of flanking levees and*
 152 *their composite nature.*

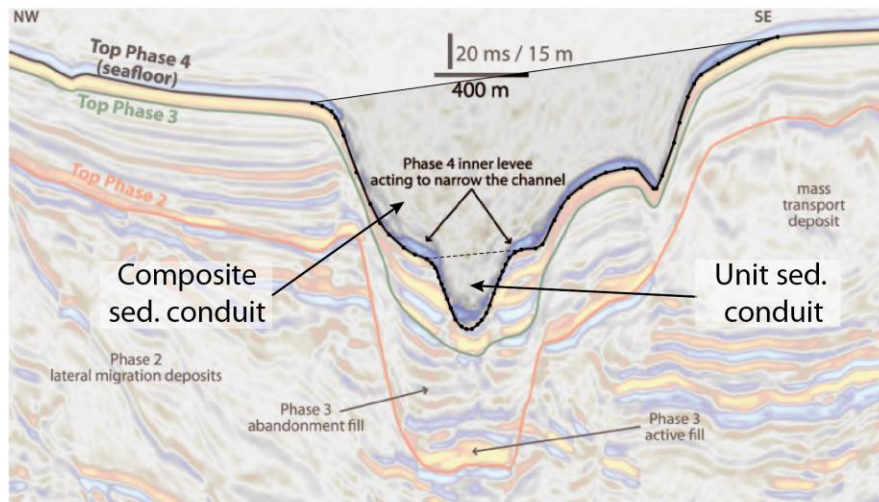
153

2.2. Measurement of the geometric parameters

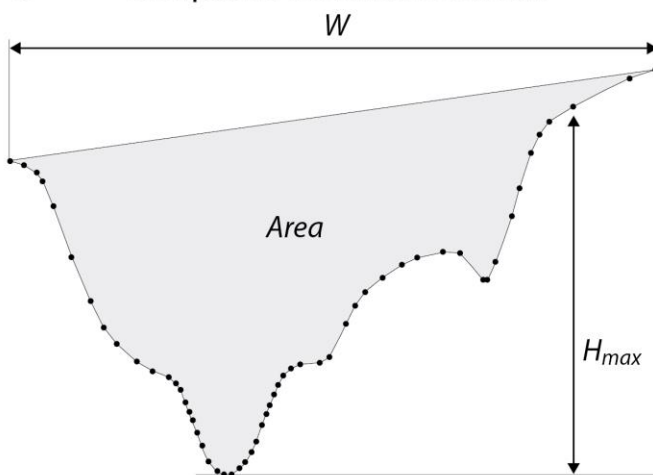
154 Submarine sediment conduits were characterized using the metrics defined for alluvial sinuous
155 rivers (Leopold and Wolman, 1960; Williams, 1986; Sauer and Turnipseed, 2010), allowing for direct
156 comparison with fluvial data. Local longitudinal conduit bed slope, planform and cross-sectional parameters
157 were measured on published images when available. The measurements were performed at specific
158 locations along the conduit course; thus a given channelized system may be characterized by one or several
159 (average 3; maximum 33) measurement points. Some submarine systems such as the Congo or the Amazon
160 are slightly over-represented due to the large amount of data available. Depending on the quality of the
161 data, all parameters may not be available for a given measurement point.

162 Cross-sectional parameters are width (W), mean (H_{mean}) and maximum (H_{max}) depths, and area. In
163 fluvial systems, these parameters are measured at the bankfull stage –i.e., the maximum discharge that a
164 river channel can contain before overbank flooding– and correspond to river channel dimensions (Leopold
165 and Wolman, 1957; Bridge, 2003). Similarly, we selected published submarine sediment conduit cross-
166 sections perpendicular or slightly oblique to straight reaches (e.g., around the inflection zone, see
167 hereafter) (Figure 3) that show a well-defined geometry. Sediment conduit floor and banks were first
168 digitized. The top of channel banks correspond to the slope break observed at the top of levees (when
169 present) or along the substrate (Figure 3a). The amount of picked points was between 15 and 50 depending
170 on the resolution of data and the complexity of the submarine sediment conduit shape as illustrated in
171 Figure 3. Based on the similarity with the bankfull width in fluvial systems (Williams, 1978; Sweet and
172 Geratz 2003), the submarine sediment conduit width was defined as the horizontal distance between the
173 two upper points of the bank (Figure 3b and 3c). Due to levee asymmetry (Peakall et al., 2000; Straub et al.,
174 2008), the maximum depth of submarine sediment conduits was defined as the vertical distance between
175 the lower point of the contour and the mean elevation of the upper banks (Babonneau et al., 2002;
176 Konsoer et al., 2013). The submarine sediment conduit cross-sectional area was defined as the area
177 comprised within the floor of the submarine sediment conduit and the line that connects the highest points
178 of the two banks. Finally, the submarine sediment conduit mean depth was computed as the ratio of the
179 cross-sectional area to the bankfull width (Leopold and Maddock, 1953).

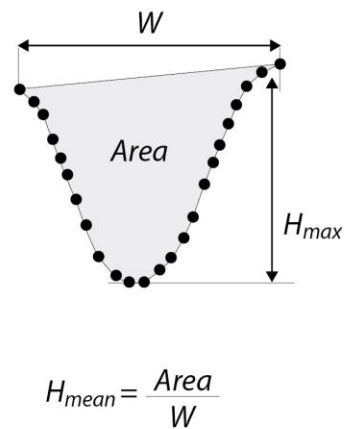
a Seismic cross-section



b Composite sediment conduit



c Unit sediment conduit



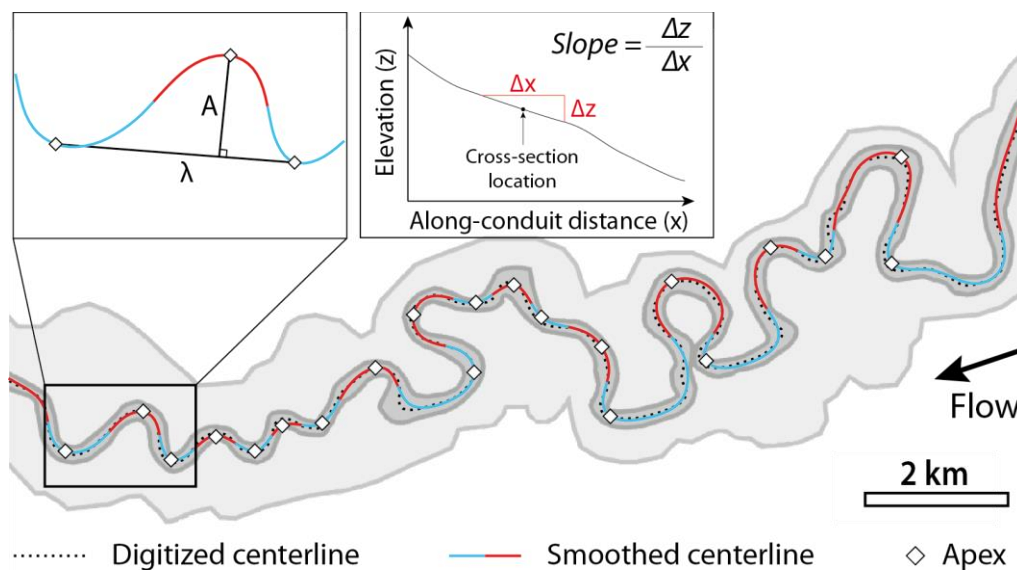
180

181 *Figure 3: Cross-sectional measurement methodology. Interpreted seismic line (from Jobe et al., 2016)*
 182 *showing a composite and an entrenched unit submarine sediment conduit (a). Definition of the bankfull*
 183 *width (W), maximum (H_{max}) and mean (H_{mean}) bankfull depths, and the cross-sectional area for the*
 184 *composite (b) and unit (c) submarine sediment conduits.*

185

186 Bed slope corresponds to the first derivative of bed elevation profile and was measured along
 187 conduits close to the location of cross-sections from published elevation profiles (Figure 4). Regional slope
 188 corresponds to the slope along the mean flow direction and is related to bed slope through conduit
 189 sinuosity. Selected planform sediment conduit parameters were sinuosity (Allen, 1984), meander
 190 wavelength (λ) and amplitude (A) (Leopold and Wolman, 1960). For a given measurement point, the
 191 sinuosity –i.e., the ratio between the curvilinear distance along the studied reach and the sum of the

192 lengths of the segments linking inflection points (Allen, 1984)– was computed over a window equal to 20
 193 times the sediment conduit width (10 times on either side away from the cross-section) allowing the
 194 sampling of several meanders. The same window was used to compute meander wavelength and
 195 amplitude following the algorithm developed by Sylvester and Pirmez (2017): (i) centerline points were first
 196 resampled every 50 m based on a parametric spline function; (ii) the centerline was smoothed using a
 197 Savitzky-Golay filter (Savitzky and Golay, 1964) with a third-order polynomial and a window length scale
 198 approximately equal to half the meander wavelength; (iii) the curvatures were computed and smoothed
 199 using the same filter; (iv) inflection points and apexes defined as null and maximum curvature points
 200 respectively are determined from the smoothed centerline; finally (v) the previously mentioned planform
 201 parameters were computed, discarding wavelength and amplitude of straight channel segments (i.e., with
 202 less than 1.01 bend sinuosity; Sylvester and Pirmez, 2017). The wavelength of a given meander is the length
 203 of the segment joining the apex of each neighboring bend (Figure 4). Meander amplitude is the length of
 204 the segment perpendicular to the previous segment and joining the apex of the given meander. This value
 205 is twice the “amplitude” of a wave as defined in physics. Note that steps ii to v were repeated until the
 206 wavelength converged. Meander wavelength and amplitude were averaged using the same window used
 207 for obtaining the sinuosity.



208

209 *Figure 4: Planform geometry measurements. A: meander amplitude, λ : meander wavelength. Submarine*
210 *sediment conduits example is from the Benin major system (Deptuck et al., 2007). Conduit bed slope is*
211 *measured along channel centerline while regional slope is measured along the flow direction.*

212 **2.3. Statistical analysis**

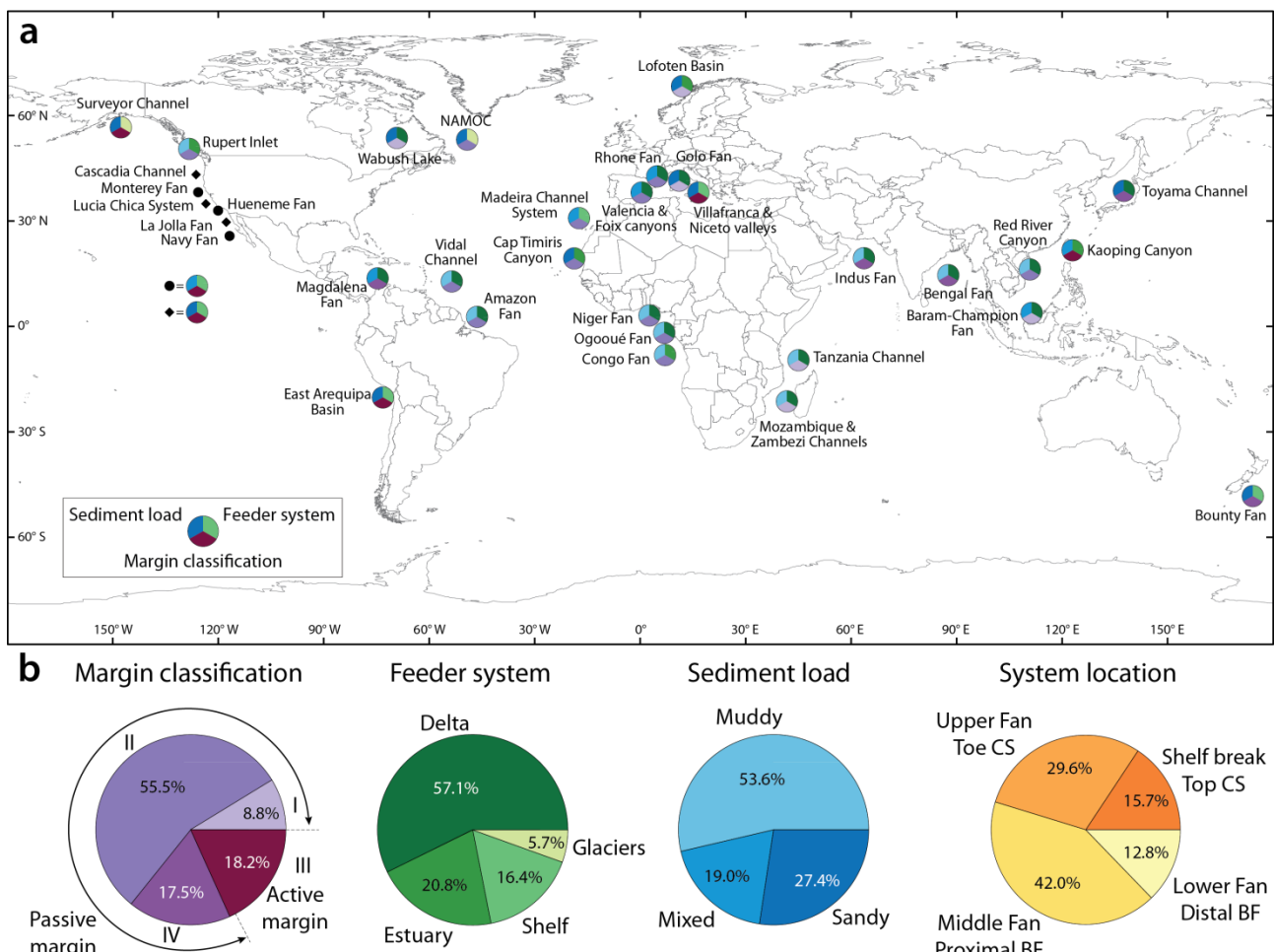
213 The distributions of morphometric parameters were displayed using box plots for each sediment
214 conduit type. Additional variance analyses were performed to test if parameters distributions significantly
215 differed between conduit types. The non-parametric one-way Kruskal-Wallis test (Kruskal and Wallis, 1952)
216 was selected based on the non-normality of our data and the reduced number of observations for some
217 parameters. When Kruskal-Wallis tests revealed statistically different conduit types, a post-hoc group
218 pairwise comparison was carried out using the Dunn's method (Dunn, 1964). This method accounts for
219 unequal sample sizes. Conduit types were considered as significantly different when the returned *p-value*
220 was lower than 0.05 (Table 1).

221 The relationships between morphometric parameters –i.e., meander wavelength, amplitude, width,
222 and mean bankfull depth– were computed for all submarine sediment conduits together and also
223 separately for leveed channels. Least-square linear regressions were performed on log-transformed data,
224 resulting in power-law equations. The equation, regression curves and associated 95% confidence intervals
225 for the mean prediction were displayed only when the *p-value* was lower than 0.05 –rejecting the non-
226 correlation hypothesis– and/or the coefficient of determination R^2 was higher than 0.1.

227 The obtained submarine sediment conduit morphometric relationships were compared first to each
228 other and then to existing relationships for fluvial channels (Table 2). As an illustration, we plotted fluvial
229 data from Held's (2011) database (i.e., 193 measures from 136 alluvial rivers in humid climate regions in
230 both the United States and Australia) for cross-section parameters, that we extended for planform
231 parameters using satellite pictures on large alluvial meandering river systems (Figures 10 and 11).

232 **2.4. A worldwide dataset of modern submarine systems**

233 Submarine sediment conduits were measured using more than 60 publications to obtain 254
 234 measurements (each measurement being therefore composed at least of the 4 cross-sectional parameters)
 235 from 35 modern submarine channelized systems (Figure 5a; see Supplementary Materials). These data
 236 come from seafloor Digital Elevation Models, shallow seismic and sonar surveys with vertical resolutions
 237 varying from few to tens of meters depending on the year of acquisition and the water depth of sediment
 238 conduits (e.g., Clark and Pickering, 1996; Wynn et al., 2007). Hence, despite our carefulness, data contain
 239 uncertainties; but this is inherent in the study of large datasets and should not preclude the identification
 240 of major trends.



241
 242 *Figure 5: Location of sampled submarine systems (a). Distribution of submarine systems according to:*
 243 *margin classification (Wetzel, 1993), feeder system, sediment load and system location (b). Colors in circles*
 244 *in (a) correspond to the first three systems characteristics shown in (b). I: immature passive margin, II:*
 245 *mature passive margin, III: active margin, IV: passive margin with active hinterland, CS: continental slope,*
 246 *BF: basin floor.*

247

248 Special attention was paid to include submarine systems from a large range of latitudes (from -45°
249 for the Bounty fan to +65° for the Lofoten basin), or tectonic settings (18.2% from active margins and 81.8%
250 from passive margins of different types according to the classification of Wetzel (1993); Figure 5). The
251 studied systems comprise very large to medium size submarine systems such as the Indus or the
252 Magdalena fans, and small ones like the Golo fan or the Rupert Inlet system. The systems are fed by a wide
253 range of sediment sources with varied mechanisms initiating the flows, i.e., deltas (57.1%), estuaries
254 (20.8%; e.g., Congo fan), directly from the shelf (16.4%; e.g., Navy fan), and glaciers (5.7%; i.e., NAMOC and
255 Surveyor Channel). The sediment load varies from muddy (53.6%; e.g., Amazon or Mississippi fans), to
256 sandy (27.4%; e.g., La Jolla fan or the Cascadia system) and mixed (19.0%; e.g., Rhone or Nile fans) (Figure
257 5b), according to the classification of Reading and Richards (1994). The majority of the sampled submarine
258 sediment conduits comes from submarine fans (58.3%) but 41.7% represent isolated submarine sediment
259 conduits such as NAMOC or the Tanzania Channel. Four marine environments are represented, based on
260 their location relative to the continental slope: (i) the top of the continental slope, (ii) the toe of the
261 continental slope (or upper fan), (iii) the proximal basin floor (usually middle fan), and (iv) the distal basin
262 floor (or lower fan) (Figures 1 and 5b). This submarine environment zonation applies to both turbidite fans
263 and isolated submarine sediment conduits.

264 **3. Results**

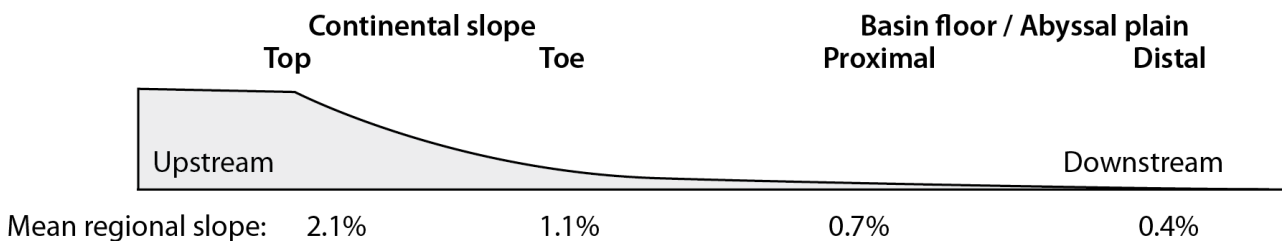
265 **3.1. Geomorphic control on the distribution of sediment conduit data**

266 The dataset encompasses a wide range of geological and geomorphic settings over four submarine
267 domains (i.e., top and toe of the continental slope, proximal and distal basin; Figures 5 and 6). The dataset
268 also covers median regional slopes ranging from 2.1% (top of continental slope) to 0.4% (distal basin floor).
269 Most features are unit submarine sediment conduits (81.1%), of which 63.4% are leveed channels (n=161)
270 and 17.7% are incised channels (n=45). Composite submarine sediment conduits (n=48) are divided into

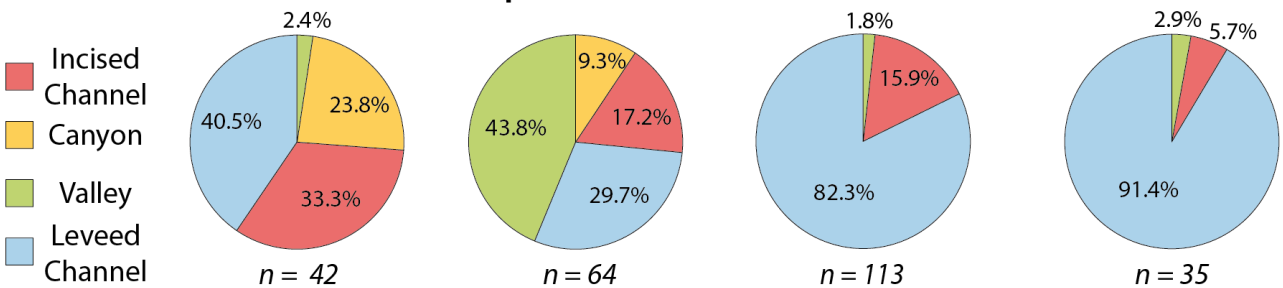
271 canyons (6.3%) and valleys (12.6%). Submarine sediment conduits are mainly located at the toe of
 272 continental slope (25.2%) and within proximal basin floor (44.5%). The remaining submarine sediment
 273 conduits (30.3%) are evenly distributed between the top of the continental slope (16.5%) and the distal
 274 basin floor (13.8%).

275 The distribution of submarine sediment conduits strongly depends on their location within the
 276 submarine system (Figure 6). The upstream part of the continental slope is dominated by incised sediment
 277 conduits of which 33.3% are classified as incised channels and 23.8% as canyons, while leveed channels and
 278 valleys represent 40.5% and 2.4% of the conduits respectively. The toe of the continental slope is
 279 dominated by valleys (43.8%), followed by leveed channels (29.7%) and incised channels (17.2%). The
 280 remaining sediment conduits correspond to canyons (9.3%). Going downslope, except for 3 valleys the
 281 great majority of sediment conduits are unit channels, with an overrepresentation of leveed channels (i.e.,
 282 increasing from 82.3% in the proximal plain to 91.4% in the distal plain).

a. Submarine domain



b. Sediment conduit distribution per submarine domain



284 *Figure 6: Distribution of submarine sediment conduit types in the submarine environment. Regional slope*
 285 *evolution along submarine domains from the continental slope to the basin floor (a), and associated*
 286 *distribution of submarine sediment conduit types (b; n: number of submarine sediment conduits in each*
 287 *domain).*

288 **3.2. Geometry of submarine sediment conduits**

289 The different submarine sediment conduit types (i.e., incised channel, canyon, valley, leveed
 290 channel) can be distinguished according to their geometry (i.e., bed slope, sinuosity, meander wavelength
 291 and amplitude, area, bankfull width, mean and maximum bankfull depths) as shown by the statistical
 292 analysis (Table 1, Figures 7-9). In the following, distributions of morphometric parameters (Figures 7 and 8)
 293 are presented following the classification scheme (Figure 2).

294 *Table 1: Results of the non-parametric analysis of variance on morphometric parameters**

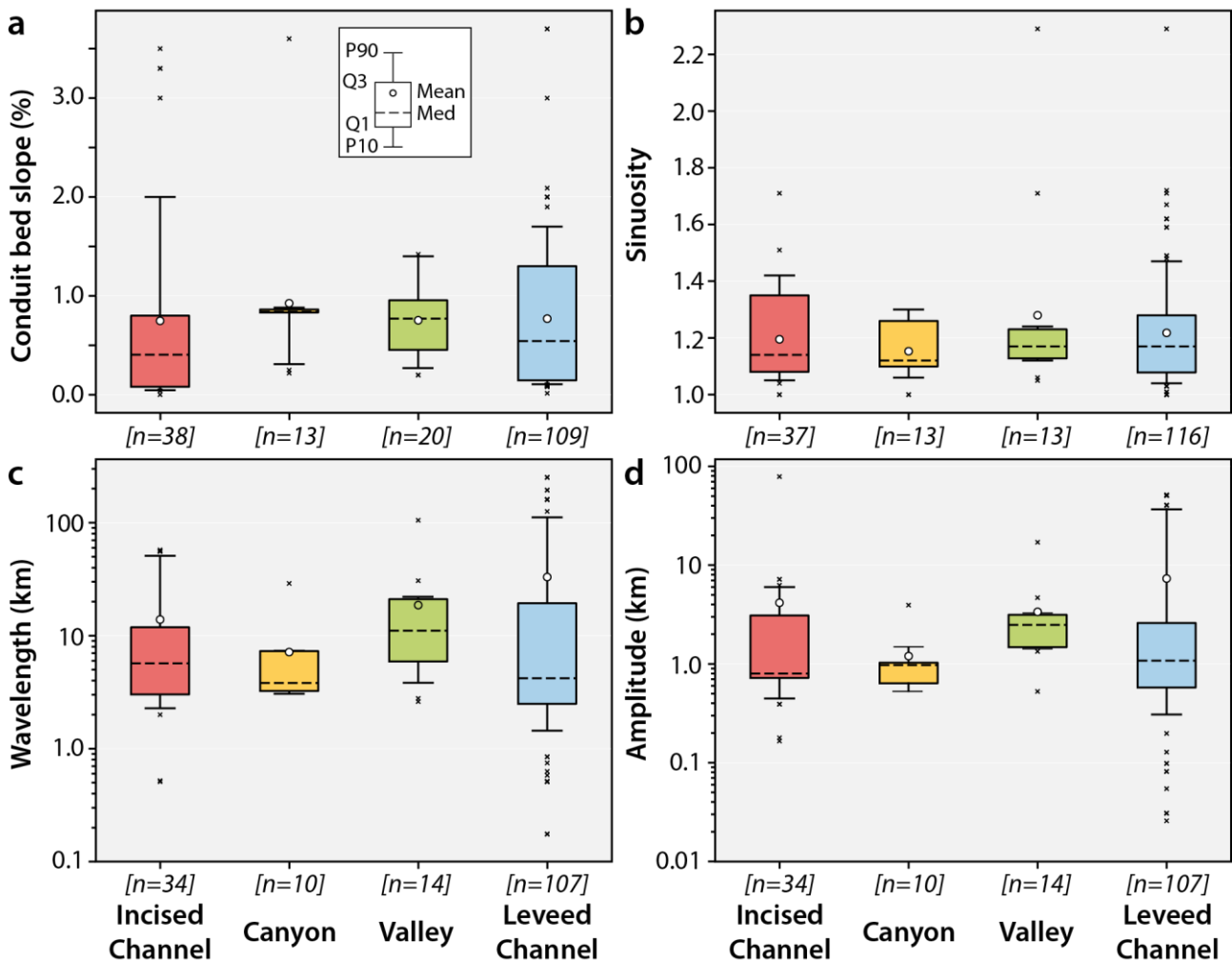
Morphometric parameter	Kruskal-Wallis test (<i>p-value</i>)	Dunn's post-hoc pairwise comparison (<i>p-value</i>)				
			IC ¹	Canyon	Valley	LC ²
Area	7.2 10 ⁻¹⁸	IC		0.025	1.0	2.2 10 ⁻⁸
		Canyon			0.018	1.9 10 ⁻¹¹
		Valley				1.2 10 ⁻⁵
Width	5.5 10 ⁻¹⁴	IC		4.7 10 ⁻³	1.0	9.5 10 ⁻⁵
		Canyon			0.046	4.7 10 ⁻⁷
		Valley				2.7 10 ⁻⁵
Mean Depth	4.1 10 ⁻¹⁷	IC		0.27	0.70	2.4 10 ⁻¹⁰
		Canyon			0.012	5.9 10 ⁻¹⁰
		Valley				6.4 10 ⁻⁴
Maximum Depth	5.9 10 ⁻¹⁹	IC		0.26	1.0	2.7 10 ⁻¹¹
		Canyon			0.020	1.4 10 ⁻¹⁰
		Valley				5.9 10 ⁻⁵
Wavelength	0.29	-				
Amplitude	0.09	-				
Bed_slope	0.044	<i>p-value</i> > 0.05 for all pairwise comparisons				
Sinuosity	0.81	-				
Depth ratio	1.2 10 ⁻⁶	IC		0.89	1.0	5.3 10 ⁻³
		Canyon			1.0	1.1 10 ⁻³
		Valley				9.4 10 ⁻⁴
Aspect ratio	0.011	IC		0.64	6.1 10 ⁻³	0.18
		Canyon			1.0	1.0
		Valley				0.24
Wavelength/Amplitude	0.36	-				
Wavelength/Width	4.2 10 ⁻⁶	IC		0.021	1.0	0.046
		Canyon			0.058	1.1 10 ⁻⁵
		Valley				0.45

Amplitude/Width	3.5 10 ⁻⁷		IC	Canyon	Valley	LC
		IC		0.020	1.0	7.6 10 ⁻³
		Canyon			0.013	1.9 10 ⁻⁶
		Valley				0.82

295 * In green are the results that support significant differences between submarine conduit types (i.e., p-
 296 value < 0.05). ¹ Incised channels; ² Leveed channels

297 **3.2.1. Submarine sediment conduit slope and dimensions**

298 Along-conduit bed slope and planform morphometric parameters (i.e., sinuosity, wavelength, and
 299 amplitude) do not show significant differences according to submarine sediment conduit types (Table 1)
 300 although the Kruskal-Wallis test results in a *p-value* slightly lower than 0.05 for bed slope. Bed slope values
 301 range from 0.01 to 3.7% with an average slope around 0.8% (Figure 7a). The mean sinuosity varies from
 302 1.15 to 1.28 and maximal values are up to 2.2 (Figure 7b). The wavelength of submarine meanders is on
 303 average 10-30 km and spans two orders of magnitude. Meander amplitude is around five times lower than
 304 the wavelength with average values around 1-7 km.

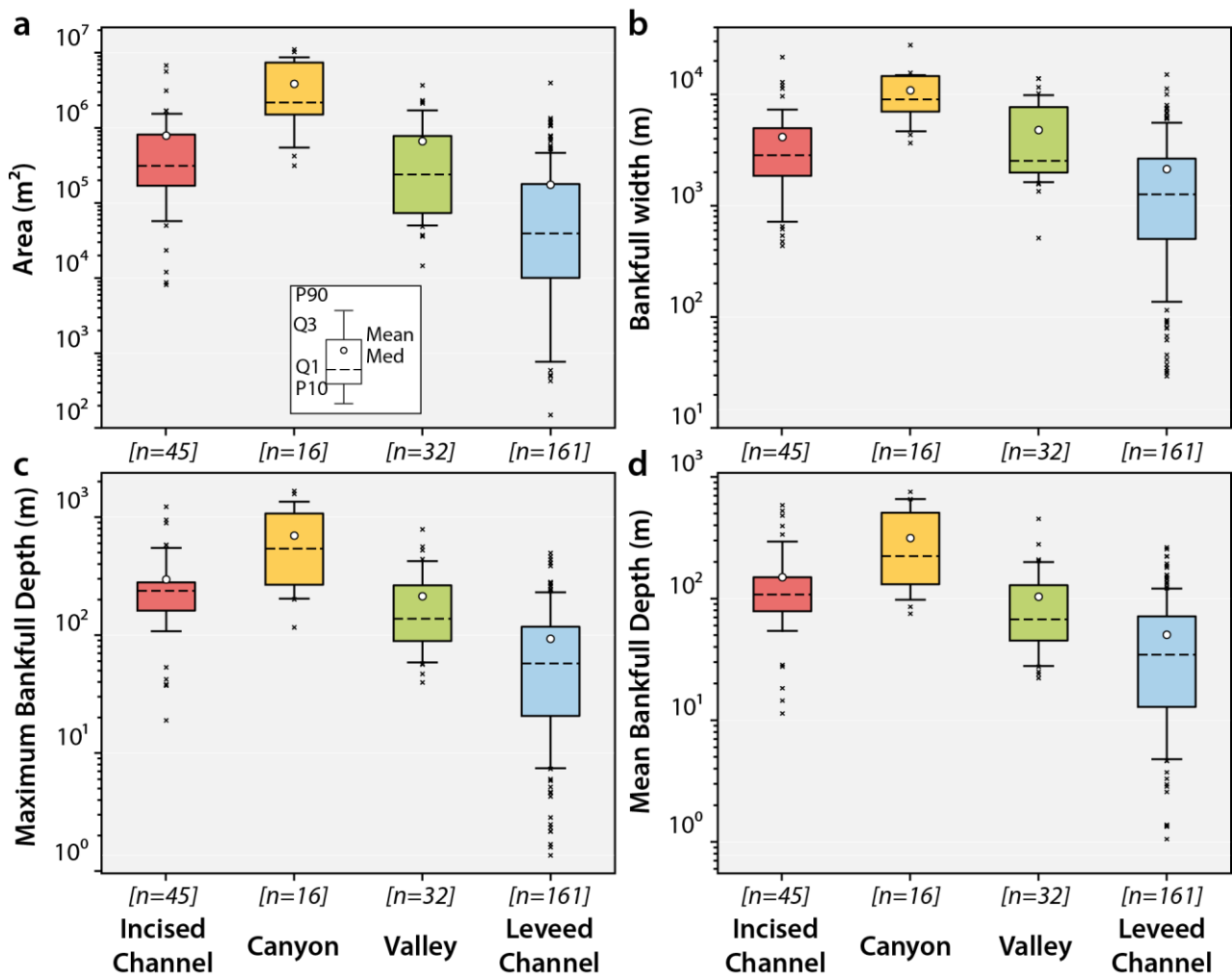


305

306 Figure 7: Submarine sediment conduit morphology: along-conduit bed slope (a), sinuosity (b), meander
 307 wavelength (c) and amplitude (d) (n: number of measurements, P10: tenth percentile, Q1: first quartile,
 308 Med: median, Q3: third quartile, P90: ninetieth percentile).

309

310 When looking at cross-sectional geometrical parameters (Figure 8), submarine sediment conduit
 311 types are significantly different (Table 1). Leveed channels appear clearly distinct from the other sediment
 312 conduits in virtue of their smaller dimensions (Figure 8). Leveed channel cross-sectional area is indeed four
 313 times lower than that of incised channels and valleys, and more than one order of magnitude lower than
 314 that of canyons (Figure 8a). Mean bankfull width and mean and maximum bankfull depths follow trends
 315 similar to that of the cross-sectional area (Figures 8b-d). Canyons are the largest submarine sediment
 316 conduits, leveed channels the smallest, while incised channels and valleys show statistically similar
 317 dimensions according to every cross-sectional metrics (Figure 8 and Table 1).

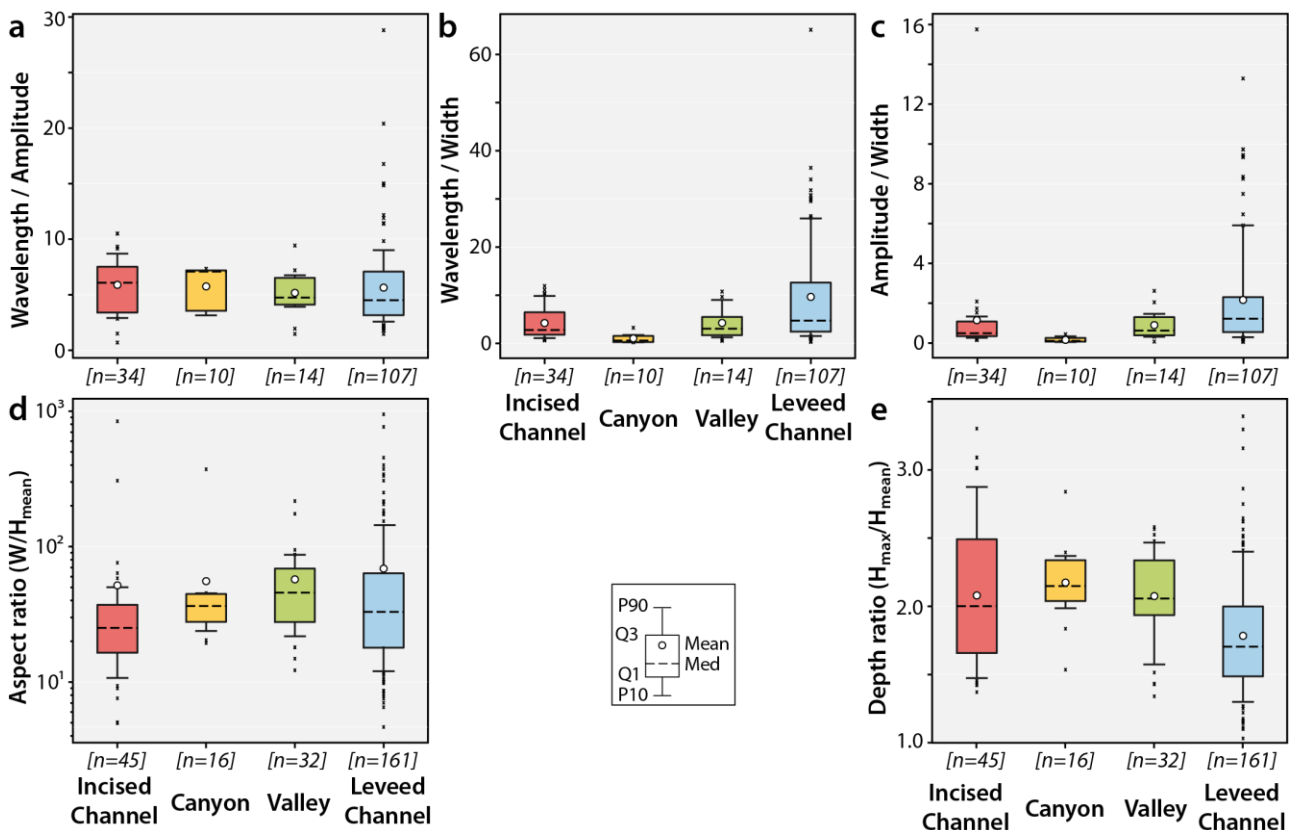


318

319 *Figure 8: Cross-sectional dimensions of submarine sediment conduits: cross-sectional area (a), bankfull*
 320 *width (b), maximum bankfull depth (c) and mean bankfull depth (d). See Figure 7 for abbreviations.*
 321

322 **3.2.2. Normalized meander dimensions and cross-section ratios**

323 When looking at cross-sectional geometrical parameters (Figure 8), submarine sediment conduit
 324 types are significantly different (Table 1). Leveed channels appear clearly distinct from the other sediment
 325 conduits in virtue of their smaller dimensions despite the greatest scatter (Figure 8). Median cross-sectional
 326 area of leveed channels ($4.0 \cdot 10^4 \text{ m}^2$) is indeed 6-8 times lower than that of incised channels ($32 \cdot 10^4 \text{ m}^2$) and
 327 valleys ($24 \cdot 10^4 \text{ m}^2$), and nearly two orders of magnitude lower than that of canyons ($222 \cdot 10^4 \text{ m}^2$ – Figure
 328 8a). Bankfull width and mean and maximum bankfull depths follow trends similar to that of the cross-
 329 sectional area (Figures 8b-d). Canyons (median values of 9082 km, 224 m and 539 m respectively) are the
 330 largest submarine sediment conduits, leveed channels (1267 m, 34 m, and 57 m) the smallest, while incised
 331 channels (2866 m, 109 m, and 237 m) and valleys (2556 m, 68 m, and 137 m) show statistically similar
 332 dimensions according to every cross-sectional metrics (Figure 8 and Table 1).



333

334 *Figure 9: Normalized planform parameters: wavelength to bankfull width ratio (a), amplitude to bankfull*
335 *width ratio (b), wavelength to amplitude ratio (c), and normalized cross-sectional parameters: aspect ratio*
336 *(d), depth ratio (e) of submarine sediment conduits.*

337

338 The aspect ratio significantly differs between valleys (median 46) and incised channels (26) whereas
339 no statistical difference is observed between the other conduit types (median values of canyon and leveed
340 channels of 33 and 36 respectively; table 1 and Figure 9d). Conversely, leveed channels significantly differ
341 from canyon, valleys and incised channels in virtue of a smaller (median 1.7) depth ratio (maximum to
342 mean bankfull depths), which tends to be higher for the latter types (> 2.0; Table 1 and Figure 9e).

343 **3.3. Submarine sediment conduits relationships and comparison with** 344 **alluvial sinuous rivers**

345 In the following, morphometric relationships are derived for all types of submarine sediment
346 conduits and then for submarine leveed channels only (see section 2.3 for the methodology). The
347 relationships are compared to published fluvial and submarine sediment conduits morphometric
348 relationships established for modern systems (Table 2; Figures 10 and 11).

349 **3.3.1. Morphometric relationships**

350 Overall, results show that submarine and fluvial sediment conduits have contrasting dimensions;
351 power law regressions differ to some degree (Figure 10). For instance, submarine sediment conduits are
352 around four times larger than rivers for a given mean depth considering Held's data (Figure 10a). Note that
353 width-to-depth relationships for submarine sediment conduits are very similar, considering all sediment
354 conduits or leveed channels only (i.e., exponents of 0.81, coefficients of 74.7 and 70.5 respectively; Figure
355 10a). Wavelength-to-amplitude regressions on submarine data have very similar exponents (0.93 and 0.94)
356 close to that of the regression performed by Williams (1986) on river data (1.0), but with coefficients 1.8-
357 3.5 times higher (7.89 and 7.48 for submarine data against 2.23 and 4.04 for rivers – Figure 10b). Thus,

358 submarine sediment conduits are less sinuous, as their amplitude is lower than that of sinuous rivers for a
 359 given wavelength.

360 In comparison with the results of Table 1, we performed a Kruskal-Wallis test and the pair-wise
 361 comparison between all submarine sediment conduits, submarine leveed channels and alluvial rivers on the
 362 aspect ratio, wavelength-to-amplitude ratio, normalized wavelength, and normalized amplitude. All of
 363 them confirmed the statistical differences between the three populations.

364

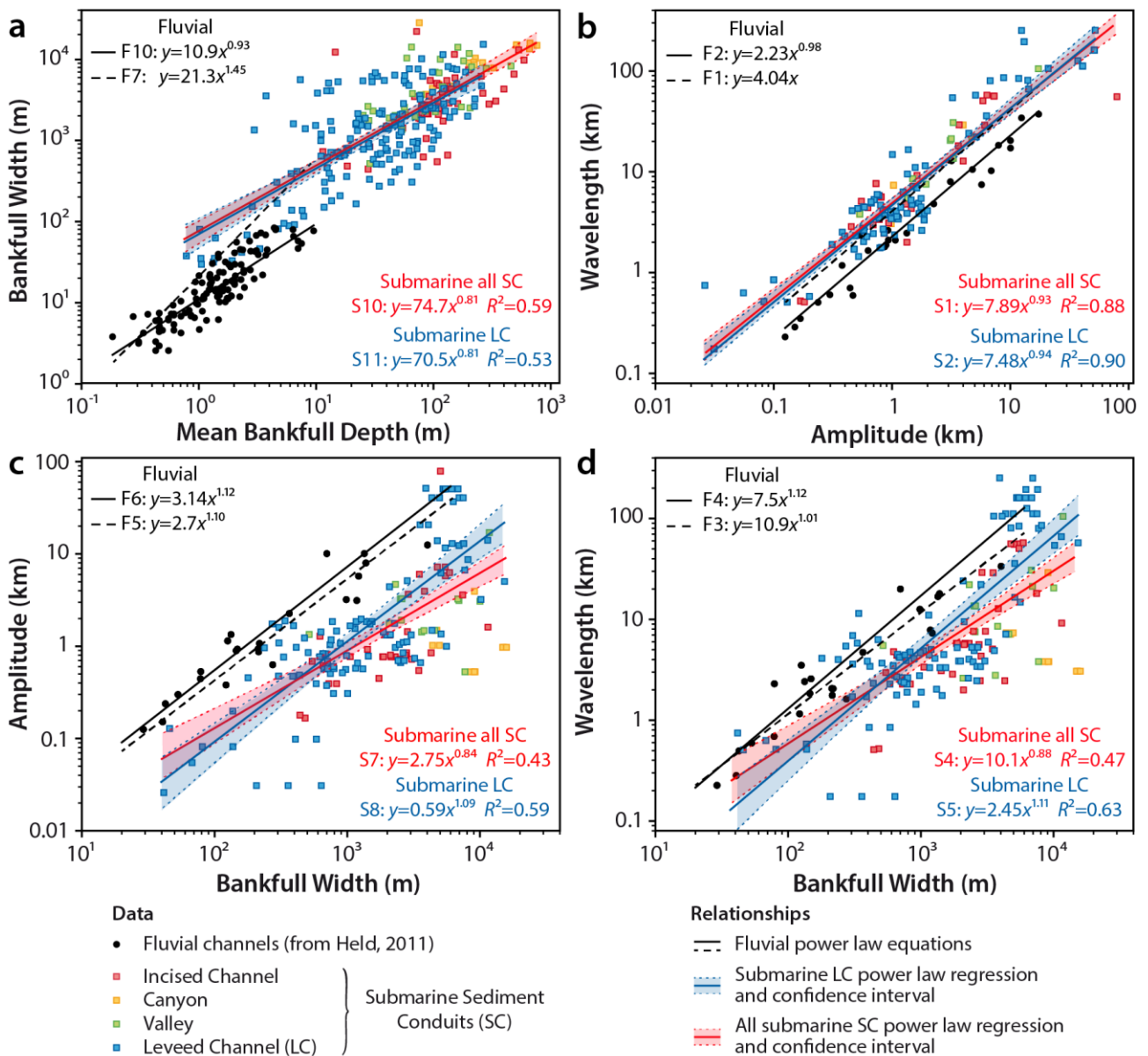
365 *Table 2: Summary of modern fluvial and submarine geometric relationships.*

Equation n°	System	Reference	Power law	R ²	Sinuosity
Meander wavelength (λ) from meander amplitude (A)					
F1	Fluvial	Leopold and Wolman (1960)	$\lambda = 4.04 A^{1.0}$	NA	NA
F2	Fluvial	Williams (1986)*	$\lambda = 2.23 A^{0.98}$	0.98	> 1.3
S1	Submarine	This study (all submarine SC)	$\lambda = 7.89 A^{0.93}$	0.88	> 1.0
S2	Submarine	This study (leveed channel)	$\lambda = 7.48 A^{0.94}$	0.90	> 1.0
Meander wavelength (λ) from bankfull width (W)					
F3	Fluvial	Leopold and Wolman (1960)	$\lambda = 10.9 W^{1.01}$	NA	NA
F4	Fluvial	Williams (1986)*	$\lambda = 7.5 W^{1.12}$	0.92	> 1.3
S3	Submarine	Clark et al. (1992)	$\lambda = 11.9 W^{0.75}$	0.68	> 1.0
S4	Submarine	This study (all SC)	$\lambda = 10.1 W^{0.88}$	0.47	> 1.0
S5	Submarine	This study (leveed channel)	$\lambda = 2.45 W^{1.11}$	0.63	> 1.0
Meander amplitude (A) from bankfull width (W)					
F5	Fluvial	Leopold and Wolman (1960)	$A = 2.7 W^{1.10}$	NA	NA
F6	Fluvial	Williams (1986)*	$A = 3.14 W^{1.12}$	0.92	> 1.3
S6	Submarine	Clark et al. (1992)	$A = 2.7 W^{1.44}$	NA	NA
S7	Submarine	This study (all SC)	$A = 2.75 W^{0.84}$	0.43	> 1.0
S8	Submarine	This study (leveed channel)	$A = 0.59 W^{1.09}$	0.59	> 1.0
Channel bankfull width (W) from mean bankfull depth (H_{mean})					
F7	Fluvial	Williams (1986)	$W = 21.3 H_{mean}^{1.45}$	0.66	> 1.3
F8	Fluvial	Williams (1986)	$W = 15.5 H_{mean}^{1.40}$	0.60	> 1.7
F9	Fluvial	Bridge and Mackey (1993)	$W = 8.9 H_{mean}^{1.82}$	0.60	> 1.0
F10	Fluvial	Held (2011)	$W = 10.9 H_{mean}^{0.93}$	0.73	> 1.5
S9	Submarine	Konsoer et al. (2013)	$W = 47.4 H_{mean}^{0.94}$	0.39	> 1.0
S10	Submarine	This study (all SC)	$W = 74.7 H_{mean}^{0.81}$	0.59	> 1.0
S11	Submarine	This study (leveed channel)	$W = 70.5 H_{mean}^{0.81}$	0.53	> 1.0

366 * Derived from combined equations.

367

368 Amplitude-to-width (Figure 10c) and wavelength-to-width (Figure 10d) relationships differ when
 369 considering all submarine sediment conduits or submarine leveed channels only, in agreement with
 370 normalized meander dimensions (Figures 9b and 9c). In both cases, the power law exponents are lower
 371 than 1 considering all sediment conduits (0.84 and 0.88 respectively; instead the exponents are greater
 372 than unity for leveed channels (1.09 and 1.11). These latter values are close to river exponents (1.12).
 373 Differences between the coefficients highlight that meander wavelength and amplitude of submarine
 374 leveed channels are around 3-5 times lower than those of river meanders for a given width (Figures 10c and
 375 10d).

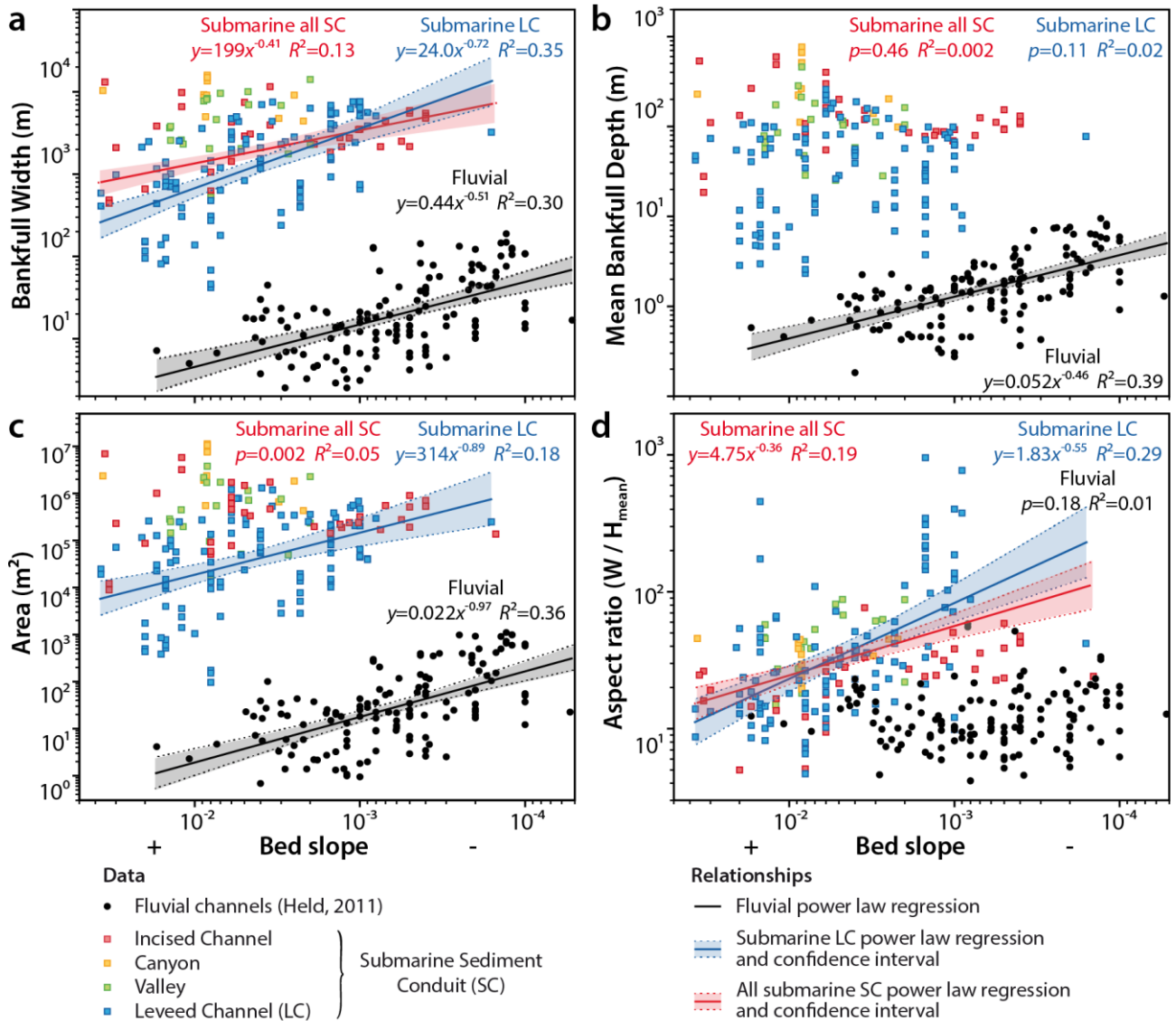


376

377 *Figure 10: Relationships of all submarine sediment conduit and leveed channel morphometric parameters*
378 *and comparison with those of sinuous rivers: bankfull width versus mean bankfull depth (a), wavelength*
379 *versus amplitude (b), amplitude versus bankfull width (c), wavelength versus bankfull width (d). Fluvial data*
380 *are from Held (2011) in (a) and from this study in (b) to (d). See Table 2 for the equation numbers.*
381

382 **3.3.2. Cross-sectional geometry related to bed slope**

383 Correlations show that cross-sectional geometric parameters tend to increase with decreasing bed
384 slope for both submarine sediment conduits and rivers (Figure 11). Bankfull width is significantly negatively
385 correlated to slope for submarine sediment conduits, submarine leveed channels, and fluvial channels
386 (Figure 11a), although the coefficients of determination are small (respectively 0.13, 0.35, and 0.30). Mean
387 bankfull depth and slope are correlated for fluvial channels ($R^2=0.39$, $p\text{-value}=5.7 \cdot 10^{-7}$), but no correlation is
388 observed for submarine sediment conduits or leveed channels alone (respectively $R^2=0.002$ and 0.02 , $p\text{-}$
389 $value=0.46$ and 0.11 , Figure 11b). There is a very small, while significant, correlation between cross-
390 sectional area and slope for submarine sediment conduits ($R^2=0.05$, $p\text{-value}=0.002$). A stronger correlation
391 exists for submarine leveed channels and fluvial channels (respectively $R^2=0.18$ and 0.36 , $p\text{-value}=3.8 \cdot 10^{-6}$
392 and $1.1 \cdot 10^{-14}$, Figure 11c). Finally, the aspect ratio is correlated to bed slope for submarine sediment
393 conduits ($R^2=0.19$, $p\text{-value}=1.42 \cdot 10^{-9}$) and submarine leveed channels alone ($R^2=0.29$, $p\text{-value}=1.9 \cdot 10^{-9}$),
394 while no correlation appears for fluvial data ($R^2=0.01$, $p\text{-value}=0.18$, Figure 11d). This indicates that
395 submarine leveed channels tend to be wider when the slope is lower (i.e., mostly going downstream).



396

397 *Figure 11: Cross-plots of bankfull width (a), mean bankfull depth (b), cross-sectional area (c), and aspect*
 398 *ratio (d) versus channel slope for all submarine sediment conduits, submarine leveed channels, and rivers.*
 399 *Regression curves are not represented for p -value > 0.05 and/or $R^2 < 0.1$.*

400 4. Discussion

401 To our knowledge, the present database is one of the most exhaustive compilation of modern
 402 submarine sediment conduits data from academic research publications, where sampled submarine
 403 sediment conduits extend over different geological settings, comprise varied sediment feeding systems,
 404 and include measurements in varied geomorphic locations from the edge of continental shelves to abyssal
 405 plains (Figure 5). Such compilation and the first-order trends identified between morphometric parameters

406 (i.e., similarly to rivers) are of use to both field and modeling-oriented geologists for understanding
407 submarine sediment conduit dynamics. In the following, we discuss the relevance of the new geomorphic
408 classification and its applications, as well as the distribution of submarine sediment conduits (particularly
409 leveed channels) and their analogy with alluvial sinuous rivers.

410 **4.1. First-order characteristics of submarine sediment conduits types**

411 **4.1.1. Relevance of the classification**

412 The classification of submarine sediment conduits developed in this work is based on two simple
413 geomorphic criteria: presence/absence of levees, composite/unit nature of the studied submarine
414 sediment conduits (Figure 2). These geomorphic criteria can be inferred from 2D cross-sections, and can be
415 applied in absence of constraints on sediment conduit location in the submarine system (Shepard, 1965;
416 Normark et al., 1993; Babonneau et al., 2002), or submarine sediment conduit planform morphology (e.g.,
417 braiding versus sinuous pattern, see Foreman et al., 2015 and references therein). The presence of levees
418 indicates partly or fully constructional conduits (Normark, 1970; Wynn et al., 2007; Straub and Mohrig,
419 2008) while their absence indicates mostly erosional conduits (Normark, 1970; Fildani et al., 2013; Weill et
420 al., 2014). As a result, our classification includes the two end-members “erosive” and “aggradational”
421 submarine sediment conduits of the classification of Normark (1970) – “mixed” conduits being included
422 into aggradational features.

423 The classification proposed in this study uses a unified nomenclature for modern systems, based on
424 geomorphic features that can also be inferred in fossil systems as well as small-scale and numerical models
425 (Lemay, 2018). The proposed hierarchical basis between unit and composite submarine sediment conduits
426 is furthermore similar to the stratigraphic division between the smaller-scale (i.e., highest-order) channel
427 fill deposits and the larger-scale (i.e., lower-order) stratigraphic valley fills (Mayall et al., 2006; Deptuck et
428 al., 2007; Hodgson et al., 2011; Janocko et al., 2013b; Covault et al., 2016). Despite this hierarchical
429 similarity, stratigraphic conduits are not directly derived from paleo-valleys since the formers are shaped

430 during both incision and filling phases (Strong and Paola, 2008; Sylvester et al., 2011). This hierarchy
431 reflects either single or multi phase submarine sediment conduit evolutions (Clark and Pickering, 1996;
432 Deptuck et al., 2007; Babonneau et al., 2004; Bain and Hubbard, 2016). Such distinction is useful because
433 the morphology or sedimentary architecture of composite submarine sediment conduits results from a
434 multi-phase evolution and the interaction of different processes (Mayall et al., 2006; Strong and Paola,
435 2008; Deptuck et al., 2007; Sylvester et al., 2011). In this sense, our nomenclature of submarine sediment
436 conduits is comparable to the one used for fluvial systems: modern submarine composite sediment
437 conduits are analogous to continental canyons and valleys while modern submarine channels are analogous
438 to rivers. In addition, sinuous streams are classically split into erosive bedrock and constructive alluvial
439 rivers based on local sediment transport conditions (Montgomery et al., 1996 and references therein). Our
440 classification allows to distinguish between incised and leveed channels, which may be seen as their
441 submarine counterparts (Normark, 1970; Wynn et al., 2007; Straub and Mohrig, 2008; Fildani et al., 2013;
442 Weill et al., 2014).

443 **4.1.2. Distribution of sediment conduit types along continental margins**

444 The distribution of submarine sediment conduit types along the continental margins shows a
445 predominance of composite conduits on the continental slope and unit channels in the basin floor (Figure
446 6). This is in agreement with the existing subdivision into *canyon*, *valley* and *channel* used in many studies
447 (e.g., Babonneau et al., 2002; Pirmez and Imran, 2003) but where precise and objective recognition criteria
448 were missing (Wynn et al., 2007). Deep incised submarine sediment conduits are mostly located on the top
449 of the continental slope while shallower leveed submarine sediment conduits are dominant in the distal
450 part of submarine systems (Figures 6, 8 and 11). Importantly, this distribution reflects major process
451 changes along the continental margin (Figures 1 and 5) that are likely related to geomorphic adjustment to
452 flow conditions similarly to those taking place in rivers (Pirmez et al., 2000; Kneller, 2003; Samuel et al.,
453 2003; Hodgson et al., 2011). The upstream part is therefore dominated by flows with high transport
454 capacity, which can carve multiple unit erosive conduits, ultimately creating composite sediment conduits

455 (Deptuck et al., 2007; Babonneau et al., 2004). These composite submarine sediment conduits have
456 experienced long-lived multi-phase evolution under varying discharge. In contrast, the downstream part of
457 continental margins is dominated by lower transport capacity unit submarine sediment conduits. These
458 short-lived conduits are laterally mobile, whether in the form of lateral migration or avulsion (Figure 1).
459 Hence, the classification can be used to infer paleo-environment, paleo-geographic location and
460 dimensions of the related submarine conduit from observed geomorphic features and geometry (e.g.,
461 Konsoer et al., 2013; Castelino et al., 2017; Harishidayat et al., 2018).

462 **4.1.3. Construction of composite sediment conduits**

463 At first order, the different submarine sediment conduit types within the classification have
464 contrasting dimensions, spanning several orders of magnitude (Figure 8). Canyons, valleys, and incised
465 channels are typically five to ten times wider and deeper than leveed channels (Figure 8). The meanders of
466 unit submarine channels are usually more developed than those of composite submarine sediment
467 conduits which is reflected in higher wavelength-to-width and amplitude-to-width ratios (Table 1, Figures
468 9b and 9c), and indicates that leveed channels are more laterally mobile. Intriguingly, the wavelength-to-
469 amplitude ratio is very similar across any type of submarine conduit (~7) but differs from the typical range
470 of 2-4 observed for fluvial meandering rivers (Tables 1 and 2, and Figure 9a). Hence, unit and composite
471 submarine sediment conduits share common properties.

472 Many processes are invoked for the formation of composite submarine conduits including slumps,
473 very large sediment gravity flows, structural control, or the heritage of an ancient fluvial canyon created
474 during lowstand of sea level (Normark et al., 1993; Antobreh and Krastel, 2006; Babonneau et al., 2004;
475 Deptuck et al., 2007). In this study, sampled submarine canyons are the straightest conduits relatively to
476 their width (Figures 8b-c), which may support an initiation by regressive erosion, whether driven by
477 submarine retrogressive failures or subaerial carving associated with sea-level lowstand. However, the
478 similar wavelength-to-amplitude ratio between composite and unit submarine conduits (Table1, Figures 9b
479 and 9c) support the entrenchment of unit submarine channels within the composite ones (at least for most

480 of the canyons present in the database), according to a mechanism similar to the formation process
481 proposed for continental canyons –e.g., the Grand Canyon (Karlstrom et al., 2014, and references therein).
482 Hence the sampled submarine canyons were likely carved into preexisting submarine features and have
483 since adjusted to frequent erosive sediment-laden flows (Mulder and Alexander, 2001). Consequently,
484 fluctuations in flow characteristics (discharge, sediment load) through time are recorded by changes in
485 small-scale channel sedimentary body morphology and grain-size distribution, and impact the location,
486 architecture, and petrophysical properties of hydrocarbon reservoirs within large-scale canyons or valleys
487 (Mayall et al., 2006; Wynn et al., 2007). The smallest submarine sediment conduits are likely key elements
488 to understand the carving and sedimentary filling of larger submarine sediment conduits. Capturing the
489 geometry and heterogeneities of composite submarine sediment conduits therefore requires
490 understanding the evolution of smaller confined channels. The present study provides morphometric
491 parameters such as distributions and scaling laws for characterizing channelized sedimentary bodies relying
492 on geometric approaches (Sylvester et al., 2011; Parquer et al., 2017; Lemay, 2018).

493 **4.1.4. Submarine channel dimensions**

494 In studies on submarine sediment conduit geometry, small submarine sediment conduits –
495 narrower than 1000 m and/or shallower than 10 m (maximum depth)– are rarely reported (e.g., Konsoer et
496 al., 2013). In our database, 5.5% of submarine sediment conduits are less than 100 m wide, and 10.9% are
497 less than 10 m deep (mean depth). McHargue et al. (2011) developed from outcrops the concept of
498 “channel elements” up to four times narrower and shallower than the unit channels identified in this study.
499 One may thus question to what extent our database is representative of submarine channel dimensions.
500 Although very large channels (> 5000 m) are observed on modern ocean floors (e.g., Zambezi channel –
501 Wiles et al., 2017), some of the largest channels we identified (particularly from old data) may in fact
502 correspond to composite submarine sediment conduits (see Supplementary Material). For example, many
503 incised sediment conduits on the top of the continental slope, for instance the Amazon, Bengal or Indus
504 systems, do not display any entrenched smaller conduit, while a multi-phase evolution of such systems is

505 undeniable. Consequently, some of the incised channels in our database, particularly those on the shelf
506 break, could be reclassified as canyons. This may partly explain the great scatter of unit channel data –
507 particularly the very large channels observed in our database– but also the low number of canyons
508 identified from our classification. Conversely, small submarine sediment conduits are locally reported in 3D
509 seismic surveys, for instance in frontal lobes (Doughty-Jones et al., 2017) or carbonate systems (Mulder et
510 al., 2014). However, low data resolution prevents from precisely measuring them. We therefore
511 acknowledge that the present dataset may consider composite sediment conduits as unit ones, and that,
512 without access to higher-resolution recent data (e.g., from the industry), very small submarine sediment
513 conduits (< 100 m wide or 10 m deep) may not be sampled. However, we emphasize that this limitation
514 should not affect the major trends observed in this study since it concerns a minority of our data, and
515 considering that the dataset covers three orders of magnitude, which highlights the larger size of composite
516 submarine sediment conduits compared to unit channels (Table 1), and unit channels compared to rivers.

517 **4.2. Submarine leveed channel flow processes**

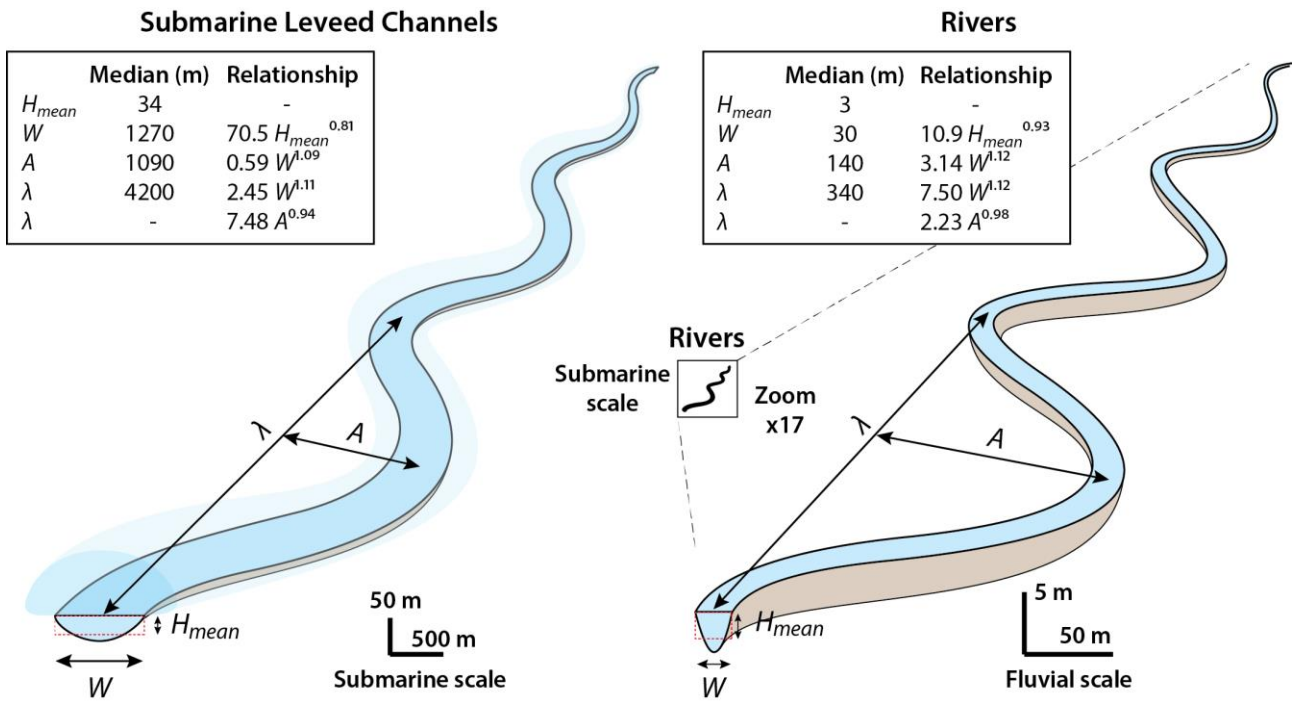
518 **4.2.1. Comparison with fluvial meandering channels dynamics**

519 As observed in other studies (Clark and Pickering, 1996; Pirmez and Imran, 2003; Konsoer et al.,
520 2013), surveyed submarine sediment conduits are one to two orders of magnitude wider and deeper than
521 alluvial sinuous channels (Figures 11 and 12a). Among them, submarine leveed channels are the most
522 analogous to alluvial rivers: (i) they have an aggradational behavior; (ii) they form a consistent group that
523 significantly differ from the other submarine sediment conduit types (Table 1) in virtue of (iii) a smaller size
524 (Figure 7b), (iv) larger meanders relatively to their size (Figures 9a-9c); (v) they display wavelength-to-width
525 and amplitude-to-width relationships more similar to those of sinuous alluvial rivers than those of all
526 submarine sediment conduits (Figures 9b and 9c); and finally (vi) they typically show downstream increases
527 of both channel width and cross-sectional area similarly to most of rivers (Figures 11a, 11c and 12a),
528 although unlike rivers they do not present an increase in depth (Figure 11b).

529 Although they are the overall smallest submarine sediment conduit type, submarine leveed
530 channels remain one order of magnitude wider and deeper than fluvial sinuous channels (i.e., Figures 11,
531 12a). 90% of the sampled submarine leveed channels are between 100 and 2000 m wide and between 10
532 and 100 m deep (maximum bankfull depth). Submarine leveed channels are also four times wider than
533 rivers for a given mean depth, since their bankfull width is around 37 times the mean depth (Figures 10a
534 and 12a). This ratio is 1.5 times lower than proposed by Konsoer et al. (2013). This result likely reflects the
535 influence of the large proportion of submarine sediment conduits narrower than 1000 m in our study (40%)
536 compared to Konsoer et al. (2013) (5%) since small-size submarine sediment conduits (i.e., leveed channels)
537 have on average the highest aspect ratios (Figures 9d and 10a). Leveed channels presented in this study are
538 therefore relatively small elements in the hierarchy of the submarine realm. They are close to the unit
539 submarine sediment conduits building larger sedimentary bodies, similarly to individual sinuous streams in
540 alluvial plains. The relationships derived from leveed channels (Table 2 and Figure 12) thus provide the first
541 order trends in terms of morphometric parameter scaling, which may be used to calibrate submarine
542 leveed channel models, and to highlight (dis-)similarities of channel morphology depending on geological
543 settings (latitude, margin type, feeder system, sediment load) in natural systems.

544 Amplitude and wavelength of submarine leveed channel meanders are three times smaller than
545 those of fluvial meanders with respect to channel width (Figures 10b-10d and 12a) in agreement with data
546 from the Amazon fan (Pirmez and Imran, 2003). This reflects a reduced growth of meander interpreted as a
547 stabilization of the flow path, which is much less pronounced in fluvial channels (Peakall et al., 2000; Jobe
548 et al., 2016). Hence, similarly to alluvial sinuous rivers, this supports that curvature drives flow asymmetry
549 and migration of submarine leveed channels (Imran et al., 1999; Sylvester et al., 2011). The reduced growth
550 of submarine meander would then more likely be the result of either clay hysteresis in the upper flow
551 layers (Peakall et al., 2000), high vertical accretion rates (Jobe et al., 2016), or change of secondary
552 circulation patterns (Azpiroz-Zabala et al., 2017).

553



554

555 *Figure 12: Comparison of median geometry and morphometric scaling between sinuous fluvial and*
 556 *submarine leveed channels.*

557

558 Morphometric scaling also reflects channel and flow dynamics as shown for fluvial systems. Two
 559 main complementary theories explain the relationships between alluvial river planform morphology, cross-
 560 sectional geometry, and bankfull discharge. On the one hand, the stability analysis of Parker (1976) defines
 561 a single-thread to braided channel transition criterion, which may be observed experimentally (Foreman et
 562 al., 2015). On the other hand Lacey's law considers that channel dimensions adapt to flow and sediment
 563 discharges as long as the banks are maintained at their threshold of sediment motion (Lacey, 1930;
 564 Métivier et al., 2017 and references therein). As such, channel width, mean depth, and the inverse of bed
 565 slope are linked together and proportional to the square root of flow discharge. The relationships between
 566 submarine leveed-channel cross-sectional parameters and slope indicate that these parameters are
 567 correlated in a manner similar to fluvial systems, although with the noticeable exception of channel depth
 568 (Figure 11). The latter may evolve non-monotonically with bed slope, which could tentatively be related to
 569 a loss of confinement for distal turbidite flow (see next section). Equilibrium between submarine channel
 570 geometry and flow discharge was hypothesized by several studies (Janocko et al., 2013a; Konsoer et al.,

571 2013; Traer et al., 2018). For instance, Konsoer et al. (2013) assumed that the shift observed between
572 fluvial and submarine datasets is explained by the differences in terms of driving force and used this shift to
573 estimate submarine flow concentration and velocity. This study thus supports their initial assumption for
574 channel area and width, but not for depth (Figure 11). Consequently, concentration, velocity and then flow
575 discharge can be better estimated using the driving force from channel width or area. In addition,
576 submarine leveed channels significantly differ from the other submarine conduits according to the depth
577 ratio equal to 1.7 (Table1, Figure 9e), which is roughly equivalent to the depth ratio according to the Lacey's
578 law ($\pi/2$). The fact that such scaling applies in the submarine realm as well further supports similar channel-
579 formative processes.

580 This result suggests that the fluvial concept of channel-forming discharge (Wolman and Miller 1960;
581 Blom et al., 2017 and references therein) may be transposed to submarine systems. Following the fluvial
582 definition, the submarine channel-forming discharge corresponds to the steady discharge that provides the
583 same channel geometry as the succession of intermittent and varied submarine flows. This concept can be
584 used for instance to simulate the long-term evolution of submarine channels by inferring their channel-
585 forming discharge from their geometry (Lemay, 2018).

586 **4.2.2. Downstream evolution of submarine leveed channel geometry**

587 Similarly to alluvial sinuous rivers, the size of submarine leveed channel sections increases
588 downstream as shown by the small negative correlation of width and cross-sectional area with channel
589 slope (Figures 11a and 11c). There is however no correlation between channel depth and slope, which
590 could be due to a non-monotonous relationship (Figure 11b). This contrasts with observations from studies
591 dealing with individual systems, which most often show constant or decreasing cross-sectional dimensions
592 downstream (Shumaker et al., 2018). Although these studies include the width of composite conduits and
593 not only that of unit channels in the upstream part of submarine systems, they reflect the complexity of the
594 submarine leveed channel geometry evolution. The present compilation may miss this complexity because
595 it is a worldwide set, which does not capture slope variations along a given system. Other phenomena may

596 be also at play such as the downstream decrease of levee thickness as pointed by Skene et al. (2002) on six
597 submarine systems and by Shumaker et al. (2018) on the Bengal system.

598 Perennial alluvial rivers used in the fluvial database are tributary systems, in which discharge
599 increases downstream while slope decreases (Held, 2011 and references therein) and channel dimensions
600 proportionally increase (Leopold and Maddock, 1953; Williams, 1978). In contrast, most submarine leveed
601 channels in our database belong to distributary systems. Similarly to the fluvial systems, submarine channel
602 slope decreases downstream, but conversely submarine flow discharge is most likely to decrease due to
603 flow overspill and sediment deposition (Hiscott et al., 1997; Konsoer et al., 2013; Traer et al., 2018). Hence,
604 without discharge contribution from tributaries, long-running submarine flows increase their width and
605 area as they migrate towards the abyssal plains (Figures 11a, 11c), a behavior that does not follow that of
606 fluvial systems.

607 This apparent contradiction with the Lacey's law can be explained as follow. Contrarily to fluvial
608 systems where the flow discharge is not affected by the sediment load (Konsoer et al., 2013), submarine
609 flows grow because of sediment entrainment from the bed (Parker et al., 1986; Garcia and Parker, 1993).
610 This phenomenon is observed particularly for supercritical currents initiated on steep slopes such as the
611 continental slope, but becomes less significant for subcritical currents flowing on gentle slopes in the distal
612 part of submarine systems (Pirmez and Imran, 2003). In this case, numerical simulations (Dorrell et al.,
613 2014; Luchi et al., 2018) –confirmed by natural observations (Paull et al., 2018)– invoked the role of flow
614 stratification to create a steady coarse-grained basal driving layer overlaid by a dilute fine-grained driven
615 layer. This steady coarse-grained basal driving layer defines the submarine flow forming discharge in the
616 sense of Wolman and Miller (1960), which controls submarine leveed channel dimensions according to the
617 threshold theory (Métivier et al., 2017). Consequently, a roughly constant or slowly decreasing discharge –
618 corresponding to the basal layer– may be maintained for long distances inside the channel, while the upper
619 layer progressively vanishes due to flow overspill (Hiscott et al., 1997; Konsoer et al., 2013; Traer et al.,
620 2018). This results in downstream decrease of levee height (Skene et al., 2002) and then loss of
621 confinement (Shumaker et al., 2018). Flow overspill is also responsible for the loss of the finest sediments

622 leading to coarsen the sediment load and levee deposits (Dorrell et al., 2014; Dennielou et al., 2017); this
623 contributes to reduce flow and bank cohesion, as well as sediment friction angle. Both effects result in
624 down-slope channel aspect ratio increase and potentially channel widening (Figures 11a and 11d) favoring
625 the development of a braiding pattern (e.g., Foreman et al., 2015) and/or ultimately to the building of
626 terminal lobes in the lower fan.

627 **5. Conclusions**

628 This study used an extensive dataset based on available publications to analyze the geometry and
629 dynamics of modern submarine sediment conduits. We defined a new classification of submarine sediment
630 conduits into four types based on two geomorphic criteria: presence/absence of flanking levees,
631 composite/unit nature of the submarine sediment conduits. This scheme allows for a precise definition of
632 submarine canyons, valleys and channels either erosive or leveed. Morphometric parameters of these
633 submarine sediment conduits were measured according to a survey methodology adapted from the fluvial
634 one.

635 We found that:

- 636 - (1) the continental margin strongly controls submarine sediment conduit geomorphology, long-
637 lived, mostly erosive, composite submarine sediment conduits being located on the continental
638 slope, and short-lived, mostly constructive, unit channels in the basin floor;
- 639 - (2) submarine unit leveed channels form a statistically significant and consistent group of
640 constructive, smaller and lateral mobile sediment conduits;
- 641 - (3) submarine unit leveed channels display planform and cross-sectional morphometric
642 relationships the most similar to alluvial sinuous rivers. Consequently, submarine unit leveed
643 channels are the most analogous to alluvial sinuous rivers;
- 644 - (4) without discharge contribution from tributaries, long-running submarine flows can increase
645 their width and area as they migrate towards the abyssal plains similarly to rivers. The latter

646 can be explained by the progressive flow deconfinement, loss of overspill-related bank and flow
647 cohesion, and associated decreasing friction angle.

648 Finally, the classification associated with the distributions of submarine sediment conduits can be
649 used to infer paleo-environments. These laws and the morphometric relationships provide the first order
650 trends in terms of parameter scaling, which may be used to calibrate submarine channelized system
651 models.

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658

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