



The Ogooue Fan (Gabon): a modern example of deep-sea system on a complex sea-floor topography

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Abstract. The Ogooue deep-sea Fan located in the northeastern part of the Gulf of Guinea expands over more than 550 km

10 westwards of the Gabonese shelf and passes through the Cameroun volcanic line. Here are presented the first study of

11 acoustic data (multibeam echosounder and 3.5 kHz seismic data) and piston cores covering the deep-sea part of this West

12 African system. This study led to the construction of the sedimentary processes map of this area. The overall system

13 corresponds to a well-developed mud-sand rich deep-sea fan, fed by the Ogooue River 'sedimentary load. This system

14 presents the typical morphological elements of clastic slope apro utary canyons, distributary channel-levees systems

15 and lobes elements. However, variations on the slope gradient cumulated with the presence of numerous seamounts, 16 including volcanic islands and mud volcanoes, led to a more complex fan architecture and sedimentary facies distribution.

17 In particular, turbidity currents derived from the Gabonese shelf deposit across several interconnected sedimentary sub-

18 basins located on the low gradient segments of the margin. The repeated spill-overs of the most energetic turbidite flows

19 have notably led to the incision of a large distal valley connecting an intermediate sedimentary basin to the more distal

20 lobe area. The sedimentary facies repartition over the fan indicates that pelagic to hemipelagic sedimentation is dominant
 21 across the a bistribution and thickness of turbidite sand beds is highly variable along the system, however turbidite

sands preferentially deposit in the bottom of channel-levee systems and on the most proximal depositional areas. The most

- distal depocenters receive only the upper parts of the flows, which are composed of fine-grained sediments. The Ogooue
- 24 deep-sea system is predominantly active during periods of low sea-level because canyon heads are separated from terrestrial
- 25 sediment sources by the broad shelf. However, the northern part of this system appears active during sea-level highstands.

26 This feature is one deeply incised canyon, the Cape Lopez canyon, located on a narrower part of the continental shelf has

- a different behaviour and receives sediments transported by the longshore drift.
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29 Keywords: Ogooue Fan, Gulf of Guinea, complex seafloor morphology, turbidity currents, sedimentary processes

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37 1 Introduction

- pgooue Fan is a turbidite system that develops along the central part of the Gabonese margin. Since the Neogene, the 38 West African margin has recorded deep clastic sedimentation forming vast and thick turbidit 39 denudation of the African contine here deep-sea fans are localized at the outlet of the main rivers, such as the Niger, 40 41 Congo, Ogooue or Orange River (Anka et al., 2009; Mougamba, 1999; Séranne and Anka, 2005). Due to the presence of 42 important petroleum resources in late Cretaceous and early Tertiary clastic reservoir formations, fed by Albian to Turonian 43 source rocks, the geology of the equatorial West African margin province has been widely studied since the early 70's 44 (Brownfield and Charpentier, 2006). Simultaneously, studies of the recent sediment dispersal pattern along this margin 45 have been initiated (Heezen et al., 1964; Weering and Iperen, 1984). These studies of recent and still active systems offers 46 the possibility to observe the continuity between the different features of deep-sea turbidite systems but also to understand 47 the processes and constraints that govern the construction of such sedimentary systems and the facies distribution. 48 Such studies have benefited from the improvement of acquisition tools such as multibeam echosounding and very-high 49 resolution seismic but also from increased frequency of oceanographic cruises allowing to obtain a better cover on the 50 seafloor. In the Gulf of Guinea, many studies focused on the recent Niger (Deptuck et al., 2007, 2003) and the Congo 51 systems (Babonneau et al., 2002; Droz et al., 2003, 1996). On the contrary, the Quaternary sediments of the Gabon passive
- 52 margin have been relatively poorly studied and the Ogooue deep-sea turbidite system, resulting from the sediment
- 53 discharge of the Ogooue River, remained for long uninvestigated especially in its deepest parts (Bourgoin et al., 1963;
- 54 Giresse, 1969; Giresse and Odin, 1973).
- 55 The survey of the area by the SHOM in 2005 and 2010, thanks to the OpticCongo and MOCOSED cruises, provided the
- 56 first dataset on the Ogooue deep-sea turbidite system, from the continental shelf to the abyssal plain. In this paper, we
- 57 present the first study of the deep-sea Ogooue turbidite system that allows to provide the overall fan morphology as well
- 58 as its subdivisions but also to understand the sedimentary processes which are involved in the development of the observed
- 59 sedimentary structures. This study provides an opportunity to investigate a modern deep-sea fan which construction appears
- 60 largely controlled by bathymetric constrains and by palaeoenvironmental evolution of the West African margin





- 4°0'0"E 5°0'0"E 10°0'0"E 11°0'0"E 12°0'0"E 13°0'0"E 14°0'0"E 15°0'0"E 3°0'0"E 6°0'0"E 7°0'0"E 8°0'0"E 9°0'0"E а Africa Cameroon 3°0'0"N Gulf of 2°0'0"N Guinea Principe Equatorial Guinea Angola 1°0'0"N Basin Sao Tome Ogooue 0°0'0" Ogooue River basin 1°0'0"S Annobon 1 Ogooue 2°0'0"S Guinea turbidite Gabon Ridge system 3°0'0"S Congo Democratic Congo Republic 4°0'0"S Basin 100 200 km b m N М -800 Delta region Ogoou 400 Present day sea level Shelf 100 200 300 400 500 600 700 800 Margin 400 Canyons depth profile km depth profile -800 Continental upper slope (mean gradient 7 %) -1200 Ogooue River -1600 Continental lower slope Main tributaries N : Ngounie, M : Mpassa, I: Indivo -2000 (mean gradient 3 %) -2400 Bathymetry -2800 Continental rise (mean gradient <1.5 %) 0 m -3200 Ogooue River Batéké Drainage basin sands -3600 4000 Abyssal plain (mean gradient < 0.5 %) 5000 m
- 61 2 Geological setting



Fig. 1: a) The Ogooue sedimentary system from source (river and drainage basin) to sink (Quaternary turbidite system). b)
 Channel depth profile of the Ogooue River (blue) and its main tributaries (grey) and mean depth profile along the Gabonese
 margin.

66 The Ogooue Fan is located in the northeastern part of the Gulf of Guinea on the Gabonese continental slope. The system 67 develops on the Guinea Ridge, which separates the two deep Congo and Angola basins. This region is notably characterized 68 by the presence of several volcanic islands belonging to the Cameroon volcanic line (Fig. 1a). The development of the Ogooue Fan started during the Late Cretaceous post-rift phase and foll 69 the deposition of a thick Aptian evaporitic formation which created salt-related deformations of the margin sedimer ameron and White, 1999; Mougamba, 1999; 70 71 Séranne and Anka, 2005; Wonham et al., 2000). The quaternary Ogooue Fan extends westwards over 550 km through the 72 Cameroon volcanic line. Overall, the modern slope profile is concave upward, similar to that of many other passive 73 margins. The mean slope gradient evolves from 12% on the very upper slope to < 0.5 % in the abyssal plain (Fig. 1b). The 74 Gabonese continental shelf, which is relatively narrow, can be divided into two sub-parts: the south Gabon margin





presenting a SE-NW orientation and the north Gabon margin presenting a SW-NE orientation. T 75 76 shelf is located at 1°00 S. The South part of the margin is characterized by the presence of numerous parallel straight gullies 77 oriented perpendicular to the slope (Lonergan et al., 2013; Séranne and Abeigne, 1999). On the north Gabon margin, the 78 area located between 1°00 S and the Mandji Island is incised by several canyons that belong to the modern Ogooue turbidite system (Fig. 2a). North of the Mandji Island, the sea vere even summerous random pockmarks as well as sinuous pockmarks 79 trains. These features are interpreted as the results of fluid migration from shallow buried channels (Gay et al., 2003; Pilcher 80 81 and Argent, 2007). 82 The Ogooue turbidite system is supplied by the sedimentary load of the Ogooue River, which is third largest African freshwater source in the Atlantic Oce espite the relatively small size of the Ogooue River basin (215,000 km²), the 83 84 river mean annual discharge reaches 4,700 m³/s due to the wet equatorial climate prevailing on the drainage basin (Lerique 85 et al., 1983; Mahé et al., 1990). The Ogooue River flows on a low slope gradient in a drainage basin where very thick 86 lateritic soils develop over the Congo craton and Proterozoic orogenic belts (Séranne et al., 2008). The estuary area includes 87 several lakes (Fig. 1b) (Lerique et al., 1983). These features contribute to the mainly muddy composition of the particle load of the Ogooue River that is estimated between 1 and 10 M t/yr (Syvitski et al., 2005). The limited portion of sand 88 89 particles in the river originates mainly from the erosion of the poorly lithified Batéké Sands located on a 550-750 m-high 90 perched plateau that forms the easternmost boundary of the Ogooue watershed (Séranne et al., 2008) (Fig. 1a). On the shelf, recent fluviatile deposits consist of fine-grained sediments deposited at the mouth of the Ogooue River (Giresse and 91 92 Odin, 1973). The wave regime along the Gabonese coast causes sediments to be transported northward. Sedimentary 93 transport linked to longshore drift ranges between 300,000 m³/yr and 400,000 m³/yr (Bourgoin et al., 1963) and is 94 responsible for the formation of the Mandji Island, a sandy spit of 50 km long located on the northern end of the Ogooue 95 Delta (Fig. 2a). Except for the Cape Lopez canyon, located just west of the Mandji Island and which head reaches only

96 5 m water depth (Biscara et al., 2013), the Ogooue turbidite system is disconnected from the Ogooue delta during the

97 present-day high sea-level.







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Fig. 2: (a) Detailed bathymetric map of the Ogooue Fan, based on the multibeam echosounder data of the Optic Congo2005 and
 MOCOSED2010 surveys. (b) Acoustic imagery of the Ogooue Fan (high backscatter: dark tones; low backscatter: light tones).

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¹⁰¹ Detail A: close-up of the deepest part of the Ogooue Fan. Red crosses: location of the studied cores.





104 **3 Material and method**

The bathymetry and acoustic imagery of the studied area result from the multibeam echosounder (Seabat 7150) surveys 105 conducted onboard the R/V "Pourquoi Pas?" and "Beautemps-Beaupré" during the MOCOSED 2010 and OpticCongo 106 107 2005 cruises (Guillou, 2010; Mouscardes, 2005) (Fig. 2a). The multibeam backscatter data (Fig. 2b) has been used to 108 characterize the distribution of sedimentary facies along the margin. Changes in the backscatter values correspond to 109 variations of the nature, the texture and the state of sediments and/or the sea-bed morphology (Hanquiez et al., 2007; 110 Unterseh, 1999). On the multibeam echosounder images, lighter areas indicate low acoustic backscatter and darker areas 111 indicate high backscatter. Five main backscatter types are identified on the basis of backscatter values and homogeneity 112 (Fig. 2b). Facies A is a homogeneous low backscatter facies, Facies B is a low backscatter heterogeneous facies, facies C 113 is a medium backscatter facies characterized by the presence of numerous higher backscatter patches. Facies D and E and 114 respectively high and very high backscatter facies. High backscatter lineations are present within facies D. 115 4,500 km of 3.5 kHz seismic lines were collected in the area of the Ogooue Fan during the MOCOSED 2010 cruise and 116 470 km during the Optic Congo 2005 cruise. These data were used to analyze the near-surface deposits. The dataset covers 117 the shelf edge, the slope and the abyssal plain. In this study, the 3.5 kHz echofacies has been classified according to 118 Damuth's methodology (Damuth, 1980, 1975; Damuth and Hayes, 1977) based on acoustic penetration and continuity of 119 bottom and sub-bottom reflection horizons, micro-topography of the seafloor, and presence of internal structures. 120 The twelve Küllenberg cores presented here were collected during the cruise MOCOSED 2010. Five of these cores have 121 already been presented in (Mignard et al., 2017) (Table 1). Visual descriptions of the cores distinguished the dominant 122 grain size (clay, silty clay, silt, and fine sand) and vertical successions of sedimentary facies. Thin slabs were collected for 123 each split core section and X-ray radiographed using a SCOPIX digital X-ray imaging system (Migeon et al., 1998). 124 Subsamples were regularly taken in order to measure carbonate content using a gasometric calcimeter and grain size using 125 a Malvern Mastersizer S. The stratigraphic framework is based on the previous work of (Mignard et al., 2017)), new AMS ¹⁴C dating and facies correlation to determine the boundary between Marine Isotopic Stage 1 (MIS1) and Marine Isotopic 126 Stage 2 (MIS2). Indeed, the transition from MIS2 to MIS1 is in the south-west Atlantic is marked by an abrupt increase in 127 128 carbonate content (Jansen et al., 1984; Olausson, 1984; Volat et al., 1980; Zachariasse et al., 1984). This feature is recorded 129 in all the deepest cores of this study (Fig. 3). 130 131 132 133 134 135

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144 Table 1: Core characteristics.

Core	Depth (m)	Latitude	Longitude	Length (m)
KC01	3504	00°57,010' S	005°31,806' E	12,96
KC02	4109	00°13,525' S	004°07,620' E	12,76
KC10	3148	00°56,666' S	006°39,809' E	11,54
KC11	3372	00°52,008' S	006°00,008' E	9,92
KC13	2852	00°32,508' S	007°08,589' E	7,62
KC14	3140	00°25,010' S	006°36,006' E	11,34
KC15	3850	00°49,996' S	004°50,009' E	12,01
KC16	3738	01°05,003' S	004°52,010' E	11,48
KC17	565	00°51,188' S	008°29,377' E	8,20
KC18	366	01°01,940' S	008°25,409' E	7,99
KC19	1610	00°41,593' S	008°18,592' E	10,03
KC21	2347	00°13,004' S	008°00,011' E	11,81

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148 KC21 KC18 KC17 KC19 KC13 KC14 KC10 KC11 KC01 KC16 KC15 KC02 0 12,135 31,080 2 3 32,350 4 7.532 5 Depth (mbsf) 6 7 41,100 8 9 Fine sand Fine sand Medium sand Mec 10 Sediment facies Facies 1 : Homogenous marly ooze 11-Facies 2 : Homogeneous structurless clay 12-Facies 3 : Thick homogeneous silty-clay Facies 4 : Sandy layers MIS2 - MIS1 boundary 13 Facies 5 : Disorganised sandy clays Volcanoclastic debris 149

Fig. 3: Sedimentological core logs from the Ogoce Din, showing grain-size variation, lithology and bed thickness (location of
 cores are presented in Fig. 2). Ages are from ¹⁴C dating (dates with a star are from (Mignard et al., 2017).





153 4 Results

154 4.1 Sedimentary facies

155 The classification in five sedimentary facies used here is based on photography and X-ray imagery; grain size analyses and

156 CaCO₃ content (Fig. 3). Interpretation of these facies is based on the comparison with previous sedimentary facies 157 classifications such as (Normark and Damuth, 1997; Pickering et al., 1986; Stow and Piper, 1984).

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- 159 Facies 1: Homogenous, structureless marly ooze. This facies is composed of structureless, light beige marly ooze with
- 160 relatively high concentration in planktonic foraminifers. The mean grain size is around 15 μ m and the CaCO₃ content
- 161 ranges between 40 and 60 %. This facies is interpreted as a pelagic drape deposits; it forms the modern seafloor of the
- 162 deepest part of the Ogooue Fan and is observed in the majority of the cores top corresponding to the MIS 1 interval.
- 163 Facies 2: Homogenous, structureless clay: Facies 2 consists of dark brown clay. The mean grain size is less than 15 µm
- and the CaCO₃ content is less than 30 %. This facies has been interpreted as hemipelagic drape deposits.
- 165 Facies 3: Thick, homogeneous silty-clay: Facies 3 consists of very thick homogeneous dark silt-clay layers containing less
- 166 than 10% of CaCO₃. This facies contains numerous quartz, micas, and plant debris indicating a continental origin of the
- 167 sediments. It results from the deposition of the fine-grained suspended load coming from the Ogooue River and flowing
- 168 down the slope or belonging to the upper term of turbidite gravity flows.
- 169 Facies 4: Silty to sandy layers: Facies 4 consists of fine to medium sand beds with a thickness up to several meters. They
- 170 display a variety of bedding structures: normally-graded or massive. The composition varies from terrigenous (quartz and
- 171 mica) to biogenic (foraminifera), some sequences are highly enriched in organic debris (Mignard et al., 2017). They are
- 172 interpreted as being deposited by turbidity currents initiated on the Gabonese continental shelf. Four sequences samples in

173 core KC01 present a high concentration of volcaniclastic debris, such particles are completely absent of all the other

- 174 sequences (Fig. 3). This specific composition and the location of the core suggests that these sequences originate from the
- 175 close Annobon volcanic island.
- 176 Facies 5: Disorganized sandy clays: Facies 5 consists of thick intervals of deformed or chaotic clay with deformed or
- 177 folded silty to sandy layers. This facies is interpreted as resulting from mass transport deposits (slump or debris flow),





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1784.2Fan morphology



Fig. 4: Interpreted gradient-shaded map of the Ogooue Fan showing the main features of the turbidite system. A, B, C, D, E and F are the six main channels discussed in the text. The sand/shale ratio of the cores are shown (Sa:Sh) as well as the maximum sand-bed thickness in each core (max sand).

Analysis of the sub-surface ta (bathymetry and acoustic imagery) reveals the different domains of the Ogooue sedimentary system and the different architectural features of the Ogooue Fan (Fig. 4).

185 The Gabon shelf is relatively narrow decreasing in width from 60 to 5 km toward the Mandji Island. The slope is

186 characterized by two main topographic elements: (1) the presence of the Mount Loiret, an inactive submarine volcano just

west of the Manji Island, which forms a bathymetric obstacle on the upper slope and (2) a ramp of several tributary canyons
located south of the Mount Loiret. This ramp is composed of ten major canyons, which deeply incise the shelf, and ten

thinner and shallower incisions, which do not reach the shelf break. The continental shelf and the slope present low backscatter values except for the canyons, which appear with very-high backscatter value.

191 The transition between the continental slope and the continental rise, between 1,200 and 1,500 m water depth, is marked

by a decrease in the slope gradient from more than 4% to 1.5%. At this water depth, several canyons merge to form five

193 mean k channels (B to F in Fig. 4). These channels appear with higher backscatter value than the surrounding seafloor

194 (Fig. 2b). These highly sinuous and meandering subparallel channel-levees complexes extend down to 2,200 m water depth

195 with a general course oriented toward the north-west (Fig. 5). At 2,200 m water depth, the southernmost channel (channel

196 F in Fig. 4) deviates its path toward the south-west.







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198Fig. 5: Detailed Bathymetric map of channel D (location in Fig. 2) and serial bathymetric profiles showing the evolution of the199channel-levees along the slope.

200 Downslope, on central part of the system, the seafloor located between 2,200 m and 2,500 m water depth, presents 201 numerous erosional features like scours, lineations and secondary channels (Fig. 4). These erosional features appear on a 202 very gentle slope area (0.6%) characterized by an heterogeneous medium backscatter facies (Fig. 2b). At 2,500 m water 203 depth, just south of the Sao Tomé Island, the head of a large, 100 km-long, distal valley appears (Fig. 6). This valley can 204 be divided in two parts of approximately equal length with two different orientations. The upper part of the valley is 205 oriented E-W whereas the lower part is oriented NE-SW. This direction change is due to the presence of a rocky seamount 206 located north of the valley and which deflects its course. The first half of the valley is up to 15 km wide with numer (us) 207 erosional scars and terraces on its flanks. Its bottom, characterized by very high backscatter value, presents, small internal 208 erosion channels. Downstream, the valley becomes narrower with a "U" shape (Fig. 6, profile 5), its flanks appear regular 209 with no scar of down-flank mass deposits. The depth of the valley decreases from 60 m in its central part to only 10 m near 210 its mouth. The area located south of the distal valley is characterized by a heterogeneous low-backscatter facies. Some 211 erosional features and secondary channels are present but scarce.







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Fig. 6: (a) Shaded bathymetry of the distal valley of the Ogooue Fan between 2,700 and 3,400 m water depth; b) Interpretation of the main morphological features of the valley; c) Six transverse profiles of the distal valley extracted from the bathymetry data.

West of the distal valley outlet, the seafloor is very flat and shows only subtle morphological variations except for local seamounts (rocky mounts and mud volcanoes). Few channel-like, narrow elongated depressions (maximum 10 m deep) presenting high backscatter values can be identified. These lineations are restrained to a long tongue of high backscatter that develops at the mouth of the valley (Fig. 2b, Detail A). This tongue is globally oriented E-W at the exit of the distal valley and then deflects toward the NW at 3,700 m water depth, following the steepest slope.
North of mount Loiret, the upper slope presents a lower slope gradient compared to the south part and is characterized by

North of mount Loiret, the upper slope presents a lower slope gradient compared to the south part and is characterized by 222 the presence of numerous linear pockmark trains on the upper part and random pockmarks fields on the lower part. These 223 pockmarks have been previously described in (Pilcher and Argent, 2007). This whole area appears with a very low and 224 homogeneous reflectivity. Trace of active sedimentation on this part of the margin is only visible in association with the 225 Cape Lopez Canyon, which is the only canyon located north of the Mount Loiret. This canyon is associated with a small 226 d lobe located just north of the Mount Loiret and referred as the Cape Lopez lobe (Biscara et al., 2011). This northern المريك 227 system is continued by Channel A which head is located in the vicinity of the Cape Lopez Lobe. At 2,200 m water depth, 228 Channel A ends and its mouth is associated on the backscatter map with a fan-shaped area of very-high reflectivity which 229 is associated with some secondary channels and erosional marks (Fig. 2b).

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235 4.3 Echofacies analysis and distribution

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238 Fig. 7 : Echofacies map of the Ogooue Fan. Each shade of grey represents a specific echofacies.

Height main seismic facies have been discriminated on the profiles based on amplitude, frequency and geometry of the

240 reflections (Fig. 7). They have been grouped into five main classes: (I) bedded, (II) bedded-rough, (III) rough, (IV)

- transparent and (V) hyperbolic. Although a few transitions between echofacies are sharp, most of them are gradual.
- 242 The echofacies of the edge of the Gabonese shelf consists of rough echofacies III (Fig. 7). Core KC18 indicates that this
- 243 area is dominated by fine-grained terrigenous sedimentation.





North of the Mount Loiret, the continental slope presents bedded echofacies I which evolves into echofacies I' down isobath 1,500 m which corresponds to an increase of the slope gradient. Bedded echofacies are commonly associated with hemipelagic sedimentation or with the alternation of hemipelagic sediments with gravity flow deposits (Damuth, 1980, 1975; Loncke et al., 2009). The very low reflectivity of the area and the absence of any channel both suggest that only hemipelagic sedimentation occurs in this area. The wavy aspect of echofacies I' could be due to creeping.
South of Mount Loiret, echofacies II and II' dominate on the continental slope. Despite the lack of sampling, the presence

250 of semi-prolonga المسلو ismic reflectors can indicate the presence of coarse sediment. The echo-mapping of the continental 251 rise reveals the presence of different facies. The central part, just upstream of the distal valley, is characterized by rough 252 echofacies III that suggests the presence of coarse sediment. Some large channels are marked by hyperbolic facies certainly 253 due to the irregular and steep seafloor. South of the distal valley, facies II dominates. Core KC10, collected in this area, 254 indicates the alternation of clayey and sandy layer but with a predominance of fine-grained sediments (Fig. 3 Fig. 4). 255 Echofacies IV is present in two main areas on the continental rise; they respectively form two lobe-shaped zones: one on 256 the northern part, following the limits of the high-reflectivity area located at the mouth of channel A; the second in the 257 southern part of the system in association with channel F. This echo-facies commonly corresponds to massive deposits 258 without internal organization for KC21, collected in the northern area indicates homogeneous silty-clay sediments 259 similar to those collected near the continental shelf.



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261 Fig. 8 : a) Transverse 3.5 kHz seismic line and b) line drawing in the upper distal lobe area, see Fig. 7 for location of the line.

262 On the abyssal plain, the area of the elongated tongue noticeable on the backscatter data presents different echofacies. 263 Based on the 3.5 kHz profiles, it can be subdivided into two main domains. The upstream part, at the outlet of the distal 264 valley, is characterized by rough echo character but with a specific organization: multiple aggradational stacked transparent 265 sub-units from 10 to 30 meters thick are visible on the seismic lines (Fig. 8). This organization is characteristic of sandy 266 lobes deposits. Core KC11, collected in this environment, presents several relatively-th (5) ndy layers and a several meter-267 thick disorganized sandy-clay sequence corresponding to slump deposit. The downstream part presents bedded-rough 268 echofacies (II) associated with hyperbolic echofacies (V). Core KC15 shows, mainly fine-grained sediments but recorded 269 also several silty layers corresponding to the distalmost turbidite deposits.

270 On the edge of this tongue, high-penetration bedded facies (I) is dominant. The very continuous parallel bedding indicates 271 hemipelagic sedimentation, which is confirmed by core KC16 and core KC02 both composed of alternating carbonate-rich 272 and carbonate-poor clay sediments. Facies V' forms some patches on the seafloor and correspond to seafloor mounts such

273 as mud volcanoes or rocky hills. The hyperbolic facies is due to the steep slopes and the irregular bathymetry.





- Facies V and IV are also present forming lenses around the island of Sao-Tomé and Annobon. These features indicates
- some downslope sedimentary transfer from these islands. The limited area covered by these facies suggests short transport
- by sliding.





290 5 Interpretation and discussion

291 5.1 Sedimentary processes along the fan



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Fig. 9: a) Synthetic map showing the architecture and the recent sedimentary processes of the Ogooue Fan determined by imagery and echofacies mapping; b) c) and d) Longitudinal profiles from the bathymetric data along the central, northern and southern part of the Ogooue Fan. The differences in slope gradient along the transects are associated with the main sedimentary processes encountered along the slope.

297 The Ogooue turbidite system is a passive-margin delta-fed deep-sea turbidite system and correspond to a mature mud/sand-

rich submarine fan according to the classification of (Reading and Richards, 1994). However, analysis of sub-surface data





(bathymetry, acoustic imagery and 3.5 kHz echo-characters) reveals a great variability of sediment processes in the different domains of the margin, controlled mainly by the variations in the slope gradient and the presence of seamounts(Fig. 9a).

302 Erosional processes seem to be predominant on the upper part of the slope as indicated by the presence of numerous straight

tributary canyons. Some of these canyons are deeply incised whereas others are much smale. These characteristics can indicate different ages for the canyons formations but also different types of formations processes. The morphology of the

solution and the second second

306 continental slope, whereas the deep incision of the others can by due to erosion by turbidity currents sourced from the 307 continental shelf (Shepard, 1981). These two processes are not mutually exclusive and are probably contemporaneous

308 along the slope.

The transition from canyons to meandering where he with developed levees is related to a decrease in slope gradient. The 309 meandering channel-levees systems develops on a relative gentle slove from 1,500 to 2,200 m water depth. These channels 310 are mainly erosive on their central part while deposition occurs on their sides (Normark et al., 1993). The level the four 311 312 central channels (B, C, D and E in Fig. 2) show high reflectivity evidencing the occurrence of turbidite overflow processes. The sinuosity of these channels is high in the upper segments and decreases westward (Fig. 5). Several studies have 313 documented that sinuosity of submarine channels increases with time (B) onneau et al., 2002; Deptuck et al., 2007, 2003; 314 315 Kolla, 2007; Peakall et al., 2000). The highly sinuous upper parts of the channels have consequently undergone a long 316 history whereas the distal straighter parts of the channels are in a more immature stage. Moreover, the height of the levees 317 and the depth of the channels both decrease in the lower parts of the system (Fig. 5). These morphological changes are due 318 to the slope that becomes gentler and progressively slows down the flow reducing its erosional power in the channel. 319 Simultaneously, deposition of fine particles by spilling of the upper part of the flow on the levees leads to a progressive

decrease of the fine-grained fraction transported by the channelized flows (Normark et al., 1993).

321 At 2,200 m water depth, the appearance of numerous erosional features such as isolated spoon-shaped scours, amalgamated 322 spoon-shaped scours erosional lineations and even secondary channel with tenuous surface expressional lineations and even secondary channel with tenuous surface expressional lineations and even secondary channel with tenuous surface expressional lineations and even secondary channel with tenuous surface expressional lineations and even secondary channel with tenuous surface expressional lineations and even secondary channel with tenuous surface expressional lineations and even secondary channel with tenuous surface expressional lineations and even secondary channel with tenuous surface expressional lineations and even secondary channel with tenuous surface expressional lineations and even secondary channel with tenuous surface expressional lineations and even secondary channel with tenuous surface expressional lineations and even secondary channel with tenuous surface expressional lineations and even secondary channel with tenuous surface expressional lineations and even secondary channel with tenuous surface expressional lineations and even secondary channel with tenuous surface expressional lineations and even secondary channel with tenuous surface expressional lineations and even secondary channel with tenuous surface expressions and even secondary 323 of the channel lobe transition zone (Jegou et al., 2008; Kenyon et al., 1995; Mulder and Etienne, 2010; Wynn et al., 2007). 324 The appearance of these features correlates with a second abrupt decrease of the slope and with the transition from bedded-325 rough to rough echo-facies indicating a change in the sedimentary process. This area corresponds to an unchannelized 326 deposition area referred as the intermediate depocenter in Fig. 9 and covering area surface of ca. 4,250 km². However, the 327 low penetration of the 3.5 kHz echosounder and the limited number of seismic lines in this area does not allow to obtain 328 an more detailed interpretation of the sedimentary processes in this part of the system.

329 The presence of a steeper slope downslope the intermediate depocenter led to the incision of the distal valley, which acts 330 as an outlet channel for turbidity currents that are energetic enough to travel through the previous flatter depositional area 331 (Fig. 9b). The upstream part of the valley is multi-sourced and migrates upstream by retrogressive erosion whereas the 332 downstream part appears more stable with a straighter pathway and steeper flanks. The pathway of the valley seems to be 333 highly controlled by the topography of the seafloor. This large distal valley corresponds to a single feeding "source" for 334 the lower fan and, consequently, the final depositional area is located downstream the valley. At the outlet of the distal 335 valley, the echofacies allows to distinguish an area mainly characterized by rough echofacies (III) forming stacked lenses. 336 This area, referred as the upper lobe area in Fig. 9, constitutes the main lobe complex of the Ogooue Fan. According to the 337 seismic data, this lobes depositional area is ~ 100 km long, reaches ~ 40 km in width, spreads over 2,860 km² and reaches 338 up to 40 m in thickness. The transparent lenses are interpreted as lobe elements and seem to be bounded by erosive bases





(Mulder and Etienne, 2010). Some incisions are imaged <u>at the surface</u> of the lobes; two of them are visible in Fig. 8. The area where incisions are present is interpreted as the channelized part of the lobe. This lobe area presents a gentle slope oriented north-south, suggesting that topographic compensation would shift southward the future lobe elements. However, the few numbers of seismic lines does not allow to precise the internal geometry and the timing of the construction of the different lobes units.

344 This depositional area is however not the distalmost part of the Ogooue Fan. Indeed, west of this lobe area, traces of active 345 sedimentation are visible on the reflectivity map (Fig. 2). The backscatter data shows high-backscatter finger-shape 346 structures organized like veins of a leaf suggesting perennial pathways of gravity flows (Fig. 2b, detail A). These lineations 347 are concentrated in a narrow 20 km wide corridor just west of the lobe area and then form a wider area extending up to 348 550 km offshore the Ogooue delta. This part of the system follows the same scheme as the one previously described 349 between the intermediate depocenter and the upper lobe area (Fig. 9b). Indeed the corridor appears on a segment of steeper 350 slope just at the downslope end of the upper lobe area. This corridor, which disappears when the slope becomes gentler, 351 was certainly formed by the repeated spill-over of the fine-grained top of turbidity currents over the upper lobe area. This 352 architecture suggests that this corridor is dominated by sediment erosion and transport. On the last segment with a very 353 low slope gradient sediment deposition dominates. 354 On the northern part of the slope, the isolated system composed of the Cape Lopez Canyon, Cape Lopez lobe, channel A 355 and northern lobe follows the same scheme (Fig. 9c). Indeed, the two successive depositional areas are located on an area 356 with a low slope-gradient whereas the erosion and bypass dominates on segments of steep slope-gradi 357 In the southern part of the fan, channel F transports sediments southward. At 2,200 m water depth, a transparent echofacies 358 appears associated with the pathway of this channel. This echofacies suggests that sediment transported by this channel 359 might be partly deposited in this area by turbidity current overflow. This channel might also be associated with a 360 depositional lobe; however, the area covered by the MOCOSED survey does not allow us to image it. 361 The Ogooue Fan presents a succession of depositional areas on segments with gentle slope (referred as 'steps' in (Smith, 2004)) and segments of steeper slow ociated with erosion or bypass (Fig. 9). The depositional behavior in such system 362 363 is guided by an equilibrium profile of the system that creates preferential areas of sedimentation or erosion (Ferry et al., 364 2005). Erosion is favored where local gradient increases, the eroded sediments being delivered downstream resulting in a 365 local increase in sediment load (Gee and Gawthorpe, 2006). This kind of fan geometry is common along the West African 366 margin where abrupt changes in slope gradient and complex seafloor morphology are inherited from salt tectonic movement 367 (Ferry et al., 2005; Gee et al., 2007; Gee and Gawthorpe, 2006; Pirmez et al., 2000). Moreover, in the case of the modern Ogooue Fan and unlike the Congo and Niger systems, the presence of several bathymetric highs including the volcanic 368 islands of the Cameroon Volcanic Line and the different mud volca constitute additional constraints for the flows. 369 370 These bathymetric highs deviate the pathways of different channels of the system as well as the pathway of the distal valley 371 and create several downslope depositional lobes. Such features are similar to the morphology of the Northwest African margin where the M 372 373 Wynn et al., 2002, 2007, This specific topography controls the distribution of sedimentary facies along the Moroccan and 374 Mauritanian margin and creates several interconnected depositional basins similarly to the different depositional areas of

the Ogooue Fan.





376 5.2 Sedimentary facies distribution

The main sedimentary processes that are involved in the deposition of the Upper Quaternary sediment of the Ogooue system are hemipelagic fall-out together with turbidity currents. Fine-grained pelagic/hemipelagic 'background' sedimentation is dominant across a large area of the margin, particularly on the lower rise and the adjacent basin plains. These sediments are then overprinted by downslope gravity flows such as turbidity currents. However, the previously described fan organization implies a specific repartition of the sedimentary facies and sand distribution within the system (Fig. 4).

383 Cores collected in the upslope area (KC18 and KC17) show mostly hemipelagic sediments with a very low proportion of 384 carbonate. This reflects significant detrital flux associated with proximity to the Ogooue platform and influences of the 385 Ogooue river plume. Core KC19 collected down the slope just at the transition from canyon to channel-levees complexes 386 show two several meters-thick sandy sequences corresponding to top-cut-out Bouma sequences (Ta) interbedded with the 387 upper slope hemipelagites. These sandy turbidites, which are the thickest sand beds recorded in all the cores (Fig. 4), 388 indicate the occurrence of high-density turbidity currents flowing down the canyons. The lack of the upper terms of the 389 turbidite is consistent with deposition in the canyon of coarse-grains located at the base of the turbidity currents, whilst the 390 finer upper part of the current is transported downstream or spills over the levees. Levee deposits have been sample by core 391 KC13, which shows numerous turbidites made up of centimeter-thick parallel or cross-bedded laminations, of silt and fine 392 $\sin(s_0)$ g. 3). Unfortunately, no core has been collected directly in the intermediate depocenter. However, the rough 393 echofacies III found in this area associated with various erosional features suggest a high sand/shale ratio.

394 The distal valley certainly acts mainly as a conduit for the sediments, transporting them further downstream. However, 395 core KC14, collected on an internal terrace of the valley, shows that this valley is also an area of active sedimentation 396 notably due to down-flank sliding. The bottom of the valley could thus be composed of slump deposits and coarse-grained 397 sediments deposited by gravity flows. Downstream the distal valley, core KC11 show that coarse-grained turbidites, are 398 deposited in the first part of the lobe area, The abrupt transitions between erosional/bypass and depositional behavior 399 observed notably at the mouth of the distal valley is the result of hydraulic jumps affecting flows when they become 400 unconfined between channel sides and spread laterally (Garcia and Parker, 1989; Komar, 1971). Core KC15, located in the 401 lower lobe area, is composed of very thin silty turbidites corresponding to the upper terms of the Bouma sequence 402 interbedded with hemipelagic deposits. The upper lobe area certainly acts as a trap for the basal sand-rich parts of gravity 403 flows. Consequently, only the upper part of the flows, which is composed of fine-grained sediments, travels beyond this 404 area. The observed facies spatial distribution suggests a filling of the successive depocenters with a downslope decrease of 405 the coarse-grained sediment proportion (Fig. 4). The same facies distribution can be observed in the northern system. 406 Indeed, no sandy turbidites are recorded in KC21, only fine-grained sedimentation, whereas the study of cores taken in the 407 Cape Lopez lobe shows the presence of numerous sandy turbidite (Biscara et al., 2011). The Northern lobe is thus fed by 408 the downslope spilling of suspended fines transported at the top of turbidity currents flowing through the Cape Lopez 409 Canyon.

410 Whatever the current pathways are, the deposited material has a continental origin as suggested by the abundance of quartz, 411 micas and plant debris in the coarse-grained fraction. The important proportion of planktic foraminifers in the coarse-412 grained fraction of turbidites located in the distal part of the system (core KC10- KC11- KC15) suggests that turbidity

413 currents previously eroded pelagic and hemipelagic deposits on the slopes located upflow where such deposits cover large

414 areas (Viana and Faugères, 1998). The presence of volcanoclastic debris in sandy layer found at the base of core KC01

415 suggests that sedimentary input may also come from the volcanic islands of Sao Tomé and Annobon. However, acoustic





416 data indicate that these inputs are limited to the close vicinity of the Sao-Tomé and Annobon islands. On the contrary, to

- 417 the model proposed by (Wynn et al., 2000) for the Northwest African slope, the volcanic islands and other seamounts
- 418 present on the Ogooue turbidite system act mainly as obstacles for the flow pathway but are not important sediment
- 419 suppliers for the deep-sea system.

420 5.3 Palaeoceanographic control on the fan activity

421 The results of Mignard et al. (2017) concerning the study of five cores located along the central part of the Ogooue fan 422 showed that the fluvial sediments fed this part of the system almost only during times of relative low sea-level. This eustatic 423 control on the turbidite activity (switch on/off behavior) is classical for mid and low latitude passive margin fans where 424 canyon heads are detached from terrestrial sediment sources (e.g. Mississippi Fan (Bouma et al., 1989), Amazon Fan (Flood 425 and Piper, 1997), Rhone Fan (Lombo Tombo et al., 2015), Indus Fan (Kolla and Coumes, 1987)). Conversely, 426 sedimentation during periods of relative high sea-level such as the Holocene, is dominated by hemipelagic to pelagic fall-427 out with a low part of fine terrigenous particles. Therefore, all cores collected in the central part of the system are capped 428 by 8 to 20 cm of light-brown nannofossil ooze corresponding to Holocene hemipelagic deposits (Fig. 3).

429 However, the northern part of the system appears to have a different behavior. (Biscara et al., 2011)) showed that the Cape 430 Lopez lobe is currently recording both hemipelagic and turbidite sedimentation despite the present-day high sea-level. This 431 lobe is fed in sediment by the Cape Lopez Canyon, which incises the shelf up to the extremity of the Mandji Island (Biscara 432 et al., 2013). The deep incision of the continental shelf up to the coast combined with the longshore sediment transport 433 along the Mandji Island and the narrow shelf in this area (4 km wide) favor the capture of sediment by this canyon during 434 time of high sea-level (Biscara et al., 2013; Reyre, 1984). The northern lobe, which is directly connected to the Cape Lopez 435 lobe by Channel A, appears to be also fed by terrigenous sediments during the Holocene. Core KC21, located at the entrance 436 of the northern lobe, is entirely composed of facies 3, even for sediments deposited during MIS1 (Fig. 3).

437 In the Ogooue Fan system, the shelf width between the littoral area and the canyon heads is the main control factor on the 438 fan activity. During periods of relative low sea-level, the canyons of the central part of the system receive sediment from 439 the river system that extended across the subaerially exposed continental shelf. During periods of relative high sea-level, 440 river sediments are unable to reach the canyon heads south of the Manji Island and accumulate on the continental shelf 441 close to the Ogooue delta. However, part of these sediments mixed with sediments coming from the south Gabon margin 442 are drift-transported and contribute to supply the Cape Lopez canyon and consequently the Cape Lopez and Northern Lobe. 443 Due to their specific location and favorable hydrodynamic conditions on the shelf, sedimentation on the Cape Lopez and 444 the Northern lobes is active during relative sea-level highstands, on the contrary to the rest of the Ogooue Fan. This type 445 of supply is similar to the activity of the California margin where the La Jolla canyon is fed by drift-transported sediments during highstand (Covault et al., 2011, 2007). 446

447 6 Conclusions

This study provides the first data on the morphology of the recent Ogooue deep-sea turbidite system and interpretations on sedimentary processes occurring in this environment. The whole system is a mature, mud/sand rich submarine fan globally organized upstream to downstream with canyons, then channel levee, then lobes. However, detailed study of acoustic data proved that inherited paleo-topography and topographic features such as the Sao-Tomé and Annobon volcanic Islands and other seamounts present in the area have significant effects on the distribution of sedimentary facies and morphological





453 elements of the system. The long-term interaction between gravity flows and the sea-floor topography have induced the 454 construction of successive depocenters and bypass areas. The gravity flows modified the topography according to a 455 theoretical equilibrium profile, eroding the seafloor when slopes are steeper than the theoretical equilibrium profiles and 456 depositing sediments when slopes are gentler than the theoretical equilibrium profile. Three successive sediment 457 depocenters have thus been identified along a longitudinal profile. They are associated with three areas of low slope The two first deposition areas - the intermediate depocenter and the upper lobe area- recorded coarse-grained 458 gradi(nt.) 459 sedimentation and are connected by a well-developed large distal valley measuring 100 km long. The distalmost depocenter 460 - the lower lobe area - received only the fine-grained portion of the sediment load that has bypassed the more proximal 461 deposit areas. The presence on the slope of the Mount Loiret has caused the formation of an isolated system composed of 462 the Cape Lopez canyon and lobe, which continues downstream by the Northern Lobe area. 463 The Ogooue Fan is currently in a low activity period since the recent Holocene rise of sea-level. Nowadays, the 464 sedimentation is mostly located on the Ogooue delta platform and on the upper slope. The turbidite system was most active 465 during the last glacial lowstand. Nonetheless, the northern part of the system appears to have an asynchronous activity with 466 the rest of the fan as this part is fed by the drift-transported sediments during time of relative high sea-level when the 467 activity in the rest of the system is shut-down.

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473 8 References

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