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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 westwards of the Gabonese shelf and passes through the Cameroun volcanic line. Here are presented the first study of acoustic data (multibeam echosounder and 3.5 kHz seismic data) and piston cores covering the deep-sea part of this West African system. This study led to the construction of the sedimentary processes map of this area. The overall system corresponds to a well-developed mud-sand rich deep-sea fan, fed by the Ogooue River 'sedimentary load. This system presents the typical morphological elements of clastic slope apron: tributary canyons, distributary channel-levees systems and lobes elements. However, variations on the slope gradient cumulated with the presence of numerous seamounts, including volcanic islands and mud volcanoes, led to a more complex fan architecture and sedimentary facies distribution. In particular, turbidity currents derived from the Gabonese shelf deposit across several interconnected sedimentary sub-basins located on the low gradient segments of the margin. The repeated spill-overs of the most energetic turbidite flows have notably led to the incision of a large distal valley connecting an intermediate sedimentary basin to the more distal lobe area. The sedimentary facies repartition over the fan indicates that pelagic to hemipelagic sedimentation is dominant across the area. Distribution 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 deep-sea system is predominantly active during periods of low sea-level because canyon heads are separated from terrestrial sediment sources by the broad shelf. However, the northern part of this system appears active during sea-level highstands. 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.

Keywords: Ogooue Fan, Gulf of Guinea, complex seafloor morphology, turbidity currents, sedimentary processes

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1 Introduction

The Ogooue Fan is a turbidite system that develops along the central part of the Gabonese margin. Since the Neogene, the West African margin has recorded deep clastic sedimentation forming vast and thick turbidite systems fed by the denudation of the African continent. These deep-sea fans are localized at the outlet of the main rivers, such as the Niger, Congo, Ogooue or Orange River (Anka et al., 2009; Mougamba, 1999; Séranne and Anka, 2005). Due to the presence of important petroleum resources in late Cretaceous and early Tertiary clastic reservoir formations fed by Albian to Turonian source rocks, the geology of the equatorial West African margin province has been widely studied since the early 70's (Brownfield and Charpentier, 2006). Simultaneously, studies of the recent sediment dispersal pattern along this margin have been initiated (Heezen et al., 1964; Weering and Iperen, 1984). These studies of recent and still active systems offers the possibility to observe the continuity between the different features of deep-sea turbidite systems but also to understand the processes and constraints that govern the construction of such sedimentary systems and the facies distribution.

Such studies have benefited from the improvement of acquisition tools such as multibeam echosounding and very-high resolution seismic but also from increased frequency of oceanographic cruises allowing to obtain a better cover on the seafloor. In the Gulf of Guinea, many studies focused on the recent Niger (Deptuck et al., 2007, 2003) and the Congo systems (Babonneau et al., 2002; Droz et al., 2003, 1996). On the contrary, the Quaternary sediments of the Gabon passive margin have been relatively poorly studied and the Ogooue deep-sea turbidite system, resulting from the sediment discharge of the Ogooue River, remained for long uninvestigated especially in its deepest parts (Bourgoin et al., 1963; Giresse, 1969; Giresse and Odin, 1973).

The survey of the area by the SHOM in 2005 and 2010, thanks to the OpticCongo and MOCOSED cruises, provided the first dataset on the Ogooue deep-sea turbidite system, from the continental shelf to the abyssal plain. In this paper, we present the first study of the deep-sea Ogooue turbidite system that allows to provide the overall fan morphology as well as its subdivisions but also to understand the sedimentary processes which are involved in the development of the observed sedimentary structures. This study provides an opportunity to investigate a modern deep-sea fan which construction appears largely controlled by bathymetric constrains and by palaeoenvironmental evolution of the West African margin.

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2 Geological setting

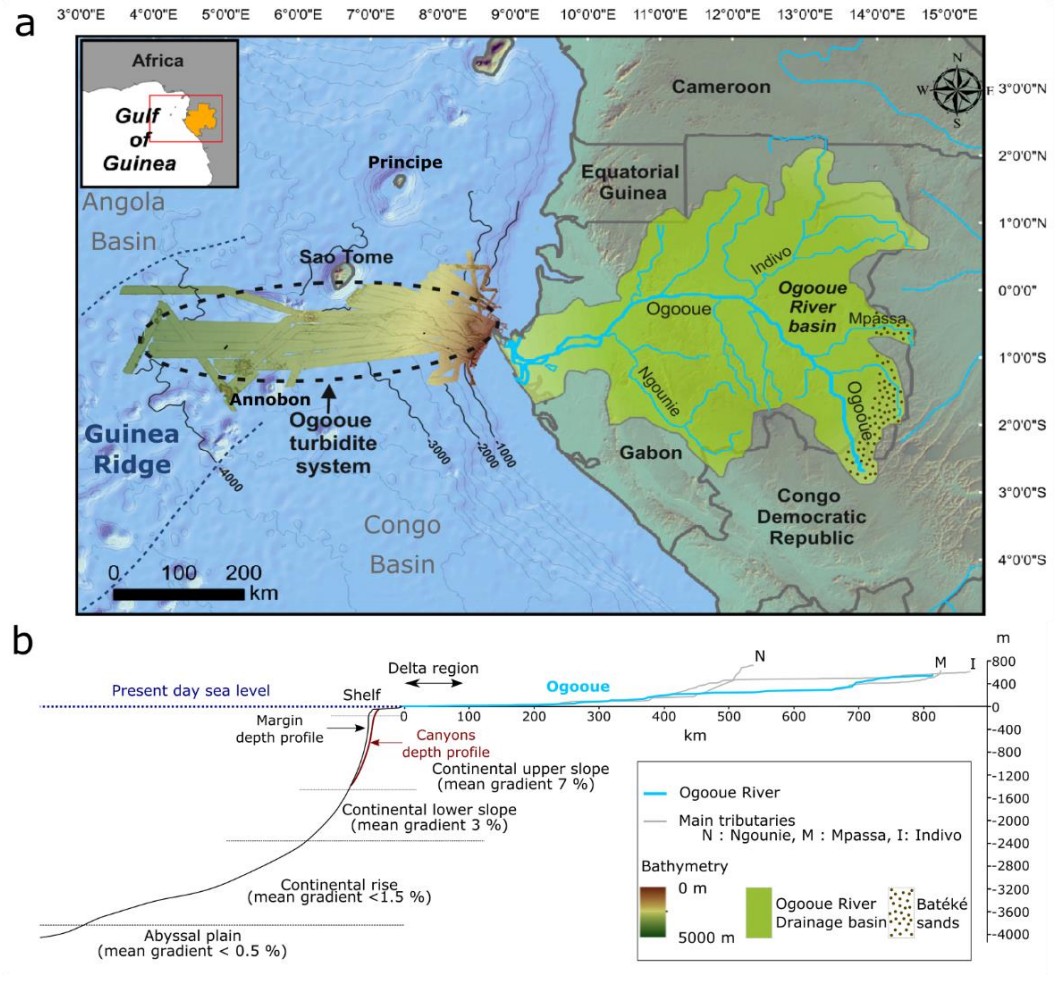

Fig. 1: a) The Ogooue sedimentary system from source (river and drainage basin) to sink (Quaternary turbidite system). b) Channel depth profile of the Ogooue River (blue) and its main tributaries (grey) and mean depth profile along the Gabonese margin.

The Ogooue Fan is located in the northeastern part of the Gulf of Guinea on the Gabonese continental slope. The system develops on the Guinea Ridge, which separates the two deep Congo and Angola basins. This region is notably characterized 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 followed the deposition of a thick Aptian evaporitic formation which created salt-related deformations of the margin sediments (Cameron and White, 1999; Mougamba, 1999; Séranne and Anka, 2005; Wonham et al., 2000). The quaternary Ogooue Fan extends westwards over 550 km through the Cameroon volcanic line. Overall, the modern slope profile is concave upward, similar to that of many other passive margins. The mean slope gradient evolves from 12% on the very upper slope to < 0.5 % in the abyssal plain (Fig. 1b). The Gabonese continental shelf, which is relatively narrow, can be divided into two sub-parts: the south Gabon margin

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presenting a SE-NW orientation and the north Gabon margin presenting a SW-NE orientation. The inflection point of the shelf is located at 1°00 S. The South part of the margin is characterized by the presence of numerous parallel straight gullies oriented perpendicular to the slope (Lonergan et al., 2013; Séranne and Abeigne, 1999). On the north Gabon margin, the 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 seabed reveals numerous random pockmarks as well as sinuous pockmarks trains. These features are interpreted as the results of fluid migration from shallow buried channels (Gay et al., 2003; Pilcher and Argent, 2007).

The Ogooue turbidite system is supplied by the sedimentary load of the Ogooue River, which is third largest African freshwater source in the Atlantic Ocean. Despite the relatively small size of the Ogooue River basin (215,000 km²), the river mean annual discharge reaches 4,700 m^3/s due to the wet equatorial climate prevailing on the drainage basin (Lerique et al., 1983; Mahé et al., 1990). The Ogooue River flows on a low slope gradient in a drainage basin where very thick lateritic soils develop over the Congo craton and Proterozoic orogenic belts (Séranne et al., 2008). The estuary area includes 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 particles in the river originates mainly from the erosion of the poorly lithified Batéké Sands located on a 550-750 m-high 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 Odin, 1973). The wave regime along the Gabonese coast causes sediments to be transported northward. Sedimentary transport linked to longshore drift ranges between 300,000 m^3/yr and 400,000 m^3/yr (Bourgoin et al., 1963) and is responsible for the formation of the Mandji Island, a sandy spit of 50 km long located on the northern end of the Ogooue Delta (Fig. 2a). Except for the Cape Lopez canyon, located just west of the Mandji Island and which head reaches only 5 m water depth (Biscara et al., 2013), the Ogooue turbidite system is disconnected from the Ogooue delta during the present-day high sea-level.

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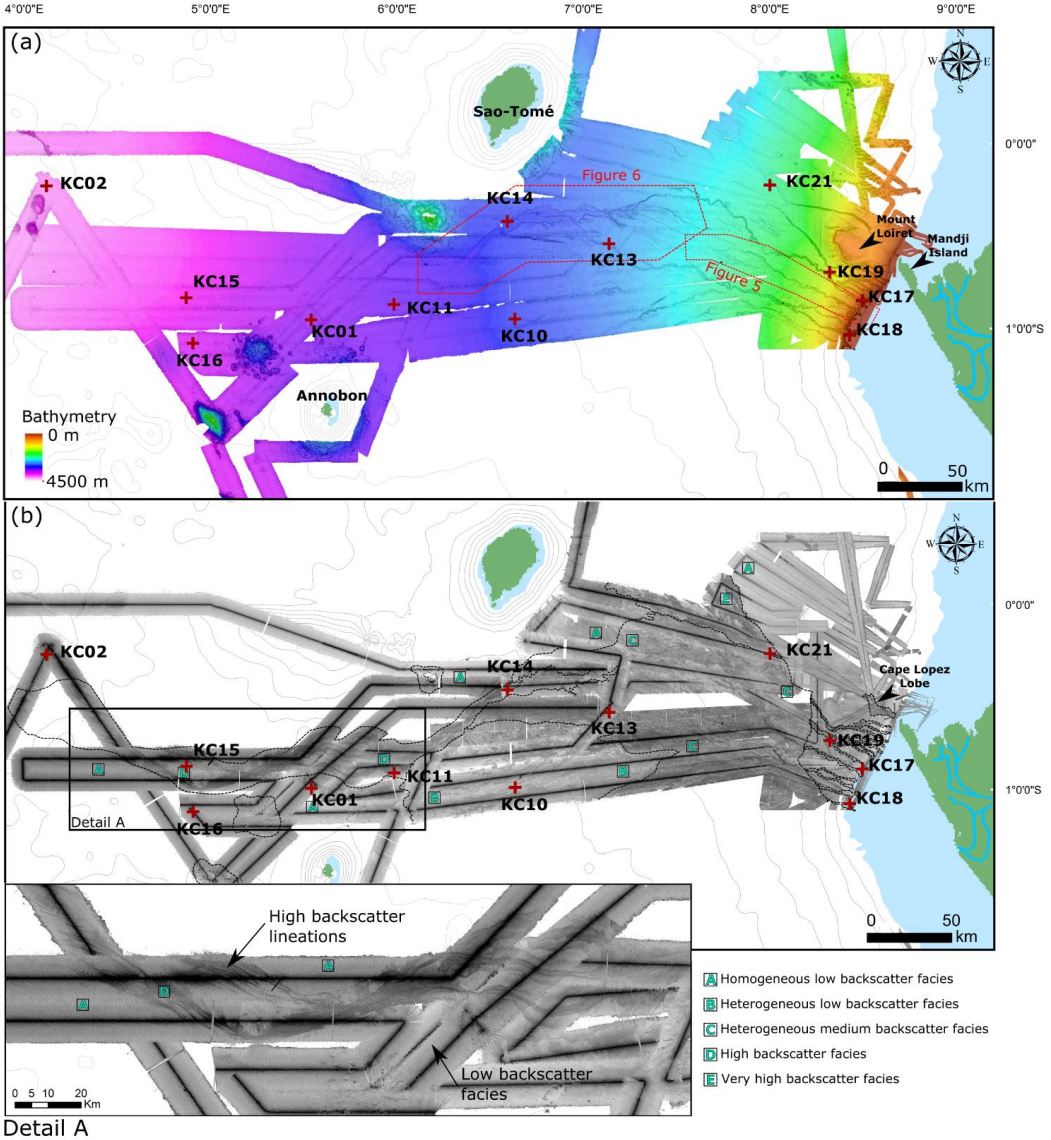

Detail A

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

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3 Material and method

The bathymetry and acoustic imagery of the studied area result from the multibeam echosounder (Seabat 7150) surveys conducted onboard the R/V "*Pourquoi Pas?*" and "*Beautemps-Beaupré*" during the MOCOSED 2010 and OpticCongo 2005 cruises (Guillou, 2010; Mouscardes, 2005) (Fig. 2a). The multibeam backscatter data (Fig. 2b) has been used to characterize the distribution of sedimentary facies along the margin. Changes in the backscatter values correspond to variations of the nature, the texture and the state of sediments and/or the sea-bed morphology (Hanquiez et al., 2007; Unterseh, 1999). On the multibeam echosounder images, lighter areas indicate low acoustic backscatter and darker areas indicate high backscatter. Five main backscatter types are identified on the basis of backscatter values and homogeneity (Fig. 2b). Facies A is a homogeneous low backscatter facies, Facies B is a low backscatter heterogeneous facies, facies C is a medium backscatter facies characterized by the presence of numerous higher backscatter patches. Facies D and E and respectively high and very high backscatter facies. High backscatter lineations are present within facies D.

4,500 km of 3.5 kHz seismic lines were collected in the area of the Ogooue Fan during the MOCOSED 2010 cruise and 470 km during the Optic Congo 2005 cruise. These data were used to analyze the near-surface deposits. The dataset covers the shelf edge, the slope and the abyssal plain. In this study, the 3.5 kHz echofacies has been classified according to Damuth's methodology (Damuth, 1980, 1975; Damuth and Hayes, 1977) based on acoustic penetration and continuity of bottom and sub-bottom reflection horizons, micro-topography of the seafloor, and presence of internal structures.

The twelve Küllenberg cores presented here were collected during the cruise MOCOSED 2010. Five of these cores have already been presented in (Mignard et al., 2017) (Table 1). Visual descriptions of the cores distinguished the dominant grain size (clay, silty clay, silt, and fine sand) and vertical successions of sedimentary facies. Thin slabs were collected for each split core section and X-ray radiographed using a SCOPIX digital X-ray imaging system (Migeon et al., 1998). Subsamples were regularly taken in order to measure carbonate content using a gasometric calcimeter and grain size using a Malvern Mastersizer S. The stratigraphic framework is based on the previous work of (Mignard et al., 2017)), new AMS ^{14}C dating and facies correlation to determine the boundary between Marine Isotopic Stage 1 (MIS1) and Marine Isotopic Stage 2 (MIS2). Indeed, the transition from MIS2 to MIS1 is in the south-west Atlantic is marked by an abrupt increase in carbonate content (Jansen et al., 1984; Olausson, 1984; Volat et al., 1980; Zachariasse et al., 1984). This feature is recorded in all the deepest cores of this study (Fig. 3).

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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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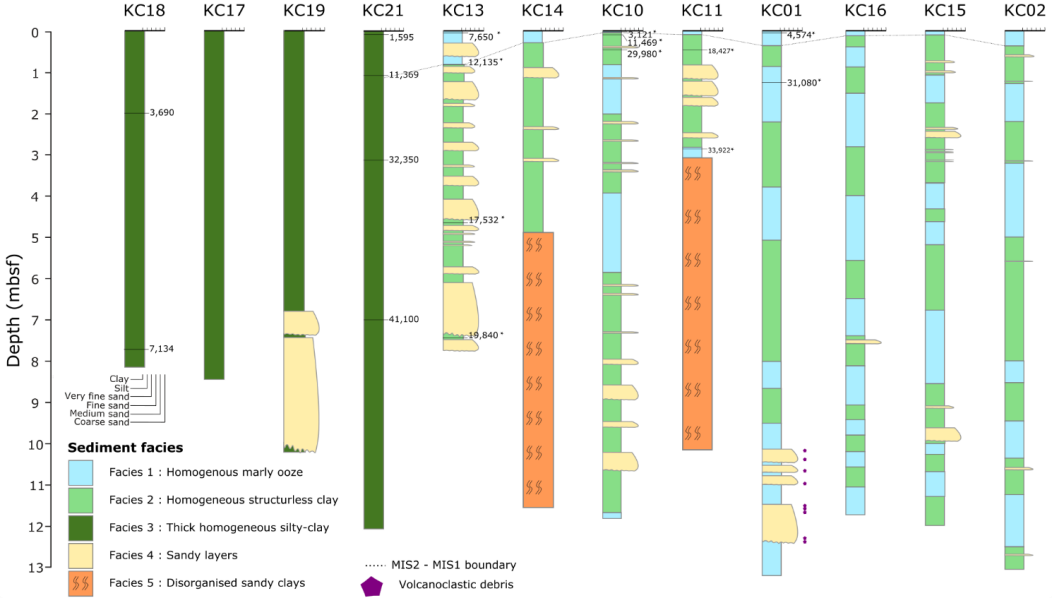

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150 **Fig. 3: Sedimentological core logs from the Ogooue Fan, showing grain-size variation, lithology and bed thickness (location of**
151 **cores are presented in Fig. 2). Ages are from ^{14}C dating (dates with a star are from (Mignard et al., 2017).**

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4 Results

4.1 Sedimentary facies

The classification in five sedimentary facies used here is based on photography and X-ray imagery; grain size analyses and $CaCO_3$ content (Fig. 3). Interpretation of these facies is based on the comparison with previous sedimentary facies classifications such as (Normark and Damuth, 1997; Pickering et al., 1986; Stow and Piper, 1984).

Facies 1: Homogenous, structureless marly ooze. This facies is composed of structureless, light beige marly ooze with relatively high concentration in planktonic foraminifers. The mean grain size is around 15 µm and the $CaCO_3$ content ranges between 40 and 60 %. This facies is interpreted as a pelagic drape deposits; it forms the modern seafloor of the deepest part of the Ogooue Fan and is observed in the majority of the cores top corresponding to the MIS 1 interval.

Facies 2: Homogenous, structureless clay: Facies 2 consists of dark brown clay. The mean grain size is less than 15 µm and the $CaCO_3$ content is less than 30 %. This facies has been interpreted as hemipelagic drape deposits.

Facies 3: Thick, homogeneous silty-clay: Facies 3 consists of very thick homogeneous dark silt-clay layers containing less than 10% of $CaCO_3$. This facies contains numerous quartz, micas and plant debris indicating a continental origin of the sediments. It results from the deposition of the fine-grained suspended load coming from the Ogooue River and flowing down the slope or belonging to the upper term of turbidite gravity flows.

Facies 4: Silty to sandy layers: Facies 4 consists of fine to medium sand beds with a thickness up to several meters. They display a variety of bedding structures: normally-graded or massive. The composition varies from terrigenous (quartz and mica) to biogenic (foraminifera), some sequences are highly enriched in organic debris (Mignard et al., 2017). They are interpreted as being deposited by turbidity currents initiated on the Gabonese continental shelf. Four sequences samples in core KC01 present a high concentration of volcaniclastic debris, such particles are completely absent of all the other sequences (Fig. 3). This specific composition and the location of the core suggests that these sequences originate from the close Annobon volcanic island.

Facies 5: Disorganized sandy clays: Facies 5 consists of thick intervals of deformed or chaotic clay with deformed or folded silty to sandy layers. This facies is interpreted as resulting from mass transport deposits (slump or debris flow).

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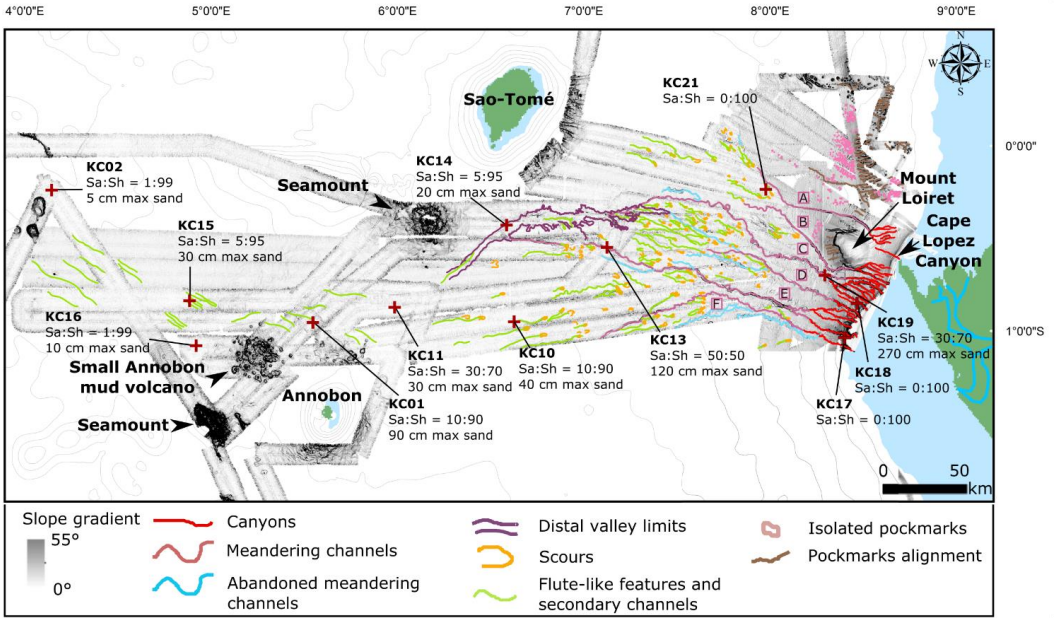
178 **4.2 Fan morphology**



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180 **Fig. 4: Interpreted gradient-shaded map of the Ogooue Fan showing the main features of the turbidite system. A, B, C, D, E and**
181 **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**
182 **sand-bed thickness in each core (max sand).**

183 Analysis of the sub-surface data (bathymetry and acoustic imagery) reveals the different domains of the Ogooue
184 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
187 west of the Manji Island, which forms a bathymetric obstacle on the upper slope and (2) a ramp of several tributary canyons
188 located south of the Mount Loiret. This ramp is composed of ten major canyons, which deeply incise the shelf, and ten
189 thinner and shallower incisions, which do not reach the shelf break. The continental shelf and the slope present low
190 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
192 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 meandering 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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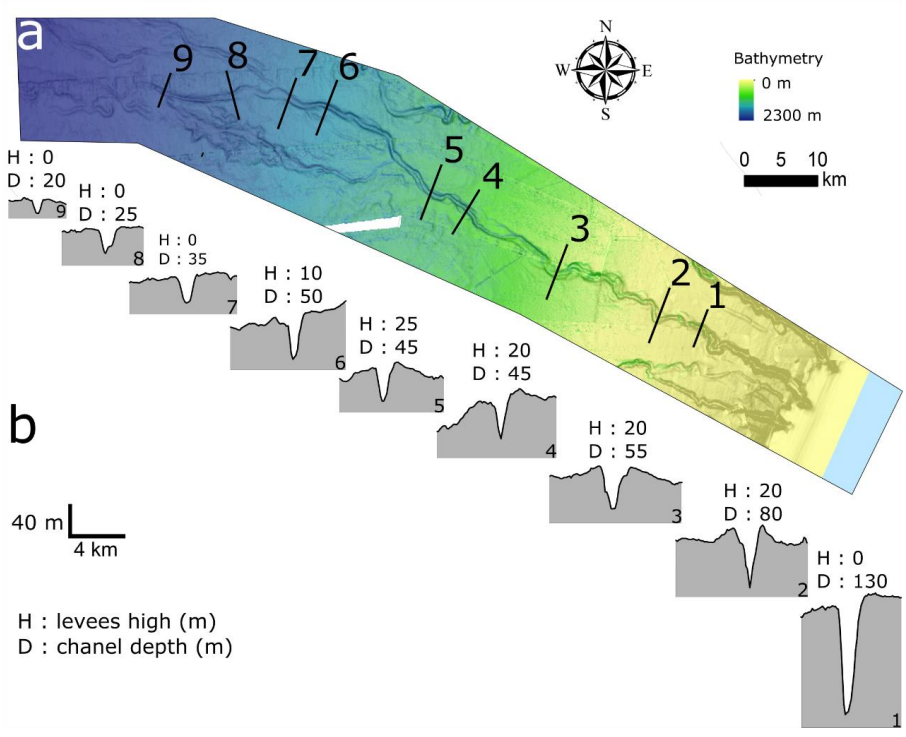

Fig. 5: Detailed Bathymetric map of channel D (location in Fig. 2) and serial bathymetric profiles showing the evolution of the channel-levees along the slope.

Downslope, on central part of the system, the seafloor located between 2,200 m and 2,500 m water depth, presents numerous erosional features like scours, lineations and secondary channels (Fig. 4). These erosional features appear on a very gentle slope area (0.6%) characterized by an heterogeneous medium backscatter facies (Fig. 2b). At 2,500 m water depth, just south of the Sao Tomé Island, the head of a large, 100 km-long, distal valley appears (Fig. 6). This valley can be divided in two parts of approximately equal length with two different orientations. The upper part of the valley is oriented E-W whereas the lower part is oriented NE-SW. This direction change is due to the presence of a rocky seamount located north of the valley and which deflects its course. The first half of the valley is up to 15 km wide with numerous erosional scars and terraces on its flanks. Its bottom, characterized by very high backscatter value, presents small internal erosion channels. Downstream, the valley becomes narrower with a "U" shape (Fig. 6, profile 5), its flanks appear regular 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 its mouth. The area located south of the distal valley is characterized by a heterogeneous low-backscatter facies. Some erosional features and secondary channels are present but scarce.

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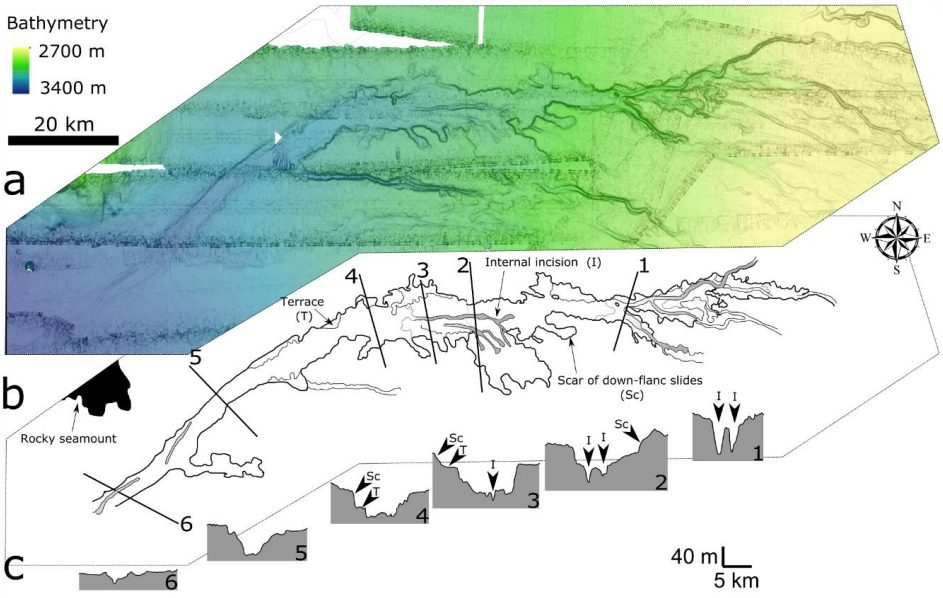

Fig. 6: (a) Shaded bathymetry of the distal valley of the Ogooue Fan between 2,700 and 3,400 m water depth; b) Interpretation of the main morphological features of the valley; c) Six transverse profiles of the distal valley extracted from the bathymetry data.

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 the presence of numerous linear pockmark trains on the upper part and random pockmarks fields on the lower part. These pockmarks have been previously described in (Pilcher and Argent, 2007). This whole area appears with a very low and homogeneous reflectivity. Trace of active sedimentation on this part of the margin is only visible in association with the Cape Lopez Canyon, which is the only canyon located north of the Mount Loiret. This canyon is associated with a small ponded lobe located just north of the Mount Loiret and referred as the Cape Lopez lobe (Biscara et al., 2011). This northern system is continued by Channel A which head is located in the vicinity of the Cape Lopez Lobe. At 2,200 m water depth, Channel A ends and its mouth is associated on the backscatter map with a fan-shaped area of very-high reflectivity which 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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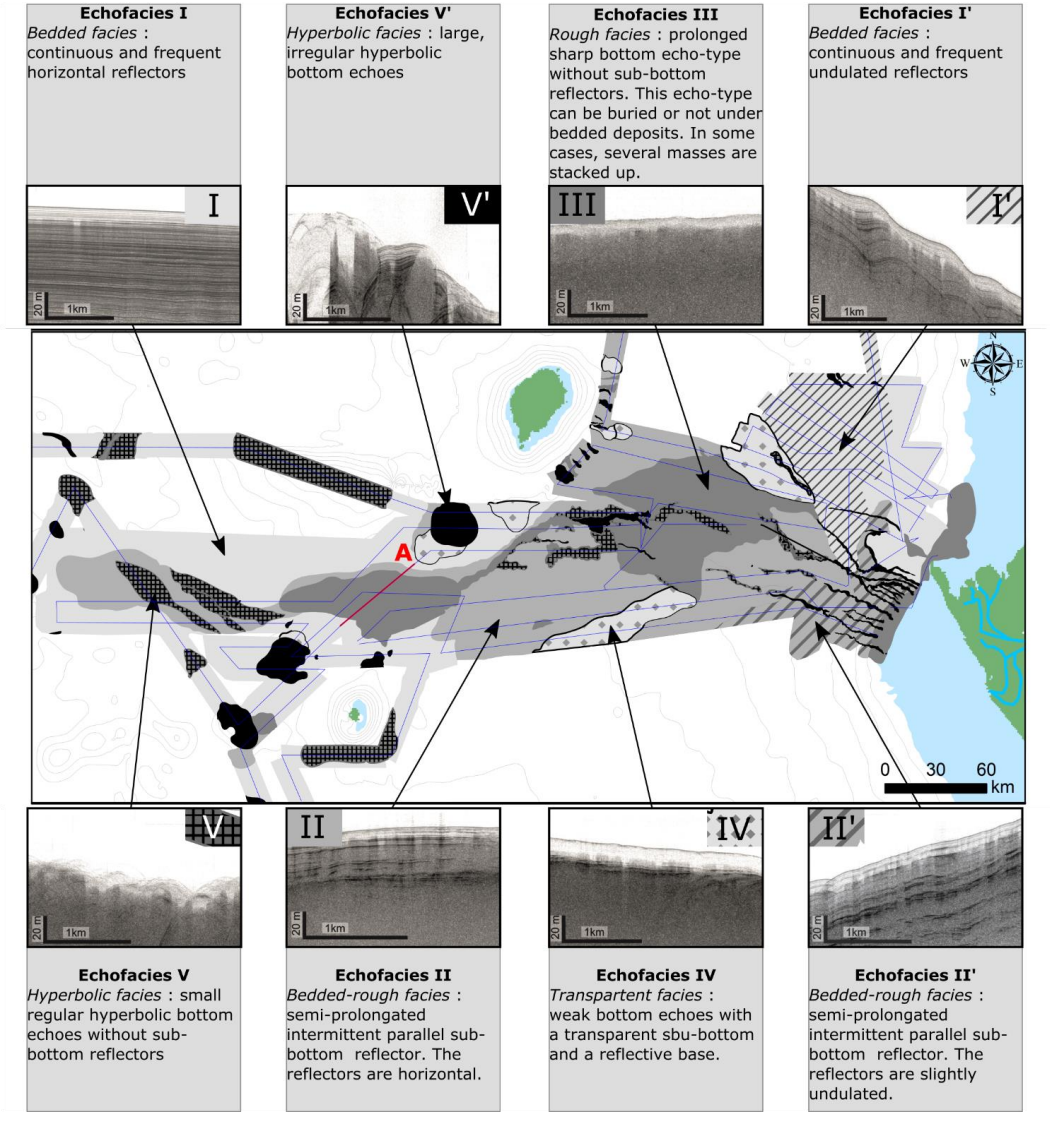

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238 **Fig. 7 : Echofacies map of the Ogooue Fan. Each shade of grey represents a specific echofacies.**

239 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)
241 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.

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

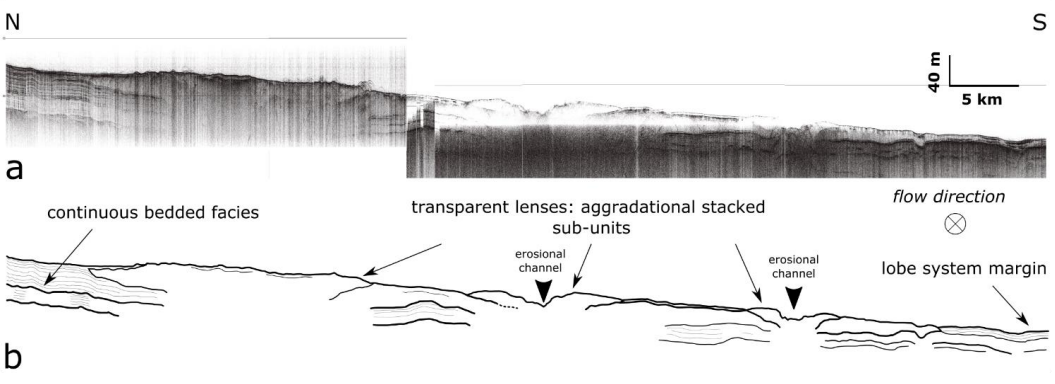

Fig. 8 : a) Transverse 3.5 kHz seismic line and b) line drawing in the upper distal lobe area, see Fig. 7 for location of the line.

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

On the edge of this tongue, high-penetration bedded facies (I) is dominant. The very continuous parallel bedding indicates hemipelagic sedimentation, which is confirmed by core KC16 and core KC02 both composed of alternating carbonate-rich and carbonate-poor clay sediments. Facies V' forms some patches on the seafloor and correspond to seafloor mounts such as mud volcanoes or rocky hills. The hyperbolic facies is due to the steep slopes and the irregular bathymetry.

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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.

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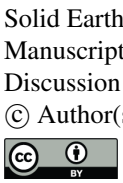

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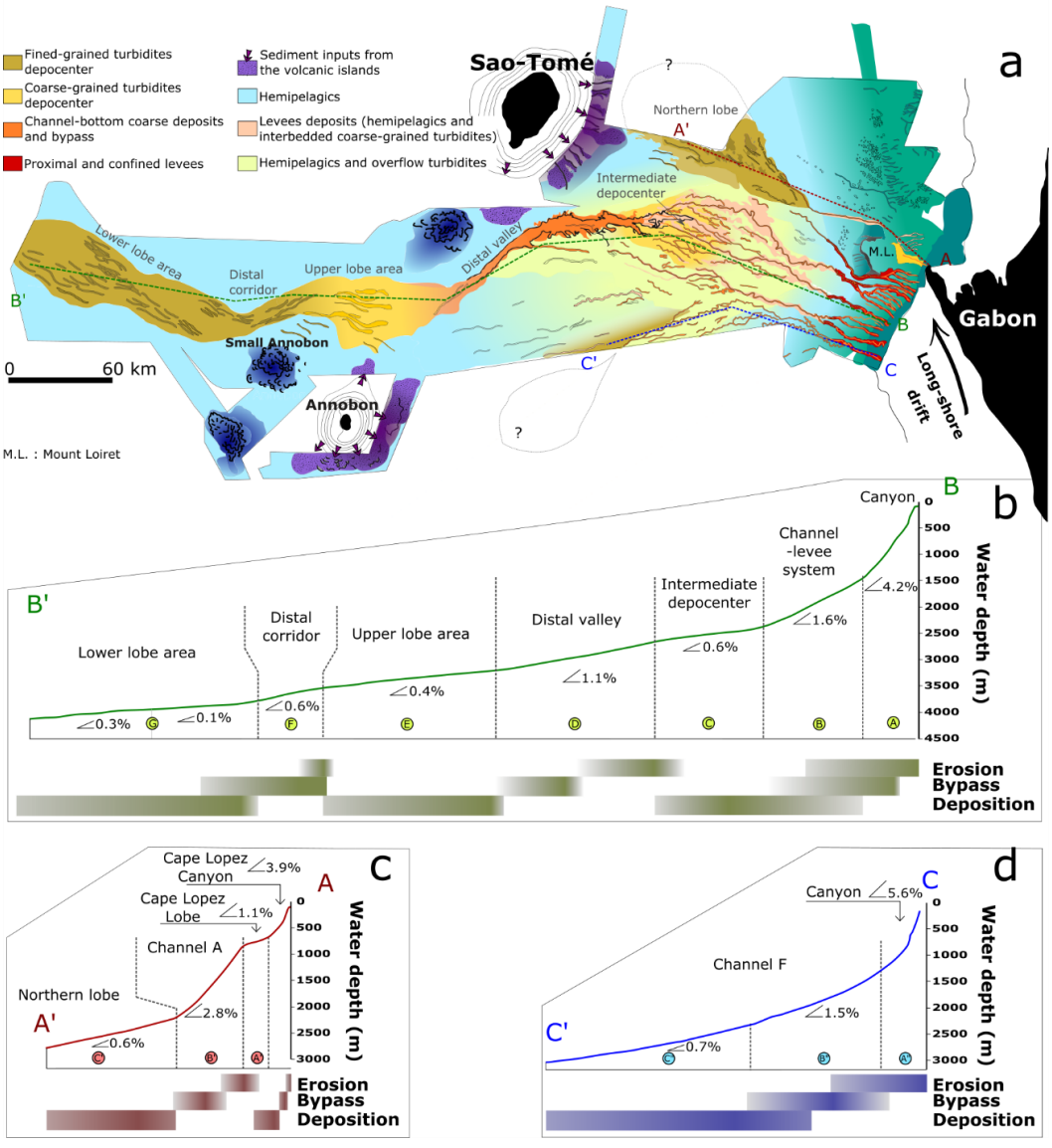
290 **5 Interpretation and discussion**

291 **5.1 Sedimentary processes along the fan**



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293 **Fig. 9: a) Synthetic map showing the architecture and the recent sedimentary processes of the Ogooue Fan determined by**
294 **imagery and echofacies mapping; b) c) and d) Longitudinal profiles from the bathymetric data along the central, northern and**
295 **southern part of the Ogooue Fan. The differences in slope gradient along the transects are associated with the main sedimentary**
296 **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-
298 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).

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 smaller. These characteristics can indicate different ages for the canyons formations but also different types of formations processes. The morphology of the smallest ones, which do not reach the shelf edge, indicates a formation by mass wasting and retrogressive erosion on the continental slope, whereas the deep incision of the others can by due to erosion by turbidity currents sourced from the continental shelf (Shepard, 1981). These two processes are not mutually exclusive and are probably contemporaneous along the slope.

The transition from canyons to meandering channels with developed levees is related to a decrease in slope gradient. The meandering channel-levees systems develops on a relative gentle slope from 1,500 to 2,200 m water depth. These channels are mainly erosive on their central part while deposition occurs on their sides (Normark et al., 1993). The levees of the four 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 documented that sinuosity of submarine channels increases with time (Babonneau et al., 2002; Deptuck et al., 2007, 2003; Kolla, 2007; Peakall et al., 2000). The highly sinuous upper parts of the channels have consequently undergone a long history whereas the distal straighter parts of the channels are in a more immature stage. Moreover, the height of the levees and the depth of the channels both decrease in the lower parts of the system (Fig. 5). These morphological changes are due to the slope that becomes gentler and progressively slows down the flow reducing its erosional power in the channel. 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).

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

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

This depositional area is however not the distalmost part of the Ogooue Fan. Indeed, west of this lobe area, traces of active sedimentation are visible on the reflectivity map (Fig. 2). The backscatter data shows high-backscatter finger-shape structures organized like veins of a leaf suggesting perennial pathways of gravity flows (Fig. 2b, detail A). These lineations are concentrated in a narrow 20 km wide corridor just west of the lobe area and then form a wider area extending up to 550 km offshore the Ogooue delta. This part of the system follows the same scheme as the one previously described between the intermediate depocenter and the upper lobe area (Fig. 9b). Indeed the corridor appears on a segment of steeper slope just at the downslope end of the upper lobe area. This corridor, which disappears when the slope becomes gentler, was certainly formed by the repeated spill-over of the fine-grained top of turbidity currents over the upper lobe area. This architecture suggests that this corridor is dominated by sediment erosion and transport. On the last segment with a very low slope gradient sediment deposition dominates.

On the northern part of the slope, the isolated system composed of the Cape Lopez Canyon, Cape Lopez lobe, channel A and northern lobe follows the same scheme (Fig. 9c). Indeed, the two successive depositional areas are located on an area with a low slope-gradient whereas the erosion and bypass dominates on segments of steep slope-gradient.

In the southern part of the fan, channel F transports sediments southward. At 2,200 m water depth, a transparent echofacies appears associated with the pathway of this channel. This echofacies suggests that sediment transported by this channel might be partly deposited in this area by turbidity current overflow. This channel might also be associated with a depositional lobe; however, the area covered by the MOCOSED survey does not allow us to image it.

The Ogooue Fan presents a succession of depositional areas on segments with gentle slope (referred as ‘steps’ in (Smith, 2004)) and segments of steeper slope associated with erosion or bypass (Fig. 9). The depositional behavior in such system is guided by an equilibrium profile of the system that creates preferential areas of sedimentation or erosion (Ferry et al., 2005). Erosion is favored where local gradient increases, the eroded sediments being delivered downstream resulting in a local increase in sediment load (Gee and Gawthorpe, 2006). This kind of fan geometry is common along the West African margin where abrupt changes in slope gradient and complex seafloor morphology are inherited from salt tectonic movement (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 islands of the Cameroon Volcanic Line and the different mud volcanoes constitute additional constraints for the flows. These bathymetric highs deviate the pathways of different channels of the system as well as the pathway of the distal valley and create several downslope depositional lobes. Such features are similar to the morphology of the Northwest African margin where the Madeira, the Canary and the Cape Verde islands create a complex slope morphology (Masson, 1994; Wynn et al., 2002, 2000). This specific topography controls the distribution of sedimentary facies along the Moroccan and Mauritanian margin and creates several interconnected depositional basins similarly to the different depositional areas of the Ogooue Fan.

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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).

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

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

Whatever the current pathways are, the deposited material has a continental origin as suggested by the abundance of quartz, micas and plant debris in the coarse-grained fraction. The important proportion of planktic foraminifers in the coarse-grained fraction of turbidites located in the distal part of the system (core KC10- KC11- KC15) suggests that turbidity currents previously eroded pelagic and hemipelagic deposits on the slopes located upflow where such deposits cover large areas (Viana and Faugères, 1998). The presence of volcanoclastic debris in sandy layer found at the base of core KC01 suggests that sedimentary input may also come from the volcanic islands of Sao Tomé and Annobon. However, acoustic

data indicate that these inputs are limited to the close vicinity of the Sao-Tomé and Annobon islands. On the contrary to the model proposed by (Wynn et al., 2000) for the Northwest African slope, the volcanic islands and other seamounts present on the Ogooue turbidite system act mainly as obstacles for the flow pathway but are not important sediment suppliers for the deep-sea system.

5.3 Palaeoceanographic control on the fan activity

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

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

In the Ogooue Fan system, the shelf width between the littoral area and the canyon heads is the main control factor on the fan activity. During periods of relative low sea-level, the canyons of the central part of the system receive sediment from the river system that extended across the subaerially exposed continental shelf. During periods of relative high sea-level, river sediments are unable to reach the canyon heads south of the Manji Island and accumulate on the continental shelf close to the Ogooue delta. However, part of these sediments mixed with sediments coming from the south Gabon margin are drift-transported and contribute to supply the Cape Lopez canyon and consequently the Cape Lopez and Northern Lobe. Due to their specific location and favorable hydrodynamic conditions on the shelf, sedimentation on the Cape Lopez and the Northern lobes is active during relative sea-level highstands, on the contrary to the rest of the Ogooue Fan. This type 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).

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

elements of the system. The long-term interaction between gravity flows and the sea-floor topography have induced the construction of successive depocenters and bypass areas. The gravity flows modified the topography according to a theoretical equilibrium profile, eroding the seafloor when slopes are steeper than the theoretical equilibrium profiles and depositing sediments when slopes are gentler than the theoretical equilibrium profile. Three successive sediment depocenters have thus been identified along a longitudinal profile. They are associated with three areas of low slope gradient. The two first deposition areas – the intermediate depocenter and the upper lobe area- recorded coarse-grained sedimentation and are connected by a well-developed large distal valley measuring 100 km long. The distalmost depocenter – the lower lobe area - received only the fine-grained portion of the sediment load that has bypassed the more proximal deposit areas. The presence on the slope of the Mount Loiret has caused the formation of an isolated system composed of the Cape Lopez canyon and lobe, which continues downstream by the Northern Lobe area.

The Ogooue Fan is currently in a low activity period since the recent Holocene rise of sea-level. Nowadays, the sedimentation is mostly located on the Ogooue delta platform and on the upper slope. The turbidite system was most active during the last glacial lowstand. Nonetheless, the northern part of the system appears to have an asynchronous activity with the rest of the fan as this part is fed by the drift-transported sediments during time of relative high sea-level when the activity in the rest of the system is shut-down.

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