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Research paper

Controls on turbidite sedimentation: Insights from a quantitative approach of submarine channel and lobe architecture (Late Quaternary Congo Fan)

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The role of internal and external forcing of sedimentation in turbidite systems remains a subject of debate. Here we propose new insights from the quantitative analysis of architectural parameters of the Congo Axial Fan.

Fifty-two channel-levee-lobe systems, spanning the last ca. 200 ka, are visible on the seafloor, most of them having slightly elongated lobe complexes at their termination. Volumes of lobe complexes (usually 3–196 km^3) are highly variable in time and space. The cumulative volume of the lobe complexes represents approximately 30% of the volume of the Axial Fan.

The Axial Fan is sequentially divided into periods of increasing/decreasing channel lengths and basinward/landward migrations of avulsion points, representing successive prograding/retrograding architectural patterns called architectural cycles. These cycles are either symmetrical saw toothed and bell-shaped with progressive progradation and retrogradation phases, or asymmetrical, with long-lasting progradation phases and abrupt retrogradation phases that correspond to channel avulsions occurring high up on the fan.

Our study points to the interplay between internal and external factors controlling the architecture of the Congo Axial Fan. The local topographic constraint is a major factor in the fan's stacking pattern. However, cyclic evolution of the architecture reveals major shifts in the deposition site that are linked to very upfan avulsion events. These events are interpreted to be driven by external factors (e.g. climate and/or eustatic sea-level change) that were able to drastically increase and/or coarsen the sediment supply to the fan.

1. Introduction

Turbidite systems are among the biggest sedimentary systems on earth and are intensively studied because they host many major offshore oil plays discovered during the last decades but also because they play a role in climate fluctuations as they trap huge amounts of sediments and carbon. Their structure and composition are highly variable and are related to sediment source composition and the nature of the supplying system, both of which are used for classification (e.g. Reading and Richards, 1994). Turbidity currents build channel-levee-lobe systems that migrate in response to channel avulsion, which is the main process governing the architecture of fans.

Factors that control the sedimentation in turbidite systems are still highly debated. Internal factors such as topographic compensation, levee aggradation, channel meandering and overcutting, and channel avulsion have all been interpreted as factors controlling the growth pattern of turbidite systems (e.g. Flood and Piper, 1997; Pirmez et al., 2000; Prélat et al., 2010, 2009).

In addition, the importance of external controls, such as eustatic and climatic fluctuations, on these sedimentary systems at different time scales has been outlined (e.g. Badalini et al., 2000; Kolla and Macurda Jr., 1988; Lopez, 2001; Manley and Flood, 1988; Payros

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and Martínez-Braceras, 2014; Toucanne et al., 2012). At a system scale, for instance on the Amazon Fan, the chrono-stratigraphic framework provided by Leg 155 ODP drillings (Flood and Piper, 1997) delivered clues that uncovered a link between sedimentation and architectural evolution to climate and eustasy. Maslin et al. (2006) assumed that channel avulsions in the Amazon Fan could be triggered by pulses of sediment flux, and therefore be externally forced by factors such as sea level and/or climate fluctuations. Lopez (2001) also suggests that sea level variations influence the occurrence of the avulsion process, which is more frequent during periods of sea level lowering. Additionally, at the levee scale it was demonstrated that external forcing mechanisms such as sediment flux pulses or sea level fluctuations control the growth of the levees (Bonneau et al., 2014; Jorry et al., 2011; Toucanne et al., 2012) therefore potentially playing a role in triggering channel avulsions and thus influencing the distribution pattern of the channel-levee-lobe systems.

The detailed morphology and structure of turbidite systems remains poorly understood as there is a limited amount of high-resolution data on modern systems. Particularly, there is a lack of integrated information on the architecture and channel-levee-lobe stacking patterns and hierarchy. Such knowledge is crucial because the channel-levee-lobe system is the elementary building block in the development of turbidite systems and as such, it is this level of detailed information that is needed about the morphology, structure, and composition to fully understand the interplay between internal and external forcing in building turbidite systems.

In this respect, this paper focuses on the detailed architecture of the Axial Fan portion of the Late Quaternary Congo turbidite system since ca. 200 ka (Droz et al., 2003). This work is the revision of a previous work carried out on the whole Quaternary turbidite system (~800 ka to present) by Marsset et al. (2009), based on new data acquired in 2011 (Droz and Marsset, 2011; Marsset and Droz, 2010). With this data set we developed a new method to quantify the morpho-sedimentary complexity of turbidite systems by determining at a fan scale an exhaustive inventory of channel-levee-lobe systems as well as their detailed morphologies, emplacement, size, and volumes and the relative chronology of avulsions.

Our objective is to detail the repetitive patterns observed in the characteristics and stacking of the channel-levee-lobe systems, in order to discuss the controls on the evolution of the Axial Fan. We focus particularly on the channels prograding/retrograding pattern and on the occurrence of infrequent major upfan avulsions and frequent minor avulsions in order to identify the role of the local topography and thus to also discuss the role of possible external control by sea level and climate.

2. Geological setting and previous work

The Quaternary Congo turbidite system, located on the Congo-Angola passive margin, extends westwards along 800–1000 km from 2000 to 5200 m water depth. Its minimum width is 400 km in the N–S direction (Fig. 1). The present mean gradient of the seabed of the Congo Fan evolves from a maximum of 3% on the continental slope to less than 0.25% in the abyssal plain (Babonneau et al., 2002) (Fig. 1B).

The margin is affected by marked halokinetic deformation caused by diapirism of the Aptian salt deposited during the rift phase that led to the opening of the South Atlantic Ocean during the Early Cretaceous (Emery et al., 1975; Jansen, 1985; Reyre, 1984). A first deep-sea fan with a maximal thickness of approximately 2.5 km had formed during the Albian-Eocene ages (Anka, 2004; Anka et al., 2010), which shows that the Congo river was already a terrigenous sediment supplier. A continental uplift in the Oligocene led to an increase in erosion and river load, resulting in an increase in sediment supply to the basin. This increased sediment supply was enhanced by a decrease in global sea-level at that time and by the humid climatic conditions that prevailed in the river basin during this period (Droz et al., 1996; Reyre, 1984). These were favorable conditions for the setup of a Tertiary turbidite system (Anka, 2004; Brice et al., 1982; Karner and Driscoll, 1999). Since then, the Congo River has fed the Quaternary turbidite system.

The Congo turbidite system is one of the largest mud-rich fans in the world. It is supplied by only one point source (the Congo River) and fed by a giant watershed basin (Reading and Richards, 1994; Stow et al., 1996; Stow and Mayall, 2000) (Fig. 1). With a 4370 km-long river which flows in a huge, low slope gradient drainage basin of 3.7×10^6 km^2 (Van Weering and Van Iperen, 1984), the Congo fluvial system is the most important hydrographic network of West Africa. These characteristics, along with its high average flow (fluid discharge) of 42,800 m^3 s^{-1} (Kinga-Mouzeo, 1986), rank the Congo River as the second largest river in the world after the Amazon River. In addition, the Congo Basin includes several lakes, which favor the trapping of coarse-grained fluvial sediments (Moguedet, 1988; Turakiewicz, 2004; Wefer et al., 1998) (Fig. 1). These topographic conditions contribute to the mud-rich composition of the Congo turbidite system.

The Congo Turbidite System is currently an active system (Droz et al., 2003, 1996; Heezen et al., 1964; Khripounoff et al., 2003; Rigaut, 1997; Van Weering and Van Iperen, 1984) due to its physical connection with the Congo River at all sea-level positions. It is also characterized by an abundance of channel-levee systems visible on the seafloor (Droz et al., 2003; Marsset et al., 2009; Savoye et al., 2000) that could be related to favorable conditions which prevented the burying or reworking of these systems, such as: (1) the absence of physiographical confinement resulting in a widespread deposition, the small amount of overlap of individual fans, and minimal burying of channels and (2) the absence of large mass-transport deposits able to obliterate the channel network.

Droz et al. (2003) and Marsset et al. (2009) showed that the architecture of the Quaternary Congo fan results from the stacking of channel-levee systems grouped into three fans, the Northern Fan (780–540 ka), the Southern Fan (540–210 ka), and the Axial Fan (210 ka to present), in response to successive major upfan channel avulsions (Fig. 2).

As observed in many fans (e.g. Bouma et al., 1985; Damuth and Flood, 1983; Kolla and Coumes, 1987) only one channel-levee of the Congo Fan is active at any given time (Droz et al., 1996; Rigaut, 1997; Savoye et al., 2000) and the abandonment of the active channel is accomplished through avulsion of the feeder channel which can be a gradual but generally non-reversible process (Droz et al., 2003).

The third important characteristic of the Congo Fan is the frequent occurrence of channel entrenchment observed both on buried channels (Turakiewicz, 2004) and on the active channel (Babonneau et al., 2004, 2002). Channel entrenchment enhances the confinement of turbidity currents and allows them to maintain their energy far downstream in the channel and increases their erosional capacity (Babonneau et al., 2004).

The channel map of Marsset et al. (2009) (Fig. 2) indicates that downstream of most channel-levees are lobe-shaped seismic units, called terminal lobes by these authors. Marsset et al. (2009) use terminal lobes as a general term for channel-mouth lobes, whatever their location, up or downfan. These terminal lobes form high aspect ratio, convex-up deposits on the seafloor, and are fed by a network of superficial channels (called lobe channels by Marsset et al., 2009) extending from the mouth of the channel-levee systems. In addition, based on very high-resolution 3.5 kHz data, Bonnel (2005) suggests that a terminal lobe can be a stack of even smaller lobes. At the termination of the active channel is a cluster of