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Sea-level control on the connection between shelf-edge deltas and the Bourcart canyon head (western Mediterranean) during the last glacial/interglacial cycle

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ABSTRACT

A dense grid of high- and very high resolution seismic data, together with piston cores and borehole data providing time constraints, enables us to reconstruct the history of the Bourcart canyon head in the western Mediterranean Sea during the last glacial/interglacial cycle. The canyon fill is composed of confined channel–levee systems fed by a series of successively active shelf fluvial systems, originating from the west and north. Most of the preserved infill corresponds to the interval between Marine Isotope Stage (MIS) 3 and the early deglacial (19 cal ka BP). Its deposition was strongly controlled by a relative sea level that impacted the direct fluvial/canyon connection. During a period of around 100 kyr between MIS 6 and MIS 2, the canyon "prograded" by about 3 km. More precisely, several parasequences can be identified within the canyon fill. They correspond to forced-regressed parasequences (linked to punctuated sea-level falls) topped by a progradational-aggradational parasequence (linked to a hypothetical 19-ka meltwater pulse (MWP)). The bounding surfaces between forced-regressed parasequences are condensed intervals formed during intervals of relative sediment starvation due to flooding episodes. The meandering pattern of the axial incision visible within the canyon head, which can be traced landward up to the Agly paleo-river, is interpreted as the result of hyperpycnal flows initiated in the river mouth in a context of increased rainfall and mountain glacier flushing during the early deglacial.

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1. Introduction

There are relatively few studies focusing on the relationship between canyon infill, fluvial delivery to canyon heads and relative sea-level changes. Most of the textbooks on sequence stratigraphy (e.g. Posamentier et al., 1988; Catuneanu, 2006) include canyons in *slope and deep-sea facies*, which are viewed as part of the lowstand (or falling stage) and transgressive systems tracts (Rasmussen, 1994, 1997). The Quaternary, and especially the last glacial/interglacial cycle, offers the possibility to investigate precise processes that control fluvial/canyon connections, because most of the world's fluvial systems reached the shelf edge during the Last Glacial Maximum (LGM, between ca. 26.5 and 19 ka BP).

Several mechanisms have been proposed to explain the origin of canyons, which are common features observed along modern (Quaternary) continental margins, as well as features that are buried in the stratigraphic record. Two main processes (not necessarily mutually exclusive) are generally proposed and have been the object of reviews and discussions (i.e. Mountain et al., 1996; Pratson and Coakley, 1996; Pratson et al., 1994).

1- ***Initiation of turbidity currents (and/or mass failure)*** at the mouth of a fluvial system situated in the vicinity of the shelf edge. Daly (1936) was the first to introduce the idea of turbidity currents as the major factor in the formation and erosion of submarine canyons in relation to sea-level variations. This mechanism of canyon formation implies overloading through sediment accumulation at the river mouth (Pratson et al., 1994) triggering mass failure and/or the initiation of hyperpycnal flows within the river, evolving into a turbidity current along the slope (Mulder et al., 2003; Normark and Piper, 1991). In the Gulf of Lions, Baztan et al. (2005) suggested that the connection of fluvial systems at some canyon heads during the Last Glacial Maximum resulted in the formation of narrow (300 m wide) axial incisions, about 100 m deep, cutting across the thalweg of the main canyons. It was proposed that this process also accounts for the broadening of the main canyon through the lateral collapse of the canyon rims, due to retrogressive slides triggered along the axial incision (Sultan et al., 2007). Instead of direct sediment delivery from rivers, littoral drift can be the main source feeding canyon heads when the continental shelf is narrow or absent (Shepard,

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1972; Shepard and Dill, 1977). This is the case of Mandji Island, in the vicinity of the Ogooue River mouth on the Gabonese Margin (Biscara et al. (2011)to the North of Fraser Island on the east coast of Australia (Boyd et al., 2008), or for the La Jolla canyon on the Californian margin (Covault et al., 2007). In these cases, however, sediment transfer to the deep sea is channelized within several gullies, rather than through a distinct axial incision meandering within a broad canyon.

2- ***Mass failure on the slope evolving through retrogressive erosion*** that may eventually "capture" fluvial systems. This scenario was based on the observation by Twichell and Roberts (1982) that some canyons cut across the shelf edge, whereas others are confined to the continental slope, the former (and older) resulting from headward erosion of the second (younger) type. This idea was also developed by Farre et al. (1983) who proposed a scenario with an initial phase dominated by slope failure, followed by the development of coarse-grained turbiditic flows fed by offshore sands after the canyon head reaches the shelf edge. This "bottom-up" scenario has been proposed to explain the origin of the Yoakum/Lavaca canyon system (Gulf of Mexico) (Galloway et al., 1991), the Andøya canyon (Norwegian Sea) (Laberg et al., 2007) or the Bari canyon (Adriatic Sea) (Ridente et al., 2007), which are not related to any river. This scenario was also proposed to explain the formation of canyons where buried paleovalleys exist on the shelf such as of the Otero River (Lo Iacono et al., 2013). Similarly, the formation of some canyons of the Argentine Continental Margin is explained by headward retrogressive erosion, increased by strong contour currents (Lastras et al., 2011). Headward erosion and lateral migration controlled by contour currents is also proposed as the mechanism at the origin of buried late Miocene canyons in the South China Sea (He et al., 2013).

These two scenarios were reconciled by Pratson and Coakley (1996) who showed, through numerical modeling, that retrogressive failure along the mid-slope can be triggered by downslope currents initiated at the shelf edge (possibly at the river mouth) and flowing along rills. In addition to these two general scenarios of canyon formation, fluid escape has been proposed as an important mechanism in the initiation and/or evolution of some canyons, such as the Benito canyon off the Equatorial Guinean coasts (Jobe et al., 2011) or along the eastern margin of Japan, where pockmarks formed by release of hydrostatic pressure during sea-level falls might be at the origin of the canyons (Nakajima et al., 2014),

In any event, as already mentioned by Shepard (1981), it is likely that most canyons result from a combination of various processes operating over long periods of time, interrupted by intervals of non-deposition or condensation. For instance, the history of the Tugela Canyon on the east coast of South Africa is related to several phases of hinterland uplift, at the origin of incisions, followed by pelagic infill and reworking by oceanic currents (Wiles et al., 2013). In the Bay of Biscay, the Capbreton canyon that cuts across the broad Aquitaine shelf displays a very meandering pattern and a distinct axial incision that is interpreted as being inherited from the period of connection of the canyon head with the Adour River (Gaudin et al., 2006). However, during the last decade, the canyon experienced distinct morphological and sedimentological evolution due to massive transfer of sand eroded from the coastline during major storms (Mazières et al., 2013).

In this paper, we focus on the head of the Bourcart canyon in the Gulf of Lions (western Mediterranean). A large number of seismic profiles at different resolutions, as well as one long piston core and two boreholes (100 and 300 m deep), allow us to reconstruct the architecture and the history of the canyon head during the last glacial/interglacial cycle in relation with the relative sea-level changes and the question of connection/disconnection of the fluvial system(s).

2. Geological framework

The Bourcart canyon is located at the western end of the Gulf of Lions (Fig. 1). The canyon starts at about 110 to 120 m water depth, 60 km from the present coastline. The Gulf of Lions is a passive and prograding margin influenced by a significant subsidence rate (about 250 m/Myr at the shelf edge) (Rabineau et al., 2014) and high sediment supply, mainly from the Rhone River. As a result, depositional sequences linked to Milankovitch and sub-orbital Quaternary sea-level changes are well preserved at the shelf edge and along the upper continental slope (i.e. (Bassetti et al., 2008; Jouet et al., 2006; Rabineau et al., 2005; Tesson et al., 2000). These units mainly consist in forced-regressive sequences, which thicken seaward and pinch out landward at a depth of 100 m. The continental slope is deeply incised by numerous canyons, some with a depth in excess of 1000 m (Berné et al., 1999). Among these, the Petit Rhone canyon to the east was, at least during the last glacial cycle, the main conduit of sediment between the Rhone watershed and the Rhone Deep Sea Fan, which drains all the canyons from the central and western Gulf of Lions (Fig. 1).

Because of overall subsidence and high sediment supply, fossil canyons have been rapidly buried. Except for the Rhone canyon, most canyons were initiated around the Middle–Late Pliocene and reached full development (similar in size to modern canyons) around the Pliocene–Quaternary transition (Lofi et al., 2003). This canyon evolution might be related to the amplification of glacial/interglacial cycles at the end of the Pliocene (Lisiecki and Raymo, 2005) and related sea-level changes.

3. Data set and methodology

3.1. Bathymetric data

The overall study area is covered by two multi-beam data sets acquired by R/V "Le Suroît" during several cruises using Simrad EM300 and EM1000 systems. For the purpose of this study, a Digital Terrain Model (DTM) with a grid spacing of 50 m was produced.

3.2. Seismic data

1500 km of high- and very high-resolution seismic profiles were acquired over the Bourcart canyon head (about 50 km^2; Fig. 2). This data set includes 24-fold multi-channel and single channel seismic profiles. Multi-channel seismic data was acquired during the "Marion" cruise aboard R/V "Le Suroît" using two Sodera™ mini-GI gun sources and a 24-channel (6.25 m, 8 hydrophones per trace) streamer. For higher resolution, we used SIG™ sparker equipment (700 J power emission, 1.5 s shooting rate) and a hull-mounted, IXSEA™ chirp sub-bottom profiler (20 to 50 ms pulse length, 2000–5200 Hz bandwidth) during several cruises of R/V "Le Suroît". These different systems give vertical resolutions in the order of > 3 m, 1 m and < 1 m, respectively. Seismic and borehole data were transferred to an interpretation station (SMT Kingdom Suite™). Seismic interpretation was based on the principle of seismic stratigraphy (Mitchum et al., 1977). Major seismic surfaces were plotted in a manual or semi-automated mode over the entire study area. For the correlation of these surfaces with borehole information, we used seismic velocity determined at sites PRGL1 and PRGL2 by the Promess project (see below).

3.3. Chrono-stratigraphic constraints

We used all the age controls from both PRGL1 and PRGL2 boreholes and from Images 5 cores MD99-2349 and MD99-2348. P-wave sonic velocities were determined along cores by direct sonic velocity measurements using a Multi-Sensor Core Logger (MSCL, Geotek™), together with interval velocity analysis performed on multi-channel seismic data at the position of borehole PRGL1 (Dennielou, 2007). Sonic velocity analysis allowed us to tie seismic surfaces to core and borehole data and thus to infer ages for each surface thanks to robust chrono-stratigraphic constraints established for PRGL1 and MD99-2348 (Frigola et al., 2012; Jouet et al., 2006; Sierro et al., 2009). Analysis and dating on PRGL2

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