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Quaternary turbidite systems on the northern margins of the Balearic Basin (Western Mediterranean): a synthesis

L. Droz · A. T. dos Reis · M. Rabineau · S. Berné · G. Bellaiche

Abstract The Balearic Basin is a young basin composed of thick Plio–Quaternary sediments, including active gravity sedimentation. During the Quaternary, gravity processes deposited (1) turbidite systems, either as symmetrical fans (Petit-Rhône and Valencia fans) or asymmetrical ridges (Marseille–Planier, Grand-Rhône and Pyreneo-Languedocian ridges) and (2) several mass-transport deposits, indicating recurrent sedimentary failures of the margin. This paper synthesizes previous works and proposes a chronological sedimentary evolution for the basin. Except for the last 20 ka, the chronostratigraphy remains poorly constrained but should soon be established for the last 500 ka, based on the PROMESS1 drillings on the outer shelf of the Gulf of Lions, and hopefully for the last 30 Ma, based on ultra-deep drilling in the deep basin from aboard the Chikyu research vessel (IODP proposal Pre699).

L. Droz (✉) · M. Rabineau
CNRS, UMR 6538, Institut Universitaire Européen de la Mer,
Place Nicolas Copernic,
29280 Plouzané, France
e-mail: ldroz@univ-brest.fr

A. T. dos Reis
Departamento de Oceanografia/UERJ-Brazil,
Rua São Francisco Xavier 524, 4 Andar, Maracanã,
Rio de Janeiro, 22550-900 RJ, Brazil

S. Berné
IFREMER, Laboratoire Environnements Sédimentaires,
29280 Plouzané, France

G. Bellaiche
CNRS, UMR 6526 GEOSCIENCES-AZUR,
B.P. 48, 06235 Villefranche/Mer, France

Introduction

The Gulf of Lions is a young passive margin which, because of a high total subsidence rate (250 m/10^6 years on the outer shelf of the Aude–Hérault interfluve; Rabineau 2001), is very favourable for the registration and preservation of sedimentary sequences from the source (mainly the Rhône River) to the sink (the turbidite sequences in the basin), including the deposition and stacking of strata on the shelf and in canyons. Since the first publication on the Rhône Deep-Sea Fan (Menard et al. 1965), data acquisition and research on the Plio–Quaternary sedimentation of the Gulf of Lions have been continuous, especially since the 1970s, resulting in a large geological and geophysical database which places the Gulf of Lions among the best known margins in the world. Numerous, mainly French and Spanish laboratories have been and are currently involved in this research, including the sedimentological laboratories of the University of Paris 6 at Villefranche/Mer and Paris, the University of Perpignan, the University of Brest (UBO), Ifremer, the Spanish CNR in Barcelona and the University of Barcelona. A synthesis of these studies was proposed by dos Reis et al. (2005) at the scale of the Plio–Quaternary, highlighting the tectonic and halokinetic control on sedimentation.

Recently, special research efforts focusing on sedimentation in the Gulf of Lions form part of the objectives of French and European programmes, including the French GDR Marges (http://gdrmarges.lgs.jussieu.fr) projects "Gulf of Lions" and "Siliciclastic and Carbonated Turbidites" and the EU projects EUROSTRATAFORM (http://www.soc.soton.ac.uk/CHD/EUROSTRATAFORM) and PROMESS1 (http://promess1.wdc-mare.org). Within the framework of these programmes, new data are currently being acquired in an effort to obtain key results on sedimentary systems from

source to sink on the timescale of 500 ka, including chronostratigraphic markers and physical parameters of hydrodynamic processes.

This paper aims to present a synthesis dealing with the recent (Quaternary) evolution of sedimentary systems around the Balearic Basin of the Western Mediterranean (Fig. 1), with special emphasis on the Gulf of Lions, in order to propose a general framework for newly acquired results.

## Tectonic, climatic and eustatic history of the margin

The margin is related to large-scale Oligocene extension coeval with the counter-clockwise rotation of the Corsican–Sardinian block (Olivet 1996). This rotation has recently been dated between 21 and 15 Ma (Speranza et al. 2002).

The evolution of the margin led to deposition of thick (several kilometres) marine deposits both on the shelf and the slope as well as in the deep basin from the end of the Miocene to the present. Three major periods characterize this sedimentation: the Messinian Salinity Crisis, the rapid Lower Pliocene sea-level rise, and the marked climatic cycles during Upper Pliocene to Quaternary times which led to cyclic sea-level variations.

The Messinian salinity crisis

Marine deposition was interrupted around 5.5 Ma by an important episode of lowering of sea level and consecutive emersion of the margins of the Mediterranean during the Messinian Salinity Crisis. During this period, the Evaporites Sequence was deposited in the basin, while the margins were severely eroded. The Evaporites Sequence has been partly drilled during DSDP Legs 13 (Ryan et al. 1973) and 42A (Hsü et al. 1978) and ODP Leg 161 (Comas et al. 1999): from top to bottom, it comprises (1) the upper evaporites, of seismically very high-amplitude stratified facies, composed of halite, gypsum and marls, (2) the salt layer, with a transparent seismic facies composed of halite, and (3) the lower evaporites, which have never been drilled but are possibly of the same composition as that of the upper evaporites, due to seismic facies similarities. Erosion of the emerged margins resulted in the Messinian Unconformity on the shelf and slope, truncating the pre-salt marine series (Burdigalian to Tortonian), and the incision of land-connected deep canyons on the continental shelf and upper slope (Gorini 1993; Gorini et al. 2005; Lofi et al. 2005), which funnelled products of erosion towards the basin while the lower evaporites were deposited in the deep basin.

Fig. 1 Bathymetry of the Western Mediterranean (contour isolines: 150, 300, 500, 1,000, 1,500, 2,000, 2,500 and 2,800 m) and topography of surrounding lands (figure by M. Rabineau at UBO, and D. Aslanian at IFREMER Brest). *Large square* Location of the synthetic map shown in Fig. 3, *arrows* origin of inputs to the Balearic and Balearo-Provençal basins (PL Rivers Pyreneo-Languedocian rivers), *closed dots* industrial boreholes (including GLP1 discussed in the text), *open squares* drilling sites of ODP Leg 13 (Ryan et al. 1973), *open dots* Calypso cores in the Balearic Basin (Rothwell et al. 1998). Bathymetric data extracted from Smith and Sandwell (1997), topography from GTOPO30 (US Geological Survey's EROS data)
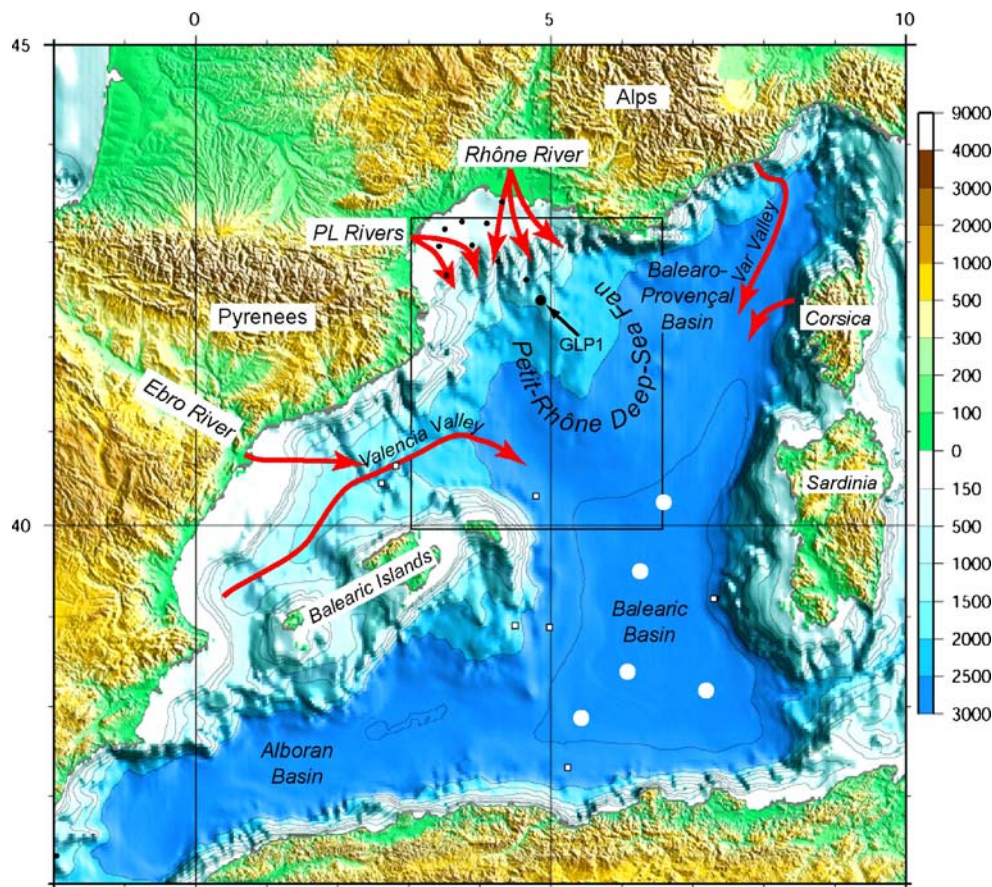
The Lower Pliocene rise of sea level

The palaeo-morphology at the end of the Messinian was very similar to that observed at present, except for the exceptionally low sea level (of the order of 1,000 m). Following this major lowstand event, the reopening of the Strait of Gibraltar during the Lower Pliocene, together with the global Pliocene rise of sea level (DSDP Leg 13, Ryan et al. 1973), resulted in a major high in sea level, well above that of the present day (about 70 m, according to Haq et al. 1987 and Clauzon et al. 1995) and lasting about 1 Ma.

Depending on the morphology of the borderlands, the sea entered large former land areas and formed deep rias of various lengths inside of main rivers on the margin (for example, reaching Lyon in the Rhône ria, 260 km upslope from the present-day shoreline). The combination of the Messinian fluvial incision and the unusually high sea level of the Lower Pliocene led to a very specific palaeo-geography characterised by the absence of shelves, and with deeply incised rias, narrow and deep marine basins fed by a mountainous hinterland with high relief and high sediment supply (Clauzon et al. 1995). Infilling of the rias was realised by prograding Gilbert-type fan deltas (Clauzon et al. 1995), while the deepest part of the Mediterranean basin was the site of condensed deposition, characterized by thin marine shales enriched with planktonic elements (DSDP Leg 13, site 132, Ryan et al. 1973).

The Upper Pliocene to Quaternary glacio-eustatic fluctuations

Extreme climatic modifications generated by fluctuations of ice development in the Northern Hemisphere followed the anomalous Lower Pliocene event. Upper Pliocene to Quaternary sedimentation became mainly controlled by glacio-eustatic sea-level changes related to Milankovitch cyclicities. During the Pleistocene, the dominant cyclicity changed (from 40 to 100 ka) and was accompanied by a change in sea-level cycle amplitudes (from 50 to 100 m). This change, called the Mid-Pleistocene Revolution, generally occurred at stage 22 (around 800–900 ka, e.g. Ruddiman et al. 1986; Paillard 2001). Sedimentation in the Gulf of Lions became dominated by terrigenous input from the main rivers to the basin (Fig. 1) through turbidite systems. Sedimentary input originated principally from the Alps which were drained by the Rhône River and its tributaries. Input from the Massif Central (Chamley 1971) and the Pyrenees remained low. Quaternary fluvial erosion was powerful, as attested by the depth of the rivers, and was variably enhanced by continental uplift (Clauzon et al. 1995).

The absence of detailed chronostratigraphic data in the Gulf of Lions is an important gap in fully understanding its sedimentary evolution as well as the factors controlling this

evolution. Industrial borehole GLP1 (e.g. in Droz 1991; dos Reis 2001; dos Reis et al. 2005) provided the depth of the Pliocene/Pleistocene boundary, which was correlated regionally on industrial HR multichannel seismic profiles (see Fig. 1 for location of GLP1). On seismic sections, Pliocene turbidites are identified at the base of the slope, under the Petit-Rhône Fan (Droz 1991) and all along the margin, except under the Pyreneo-Languedocian Ridge (dos Reis 2001; dos Reis et al. 2005), as small channel/levee systems grouped into a basal complex of channellized units, with little architectural organisation and distal seismic character, compared to the Quaternary deposits (see below). Droz and Bellaiche (1985) proposed that the huge Pleistocene channel/levee complexes on top of the distal Pliocene turbidites at the base of the slope were related to a strong progradation of the margin during the Quaternary, as expected from glacio-eustatic changes of sea level. Pliocene turbidites probably used former Messinian canyons/fluvial incisions observed on the isochron and isobath map of the Messinian surface (Gorini 1993; Guennoc et al. 2000; Gorini et al. 2005). The initiation of turbidite deposition during the Pliocene is to date not age-constrained but probably occurred early, as suggested by their identification close to the Messinian upper evaporites (Droz 1991). The thickening of Pliocene sediments downslope from the Marti Canyon and the Rhône Canyon (dos Reis, unpublished data, and Fig. 4 in Rabineau and Gorini 2006) attests that they were dominant input paths to the basin at that time.

Quaternary gravity sedimentation of the northern Balearic Basin

During the Quaternary, the Gulf of Lions' slope and rise were the site of thick sedimentary accumulations deposited by gravity processes (Droz 1991; dos Reis 2001; Fig. 2). Several huge allochtonous unconformable transparent bodies, interpreted as mass-transport deposits, also attest to the importance of repeated periods of instability during the Quaternary.

Recent morphology of the shelf and slope of the Gulf of Lions

The newly published bathymetric map of the Gulf of Lions (Berné et al. 2001), together with the interpretation of seismic data, enabled a detailed morpho-sedimentary description of the margin and provided an origin for the observed sedimentary features (Berné et al. 2002). The shelf of the Gulf of Lions is 80 km wide in its central part and less than 20 km wide at its western and eastern limits. The outer shelf shows two main types of topographical features which are markers of sea-level changes during and

Fig. 2 Thickness of Quaternary sediments on the slope and rise of the Gulf of Lions (slightly modified from dos Reis et al. 2005)
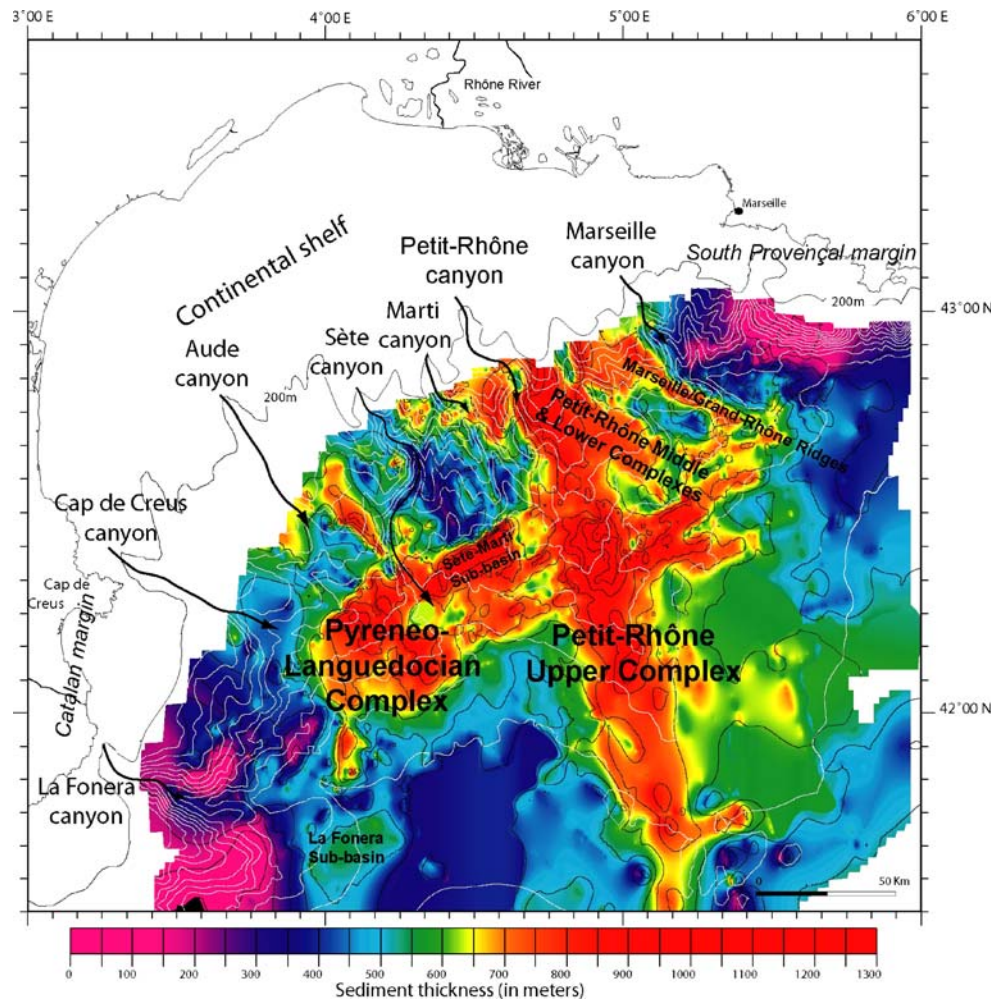
after the Last Glacial Maximum (LGM): (1) a shore-parallel main break in slope of regional extent occurs at 98–112 m (depending on the location on the shelf) down to about 120–128 m, creating a clear and continuous step which is interpreted as isotopic stage 2, sandy shoreline remnants (Rabineau 2001; Berné et al. 2002, 2004; Rabineau et al. 2005); (2) shore-transverse elongated features, either lows or bulges, are representative of the retreat path of palaeo-river courses during the deglacial sea-level rise (Torres 1995; Rabineau 2001; Berné et al. 2001, 2002; Marsset and Bellec 2002). During the LGM, the Petit-Rhône River was connected to the Petit-Rhône, Marti and Hérault canyons, and the Pyrenean rivers were connected to the Aude (also called Bourcart) and Lacaze–Duthiers canyons to the west (Figs. 1 and 3). The connection of rivers has also been demonstrated by Baztan (2004) and Baztan et al. (2005) by the existence of an active axial incision in the Marti, Hérault, Aude, Lacaze–Duthiers and Cap Creus canyons.

On a larger timescale, detailed analysis on the outer shelf using seismic facies and geometries together with short cores showed that the uppermost sequence is made of two horizontally stacked prisms (PI/PII) which are related to the

last 100,000 year cycle (Rabineau et al. 1998, 2005; Rabineau 2001). Prism PI corresponds to deposition through MIS5 to MIS3 (but mostly to MIS3, as previously deposited sediments are eroded on the shelf during sea-level lowering); prism PII corresponds to MIS2. Vertically, at least five sequences with the same motif are stacked and have been related to the last five climatic cycles (540,000 years); numerical stratigraphic modelling has confirmed this interpretation (Rabineau et al. 2005). Each of these cycles brought the shoreline very near to the canyon heads and shelf break at glacial maxima, with direct connections to canyons, favouring transfer to the slope. This interpretation ought to be fully confirmed by the PROMESS1 deep drillings carried out in June 2004 on the outer shelf and upper slope.

The continental slope is characterized by strong incisions by canyons (Fig. 3). Three groups of canyons can be distinguished.

1. To the west, the Pyreneo-Languedocian canyons (from west to east, the Cap Creus, Lacaze–Duthiers, Pruvost, Aude and Hérault canyons) and the Marti and
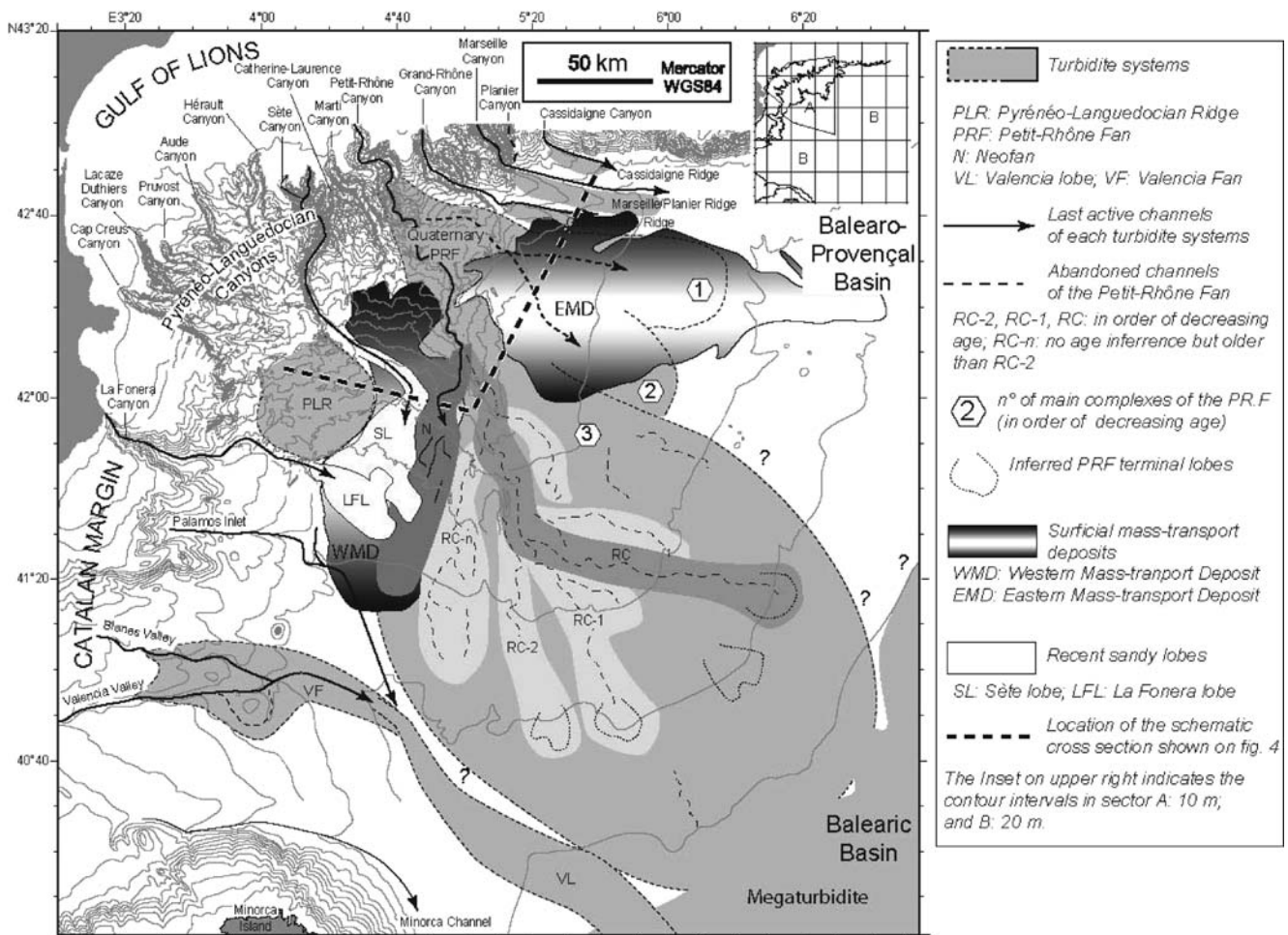
Fig. 3 Synthetic map showing the main sedimentary systems in the northern Balearic Basin and western Balearo-Provençal Basin. Most of the sediments originate from the southern margin of France, via the Rhône River which channels Alpine continental inputs into the Gulf of Lions, and the smaller Pyreneo-Languedocian rivers which drain mainly the Pyrenees. The principal turbidite system is the Petit-Rhône Fan, which extends basinwards up to the northern limit of the Balearic Basin. The map is based mainly on Droz and Bellaiche (1985); dos Reis (2001) and dos Reis et al. (2005) for the Gulf of Lions turbidite systems, Droz et al. (2001, 2003, 2004) and Bonnel et al. (2005) for the Neofan and recent Sète and La Fonera sandy lobes, and Palanques et al. (1995) for the Valencia Fan

Catherine–Laurence canyons form a converging network which joins the Sète Canyon at various depths. Seismic data revealed that these canyons were more or less parallel to each other and oriented approximately N–S, parallel to the slope gradient during the Early Quaternary, and that the converging pattern presently observed was acquired recently (very Late Pleistocene, maybe between 150 and 20 ka; Droz et al. 1998; dos Reis et al. 2005). In the basin, the Pyreneo-Languedocian canyons fed an asymmetrical turbidite system, the Pyreneo-Languedocian Ridge.

2. To the east of the Gulf of Lions, the Grand-Rhône, Marseille/Planier and Cassidaigne canyons (from west to east) are NW–SE-oriented and are followed at the base of the slope by nearly W–E valleys which are bordered on their right-hand side by elongated ridges of turbidite origin.

3. In the central part, between these two groups of canyons, the Petit-Rhône Canyon has a contrasting morphology with a meandering, inner erosional thalweg along its entire length. Meandering inner thalwegs are not known elsewhere in the Gulf of Lions, except in the very upper course of the Aude Canyon where a meandering axial incision is present (Berné et al. 2002; Gaudin et al. 2003, 2006; Baztan et al. 2005). The Petit-Rhône Canyon, presently connected to the Neochannel (see below), has been the only path for feeding alpine detritic material to the Petit-Rhône Deep-Sea Fan during the Quaternary.

The turbidite systems in and around the Balearic Basin

Two thick turbidite systems, the Petit-Rhône Fan and the Pyreneo-Languedocian Ridge, observable on the isopach

map of the Quaternary of the Gulf of Lions (Fig. 2; dos Reis 2001; dos Reis et al. 2005), face the main river outlets of the French Mediterranean margin.

The Petit-Rhône Fan

The Petit-Rhône Fan (Droz 1983, 1991; Coutellier 1985; Droz and Bellaiche 1985; Torres 1995; dos Reis 2001) is the largest turbidite system in the Gulf of Lions. Situated in the central part of the gulf, it represents an accumulation of 3,600 m of turbidites and mass-transport deposits, the Quaternary fan being about 1,300 m thick (Fig. 2). The fan was fed mainly by alpine inputs through the Rhône River and Delta and the Petit-Rhône Canyon.

The Quaternary Petit-Rhône Fan is an overall symmetrical feature extending to at least 2,850 m water depth where channels have been recorded (Droz et al. 2003). At 2,750 m water depth, cores sampled coarse turbidites (Méar 1984). The fan is composed of stacked channel/levee systems characterized by typical lens-shaped seismic bodies associated to stratified facies in levees and high-amplitude chaotic facies in a central channel. The channel/levee systems are grouped into three main complexes (1 lower, 2 middle and 3 upper complexes, from the oldest to the youngest), overlapping each other while avulsing westwards and showing a basinward divergent architecture from a common landward point source, the Petit-Rhône Canyon (Fig. 3). Although absolute ages are not available for these turbidite complexes, they are assumed to have accumulated during Quaternary lowstands of sea level. Based on this assumption and on the palaeo-drainage reconstruction on the shelf during the Quaternary (Monjuvent 1984), a chronostratigraphic history was proposed by Bellaiche et al. (1989) which places the transition from the middle complex to the upper complex during the Mindel/Riss interglacial, i.e. a high sea level dated between 200 to 500 ka, depending on

correlations between continental and marine studies (Van Eysinga and Haq 1987; Kukla and Cilek 1996).

During the Late Quaternary, the Rhône Fan underwent a last westward avulsion of its main channel and built, partly on its right levee and partly on a transparent mass-transport body (see below), the lobate Neofan (Droz and Bellaiche 1985; Torres et al. 1997; Fig. 4). The Neofan includes two main units (Bonnel 2001; Bonnel et al. 2005), a basal one (the Neofan Chaotic Unit) made of high-amplitude seismic facies of about 50 m thickness, interpreted as an avulsion lobe similar to the HARPs of the Amazon Fan (e.g. Pirmez et al. 1997), and an upper unit (the Neofan Transparent Unit) about 30 m thick, representing a small channel/levee system, seismically transparent on sparker data and stratified on chirp data, which prograded on its avulsion lobe (Fig. 4). The Neofan extends south-westwards for at least 100 km down from the Neochannel bifurcation point to a distal area where several generations of lobate features, interpreted as terminal lobes, are present (Droz et al. 2004). The seafloor in the western part of the Neofan shows giant scours which are erosional features typical of a channel/lobe transition zone, according to Kenyon et al. (1995), and are considered to originate from hydraulic jump processes of the turbidity currents at the termination of the Neo-channel (Kenyon et al. 1995; Bonnel et al. 2005).

AMS radiocarbon dating indicates that the starvation of the Neofan occurred at 15.1 ka B.P. (in this paper, all the ages younger than about 20 ka are expressed in ^{14}C timescale; Table 1 shows the corresponding calibrated ages and reservoir correction age, if known) when it became inactive. Upstream of the avulsion point, the starvation and inactivity of the fan seems to have occurred 4 ka later at 11 ka B.P. (Bonnel et al. 2005). The onset of the Neofan is still unknown because it is too thick (~80 m) to be reached by conventional coring. From pollen analysis in a core located on the right levee of the Neochannel, Beaudouin et
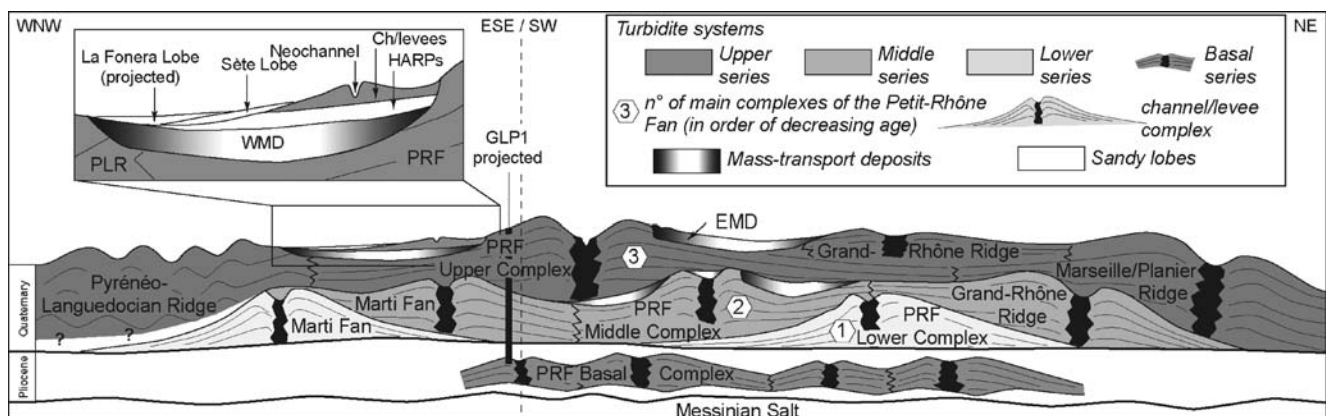

Fig. 4 Schematic cross section of the rise of the Gulf of Lions (see Fig. 3 for approximate location), showing the Plio–Quaternary sedimentary architecture of the margin and stacking pattern of the turbidite systems and mass-transport deposits. Ages are inferred from industrial boreholes (GLP1, courtesy of Total, in Droz 1991 and dos Reis 2001). The cross section is modified from dos Reis et al. (2005) to illustrate the mass-transport deposits and the most recent sedimentary events (Neofan and Sète and La Fonera sandy lobes). Not to scale

Table 1 ^{14}C dates cited in the text and corresponding calendar ages (when published)

Location	Units	Material dated	^{14}C ages (ka)	Reservoir correction (year)	Calendar ages[a] (ka)	References
Western Gulf of Lions	La Fonera Lobe, last event of sand deposition	Interpolation using mean sedimentation rate (0.15 m/10^3 years)	~4.4	Not available	–	Bonnel et al. (2005)
	Sète Lobe, last event of sand deposition	Interpolation using mean sedimentation rate (0.15 m/10^3 years)	~8.0	Not available	–	
Catalan Margin	Big'95	Foraminifer at the bottom of the overlying hemipelagic unit	10.3	402	11.5	Lastras et al. (2004)
Petit-Rhône Fan	Petit-Rhône Fan main body, north of the avulsion point, end	Not mentioned	11.0	Not available	–	Bonnel et al. (2005)
	Neofan, end	Foraminifers at the bottom of overlying hemipelagic sediments	15.1	600	18.0	Bonnel et al. (2005)
	Petit-Rhône Fan main body, south of the avulsion point, end	Not mentioned	20.0	Not available	–	Méar (1984)
Balearic Plain	Megaturbidite, end	Foraminifers at the bottom of overlying hemipelagic sediments	17.6	Not mentioned	20.0	Hoogakker et al. (2004)
	Megaturbidite, start	Foraminifers at the top of overlying hemipelagic sediments	20.3	Not mentioned	23.0	

[a] Using INTCAL98 (Stuiver et al. 1998)

al. (2004) provided an estimated age of 18.6 ka B.P. at 8.5 m inside the upper unit of the Neofan, which allowed Bonnel et al. (2005) to calculate a mean deposition rate of ~1 m/10^3 years and a linearly extrapolated maximum age of 100 ka B.P. for the occurrence of the avulsion and beginning of growth of the Neofan. However, turbidite deposition rates are not linear but rather highly discontinuous, with short periods of accelerated deposition (for example, up to 3–4 m/10^3 years in the Amazon Fan, according to Showers et al. 1997) alternating with periods of slower hemipelagic deposition. Therefore, the use of mean deposition rates is highly unreliable, and the proposed age is probably greatly overestimated. Previously, Méar (1984) had indicated that turbidite sedimentation on levees stopped at about 20 ka B.P. in water depths greater than 2,000 m, i.e. downslope from the Neochannel bifurcation point. This starvation of the fan beyond −2,000 m possibly relates to the shift of the Petit-Rhône Fan depocentres towards the Neofan. Admitting that this age is indicative of the approximate onset of the Neofan, a much higher mean deposition rate is calculated (16 m/10^3 years), which is also not accurate but is probably closer to the real deposition rate of the avulsion lobe, accounting for more than 60% of the Neofan thickness.

The Pyreneo-Languedocian Ridge

In the western corner of the Gulf of Lions, the Pyreneo-Languedocian Ridge is a 900–1,000 m thick sediment accumulation at the base of the western slope which connects with the Pyreneo-Languedocian as well as the Marti and

Catherine–Laurence canyons (Fig. 3). Berné et al. (1999) and Droz et al. (2001) proposed that the Pyreneo-Languedocian Ridge is an asymmetrical feature located on the right-hand side of the Sète Valley, with strong similarities to the Var Ridge on the Provençal Margin (Savoye et al. 1993) and fed by sediment funnelled in the converging network of the Pyreneo-Languedocian canyons. More recently, dos Reis et al. (2004a, 2005) considered a two-stage formation, i.e. an early fan-like period, related to the abandoned N–S lower courses of the Pyreneo-Languedocian canyons and a subsequent asymmetrical, ridge-like period associated with overflow from the Sète Canyon fed by the Pyreneo-Languedocian canyons.

Shelf studies have shown that detritic sediments were supplied to the ridge partly by the Pyreneo-Languedocian rivers (from southwest to northeast, the Tech, Têt, Agly, Aude, Orb and Hérault) and partly by the Rhône River which fed not only the Petit-Rhône Canyon but also the Marti Canyon and maybe the Hérault Canyon during the LGM (Berné et al. 1999, 2002). According to Baztan (2004), the Sète Canyon has also been connected to the Rhône River.

The Pyreneo-Languedocian complex is spatially restricted, extending from about 2,000 to 2,500 m water depths, over approximately 50 km in a NW–SE direction. It is made of stratified, undulating seismic facies interpreted as migrating sediment waves (e.g. Jallet and Giresse 2005), which aggraded vertically throughout the Quaternary, the Sète Valley undergoing only a slight progressive lateral migration towards the east. Although direct dating information is lacking, geometrical relationships from seismic

profiles indicate that the formation of the ridge was probably contemporaneous to that of the upper complex of the Petit-Rhône Fan and, therefore, is inferred to be Upper Pleistocene (around 200–500 ka; Bellaiche et al. 1989). In contrast to the Petit-Rhône Fan, no channel/levee systems are observable during the Pliocene, suggesting that the activity of the Pyreneo-Languedocian canyons began later than that of the Petit-Rhône Canyon and Deep-Sea Fan.

The area in the vicinity of the outlet of the Sète and La Fonera canyons (on the Catalan Margin) remained active very late during the Quaternary (Late Pleistocene–Holocene) whereas the Petit-Rhône Fan and Neofan had already been abandoned (Droz et al. 2001). This recent activity is highlighted by thin, low-backscattering patchy lobes at the outlet of both canyons, in which cores revealed beds of silts to fine sands intercalated within a 2.3-m-thick unit of foraminiferal and nannofossil oozes (Bonnel et al. 2005). In both cases, the hemipelagic unit has been deposited since the abandonment of the Neofan at 15.1 ka B.P., and radiocarbon data at the top of the hemipelagic unit (2.5 ka B.P.) indicated an estimated age of 8 ka B.P. in the Sète Lobe and 4 ka B.P. in the La Fonera Lobe for the last events of sand deposition, by linear interpolation using mean sedimentation rates (Bonnel et al. 2005; Figs. 3 and 5).

Other turbidite systems around the Balearic Basin

Eastern part of the Gulf of Lions and Provençal Margin In the eastern corner of the Gulf of Lions, the Grand-Rhône, Marseille/Planier and Cassidaigne canyons (from west to east) gave rise to elongated turbidite ridges (Droz 1991; dos Reis 2001; dos Reis et al. 2004b), extending for up to 90 km parallel to the south Provençal Margin. Except for the Cassidaigne Canyon, which does not have a clear relationship with a river, both the other canyons received Alpine detrital input from the Grand-Rhône outlet of the Rhône River, to the east of the Petit-Rhône outlet. The lower courses of the canyons are deflected towards the east, in response to halokinetic control (dos Reis et al. 2004b), rather than Coriolis control, and are bordered on their southern side by the ridges.

Detailed analysis of the architecture of the ridges showed that the current, highly asymmetrical ridge-like morphology is salt-tectonically imposed and not hydrodynamically dependent and, therefore, is not representative of the true architectural style of the depocentres. dos Reis et al. (2004b) showed that, along the Marseille/Planier Valley, overbanking of turbidity currents occurred on both sides but that, on the northern side, syn-sedimentary activity of growth faults created hemi-grabens which trapped turbidites, preventing the typical levee morphology from developing on the left levee. The left levee of the Grand-Rhône Valley was also shown to be inhibited by a local buttress in the form of the prominent Marseille sedimentary ridge, up to about 600 m high.

Eastern Iberian Margin To the west of the Balearic Basin, short canyons and gullies are cut into the continental shelf and slope of the Catalan Margin (Amblas et al. 2004) but no thick turbidite systems have to date been documented. The main river delivering sediments to the basin is the Ebro River (Fig. 1), which contributed to the formation of a turbidite system made of short channel/levee systems, debris flows and apron deposits on the upper slope of the Ebro Margin (Alonso and Maldonado 1990; Alonso et al. 1991; Alonso and Ercilla 2002).

The main deep turbidite system on the eastern Iberian Margin is the Valencia Fan. The Valencia Valley has a tectonically controlled SW–NE course, between the Iberian continental slope and the Balearic Islands until it merges with the open Balearic Basin where it is deflected towards the southeast (Figs. 1 and 3). The Valencia Valley is not connected to a river but collects inputs from tributaries dissecting the Iberian Margin on its northern side, including from the Ebro.

The Valencia Valley is a long, leveed valley of the mid-ocean submarine valley type (Canals et al. 2000), which ends with a terminal lobe on the Balearic Plain east of Minorca Island (Palanques et al. 1995). The Valencia Lobe extends more than 150 km downdip and is at most 25 km across (Fig. 3). Although not dated, it appears to be a very recent feature (Late Pleistocene–Holocene), as suggested by fresh bedforms and erosional features as well as sandy turbidites containing pteropod shells of Holocene age, recovered in cores (Morris et al. 1998).

Mass-movement deposits

In addition to the turbidite systems, gravity deposits are present on the northern and western margins of the Balearic Basin, as broad and thick (up to 75 m thick for a volume of up to 200 km³) unconformable transparent mass-transport deposits.

In the Gulf of Lions, the western and eastern mass-transport bodies (representing an estimated total volume of 370 km³) truncate both levees of the Petit-Rhône Fan (Bellaiche et al. 1986; Figs. 3 and 4). The western mass-transport body extends along 150 km at the base of the Gulf of Lions slope between the Pyreneo-Languedocian Ridge and the Petit-Rhône Fan. It is up to 120 ms two-way travel time (about 100 m) thick in its upslope part, and represents an estimated volume of 217 km³. Because of its transparent seismic facies, erosional basal surface and allochtonous origin, this mass-transport body is interpreted as a debris flow and was previously named the Western Debris-Flow (Droz and Bellaiche 1985). Direct dating is not yet available for this body. However, it is intercalated between

the Petit-Rhone Fan (below) and the Neofan (above). Considering that its onset has been most likely of very short duration (instantaneous at a geological timescale), we can infer that instability processes occurred around 20 ka B.P., between the end of activity of the Petit-Rhône Fan south of the Neochannel bifurcation point (Méar 1984) and the onset of the Neofan (see above).

On the Ebro Margin, the Columbretes Slide (Field and Gardner 1990), subsequently renamed the Big'95 debris flow by Canals et al. (2000) and Lastras et al. (2002), is identified on sub-bottom profiles as a transparent sediment body located on the Ebro slope, at the base of the slope and in the Valencia Valley. This transparent body shows thickness ranging from 153 m near the source area to less than 15 m in its distal depositional area, and extends over a surface of about 2,000 km^2 corresponding to a sediment volume exceeding 26 km^3 (Lastras et al. 2002, 2004). From radiocarbon dating, the minimum age of the debris flow is about 10.3 ka B.P. Other indications of recent instability processes have also been recorded on both sides of the Valencia Valley by Alonso et al. (1995).

Altogether, these allochtonous bodies of Late Quaternary age, although not occurring synchronously along the margins of the Balearic Basin, represent an estimated minimum volume of 400 km^3, attesting to major episodes of instability at the end of the Quaternary (around the LGM and the following deglacial period).

Similar but buried mass-transport deposits are known in the Gulf of Lions and on the Iberian Margin. Under the Petit-Rhône Fan, mass-transport bodies are interstratified between the middle and upper complexes (complexes 2 and 3), on both levees of the middle complex and inside the channel (Droz and Bellaiche 1985; Fig. 4), suggesting that sediment instability has been a recurrent phenomenon throughout the Quaternary. In the present state of knowledge, without age assignment, the origin, age and recurrence during the Quaternary of such huge mass-transport events cannot be specified. On the Catalan Margin, Lastras et al. (2004) identified several debris flow events under the Big'95 debris flow. The biggest one rests on a seismic reflector (G) which separates Pliocene from Quaternary deposits, and is therefore probably older than those in the area of the Rhône Fan where the buried mass-transport deposit rests on the middle complex and would therefore be Middle Quaternary (see above).

The Balearic Abyssal Plain "Megaturbidite"

Rothwell et al. (1998, 2000) described an approximately 9-m-thick, seismically transparent unit of turbidites, called the "Megaturbidite", at about 10 m below seafloor infilling the deepest part of the Balearic Basin. This megaturbidite was interpreted as a single depositional event (Rothwell et al.

1998). However, more recent seismic data provide evidence for possibly at least two successive episodes of deposition (Droz et al. 2003). This unit is considered to extend in the centre of the basin, bounded by the 2,800 m isobath, representing a total estimated surface of 60,000 km^2 and a volume of about 500 km^3. Recent bathymetric and seismic surveys (Droz et al. 2003) refined the north-western boundary of the transparent unit to a water depth of about 2,850 m. This megaturbidite was sampled by five Calypso cores taken from aboard the R/V Marion Dufresne (cruise 81, 1995). The cores are up to 32 m long, located along a N–S transect from seawards of the Petit-Rhône Fan to the Algerian Margin (Fig. 1). The megaturbidite is composed of a thick mud megabed (up to 8 m in LC04), considered to correlate with the conspicuous transparent layer seen on 3.5-kHz seismic profiles; at the base of this mud megabed is a silty to sandy interval (Rothwell et al. 1998). AMS radiocarbon dating in hemipelagic intervals bounding the megaturbidite give ages of about 17.6 ka B.P. at the top and about 20.3 ka B.P. at the bottom (Rothwell et al. 1998; Hoogakker et al. 2004), indicating that the megaturbidite event was of short duration (2 ka) and deposited sediments at a rate of 3 m/10^3 years during the Last Glacial Maximum (beginning of stage MIS2).

The megaturbidite is included into a lithological unit at least 30 m thick made of upward-fining sequences (basal sands, silt to thick structureless muds), interpreted as a succession of pounded turbidite deposits, intercalated with thinner bioturbated foraminifer-rich mud intervals of hemi-pelagic origin. In the Calypso cores, turbidites account for about 90% of the sediment column, with a percentage increase towards the north. This northward evolution is emphasized also by the northward coarsening of basal sands in the megaturbidite, suggesting that sediments in the megaturbidite possibly originated from the northern parts of the basin (Gulf of Lions via the Petit-Rhône or Sète Canyon, Catalan Margin, Ligurian Margin via the Var Valley or Corsican Margin). Preliminary analysis of recent seismic data (Ferrer 2004) did not reveal any physical continuity of the megaturbidite with any of the northern and western seismic bodies (neither the Rhône Fan, the Western Mass-Transport Deposit, nor the Valencia Fan). Very high-resolution seismic profiles indicate that the transparent unit is intercalated between the distal Rhône Fan (which became inactive around 20 ka B.P. at water depths greater than 2,000 m; Méar 1984) and the Valencia Lobe which, according to Limonov et al. (1995), is Late Pleistocene–Holocene. A more precise origin for the material accumulated in the megaturbidite remains unknown. However, in the basinal turbidites which cover the megaturbidite, analysis of clay minerals of sediments collected in short cores from the Balearic Basin (Méar 1984) indicates a rhodanian origin of the inputs, possibly through the Grand-

Rhône River and canyon head where the suspended material has been concentrated during the Holocene (Aloïsi et al. 1982).

## Quaternary sedimentary evolution of the northern Balearic Basin

This synthesis allows us to recapitulate the sedimentary evolution of the northern Balearic Basin during the Quaternary. The known or inferred ages for the different sedimentary systems are summarized in Fig. 5.

Pleistocene

Following the formation of the Pliocene basal complex of the Rhône Fan, strong turbidite sedimentation occurred during the Pleistocene and led to aggradation and progradation of thick turbidite systems (up to 1,300 m thick) linked to the main canyons or the convergent system of canyons on the Gulf of Lions Margin.

From indirect estimates, the formation of the southern part of the upper complex of the Petit-Rhône Fan ended around 20 ka B.P., in response to the instability of the levees and the

Fig. 5 Synthesis of the ages known from coring or inferred from correlations for the main sedimentary systems of the northern Balearic Basin. References for age attribution: a Bonnel et al. (2005), b Lastras et al. (2002, 2004), c Méar (1984), d Hoogakker et al. (2004), e this study, f Méar (1984), g Bellaiche et al. (1989), h e.g. Van Eysinga and Haq (1987); Kukla and Cilek (1996), i e.g. Ruddiman et al. (1986); Paillard (2001), j GLP1 borehole in Droz (1991) and dos Reis et al. (2005), k e.g. Conchon (1992), l e.g. Gautier et al. (1994); Krijgsman et al. (1999)
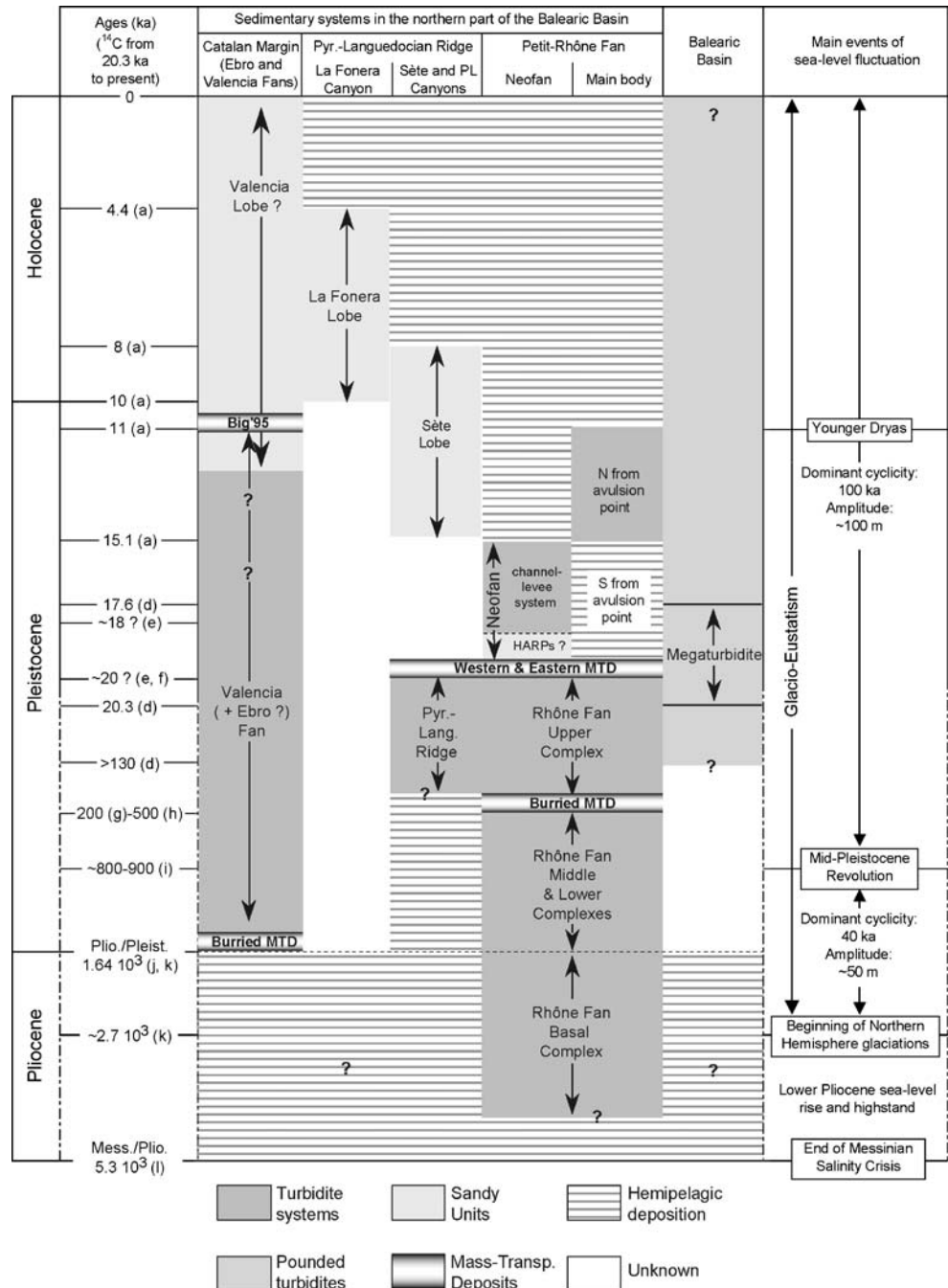
lower continental slope inducing mass-transport events which probably were of short duration. During this episode of instability, collapse of the levees inside the main channel blocked the channel and induced its avulsion. Renewed aggrading activity occurred, leading to the construction of the small channel/levee system of the Neofan on top of its avulsion lobe. The starvation of the Neofan probably relates to the progressive disconnection of the Rhône River and Petit-Rhône Canyon as sea level rose following the Last Glacial Maximum (MIS 2), and the definitive abandonment of the fan occurred 4 ka later upstream of the bifurcation point.

Distal turbidites accumulated in the Balearic Basin as a 9-m-thick megaturbidite bed between 20.3 and 17.6 ka B.P., approximately at the time when the architecture and evolution of the Rhône Fan was strongly modified by instability processes which resulted in a shift of the depocenters towards the Neofan. However, because of uncertainties about the age of these events, there is no clear relationship between the accumulation of the megaturbidite and either the mass-transport processes or the turbidite processes.

15 ka B.P. to present

During the deglacial period, turbidite activity diminished progressively as sea level rose. Definitive abandonment of the Rhône Fan occurred at 11 ka B.P. However, erosional activity remained in some canyons, until 8 ka B.P. for the Sète Canyon and 4 ka B.P. for the La Fonera Canyon (Droz et al. 2001; Bonnel et al. 2005), resulting in the re-deposition of eroded sediments as very thin, unchannellized lobes at the outlet of the canyons. In addition, new hydrodynamic data obtained within the framework of the EUROSTRATAFORM programme show that some canyons of the Gulf of Lions (Cap de Creus, Lacaze–Duthiers and Petit-Rhône canyons) are presently registering strong currents (e.g. Fabres et al. 2005).

Conclusions

Based on extensive results obtained over the last 20 years of research in the Gulf of Lions and northern Western Mediterranean, the Plio–Quaternary sedimentary evolution of the southern margin of France is now among the best known in the world. However, our knowledge of this margin is still lacking a good chronostratigraphy to constrain its general evolution and to precisely determine the main factors controlling sedimentation during the Quaternary.

New data from the PROMESS1 drilling cruise (June 2004; Berné 2004) will bring some stratigraphic constraint for the last 500 ka (Upper Quaternary) on the outer shelf and upper slope. Despite mass movements which have affected most of the continental slope, it is hoped to utilize high-resolution multichannel seismic profiles across the margin to tie in the precise chronostratigraphic framework of PROMESS1 to the turbiditic depositional sequences along the continental rise. On a longer timescale, we hope to be able to drill a very deep hole in the deep basin, sampling the last 30 Ma, as proposed to IODP in April 2006 (Pre699; Jolivet et al. 2006).

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