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ORIGINAL

Introduction to "Turbidite systems off France and the Lesser Antilles"

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Importance of the study of continental margins for human interests

Continental margins are a key region for solving future human challenges. They represent important hydrocarbon reservoirs including both oilfields and methane hydrates. This importance has not only an economic aspect. Indeed, 40% of the people in the World live at less than 60 km from the shoreline (http://www.unep.org). As a consequence, the study of continental margins is also of societal importance. For example, geohazards such as sediment slides, which occur frequently on continental margins and may trigger catastrophic tsunamis, can be generated solely by gravity, the most common force on Earth, without any tectonic forces being involved. In addition, continental margins represent an effective hydrocarbon trap. Productivity is high and associated with high sedimentation rates, which plays an important part in the terrestrial carbon dioxide cycle.

Within this framework, deep-sea turbidite systems play a fundamental part. They are the locations on the margins where sediment transport and accumulation are highest. As a consequence, these are the sites where organic matter can be rapidly buried and then preserved before decomposition. This both prevents carbon release to the atmosphere and contributes to future hydrocarbon reservoir formation. The understanding of the actual process of carbon trapping is necessary to explore ancient potential reservoirs and to understand how the Earth system can react to the increase of carbon dioxide in the near future.

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As sediment loading is very important in submarine sedimentary systems, overloading and oversteepening are usually sufficient to generate large-scale instabilities. The instabilities might be tsunamogenic, as for the 16 October 1979 Var event (Habib 1994). The slide and/or the motion of the induced turbidity current generated a 4-m-high tsunami along the shore of Nice, killing 11 people.

In the upper part of continental margins, additional processes can substantially increase the failure hazard — hydrodynamic shelf processes (storm waves, surge, and sediment accumulation under the action of shelf currents). During sea-level lowstand, hazard is even enhanced because of the accumulation of sediment close to the steep slopes near the shelf break, the possible presence of a non-buoyant ice cap, and the destabilisation of methane hydrates due to changes in temperature and pressure conditions. The upward force created by the methane bubbles can lead to giant failures, as it is suspected in parts of the giant Storrega slide off Norway (Bugge 1983; Mienert et al. 1998).

In deep-sea turbidite systems, canyons are the most important locations to study sediment transport and slope failures because they are bordered by steep flanks generating frequent sediment slides, and because many canyons are situated along the axes of river mouths where the sediments eroded in the continental drainage basins are concentrated.

As a consequence, canyons and the related deep-sea turbidite systems represent a sedimentary record of changes occurring with time at the mouths of rivers, such as flood intensity and frequency, and changes in the nature and volume of sediment loads. These are strongly related to climate changes (cf. precipitation, temperature and related vegetation cover) influencing drainage basins. In that sense, canyons and deep-sea turbidite systems represent important targets to understand the linkage between the impact of climatic changes on continents and their record in deep-sea sedimentation.

Tool evolution

The rapid progress in our knowledge of deep-sea submarine systems which has occurred during the last 25 years is mainly due to technological improvements. Figure 1 shows the comparison between a map of the Capbreton Canyon published by Reclus (1872) and the most recent map of the same morphological area (Cirac et al. 2001). Figure 2 shows the more recent improvement of collected data by comparing the map of deep-sea fans on the east Corsica margin by Bellaiche et al. (1993) and that of Gervais (2002).

Several tools are used to collect data on submerged margins. They enable either direct observation (submersible dives, sediment or rock sampling) or indirect measurements, usually using artificial reflected acoustic waves.

Sidescan sonar transmits a beam of sound on both side of a "fish" (sidescan tool). A backscatter signal is returned, recorded and processed. This signal depends on both the topography and the nature of the seafloor. As a consequence, sidescan sonar provides information on seafloor morphology, especially on its roughness (presence of sedimentary structures; Blondel and Murton 1996) and nature, mainly grain size and consolidation state (Masson 2003). Sidescan sonar used for rapid and large surveys are usually towed at a velocity of about 10 knots and at a few 10s of metres below the water surface to avoid the effect of large temperature change close to the ocean surface. They allow one to map a surface of several 10,000 km per day (Masson 2003). Sidescan sonar used for more detailed surveys are usually towed at a velocity of less than 3 knots and at a few 10s of metres above the seafloor. Best resolution for sidescan sonar is about 1 m.

Use of sidescan sonar for detailed surveys necessitates preliminary surveys at a large scale with a multibeam sounder. Interpretation of sediment nature necessitates ground truth provided either by coring or by submersible dives (submarines or remote operated vehicles).

Multibeam echosounders transmit a fan of beams typically 120–150° on cross track of the boat direction (Blondel and Murton 1996). Backscatter information allows one to generate bathymetry maps and, after processing, three-dimensional viewing and videos. This tool is usually embedded on the boat hull, and is operated usually at speeds larger than 10 knots. The frequency at which the tool is operated depends on the bathymetry being investigated. The swath width depends also on this frequency, and varies between a few 100s of metres (shallow water on continental shelves) and several 10s of km on abyssal plains (Masson 2003). An acoustic imagery system is generally associated to the bathymetric tool, and recorded simultaneously. It works similarly to side-scan sonar but with different frequencies.

Seismic devices include a sound source (air gun, sparker), an array of hydrophones and a transceiver unit. The sound source and the hydrophone array are towed behind the ship (Jones 1999). Acoustic pulses are emitted into the water. The acoustic beam is reflected from the seafloor and from any interfaces located below the seafloor. Interfaces called seismic reflectors are generated by physical changes in sediment properties, especially sediment density including parameters such as grain size, water content, and porosity. As a consequence, seismic records provide images of the geometry below the seafloor. The vertical distance corresponds to the time the signals took to travel from the sound source to a given interface and back to the hydrophone array (two-way travel time, TWTT).

Seismic tools are classified by the frequency of the acoustic input.

- Low-frequency tools (a few Hz) enable a good penetration (whole Earth crust) but have a low resolution (low-resolution seismics), no more than a few 10s of metres. They are rarely used in sedimentology studies.
- Medium-frequency tools (10s–100s Hz) enable a penetration of several seconds TWTT, corresponding to approximately 2,000–3,000 m and a precision of about 10 m. They are the tool used for studies at the basin scale, particularly for oil exploration and well correlation.
- High-frequency tools (kHz) enable a penetration of a few tenths of a second TWTT, which corresponds to a few 100s of metres and a precision of a few metres (high-resolution seismics). They are the tool used for the study of entire submarine sedimentary systems or large parts of these.
- Very high-frequency tools (<10 kHz) enable a penetration of a few metres in coarse-grained sediments to a few 10s of metres in fine-grained sediments, with a vertical accuracy of about 1 m to a few 10s of centimetres (very high-resolution seismics). They are the tool used for the study of recent sedimentary processes as well as of palaeoclimatic changes. They facilitate precise correlations with sediment cores.

Three-dimensional seismics is used for very detailed study of a very restricted surface. It necessitates an important network of hydrophone lines with a close spacing. Complex processing allows one to generate three-dimensional "cube" representations of the geometry of sedimentary or other geological objects below the

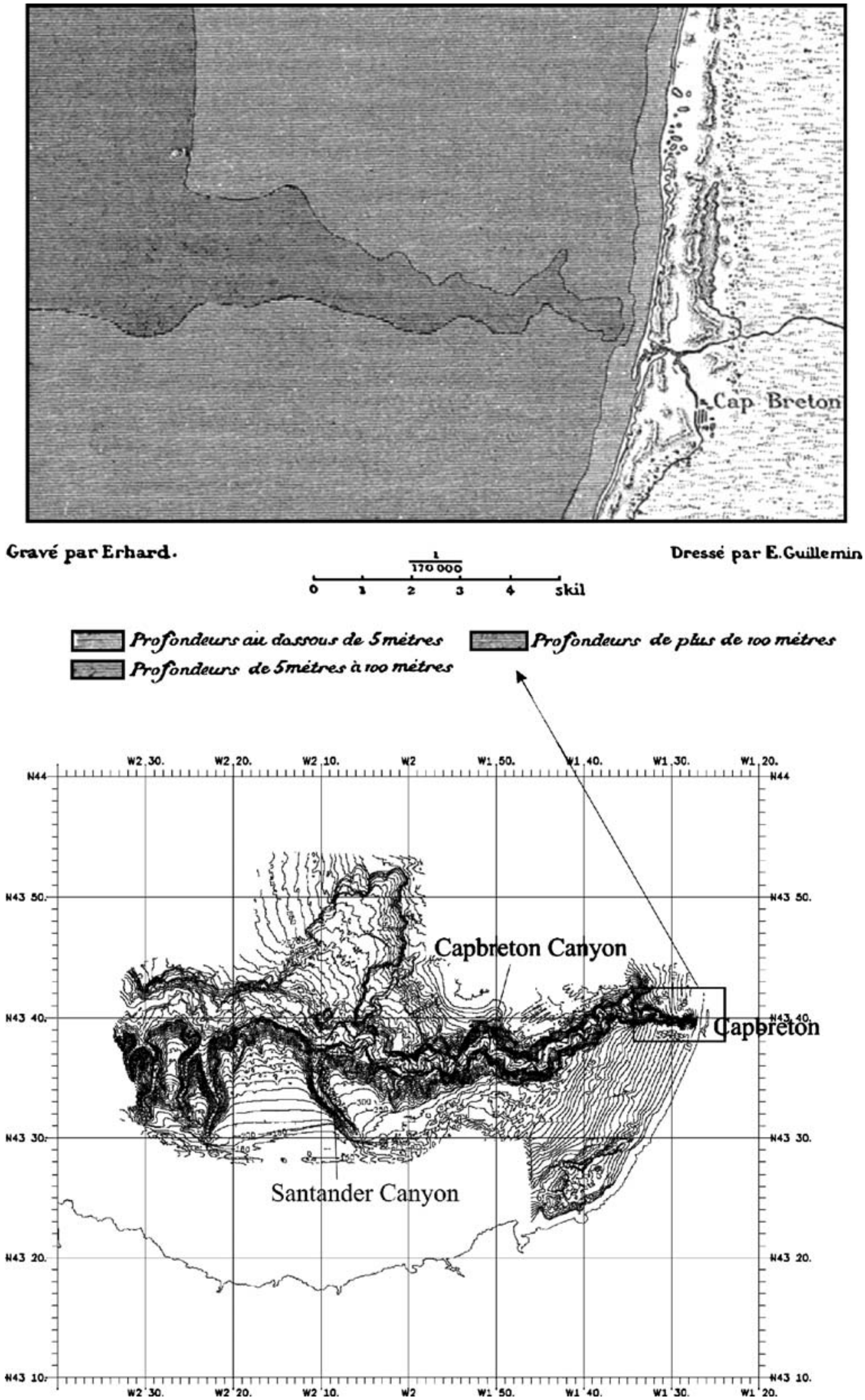

Fig. 1 Map of the Capbreton Canyon by *top* Reclus (1872) and *bottom* Cirac et al. (2001)

seafloor. Time slices based on such cubes are used to represent the palaeomorphology at a given time.

Coring is probably the tool which has evolved the less during the last two decades. The most classical way to sample sediment is still to use gravity or piston cores. The length of recovery rarely exceeds 20–25 m, and can exceptionally reach 60–70 m in soft sediments but not more than 5 m in coarse-grained sediment. Core perturba-

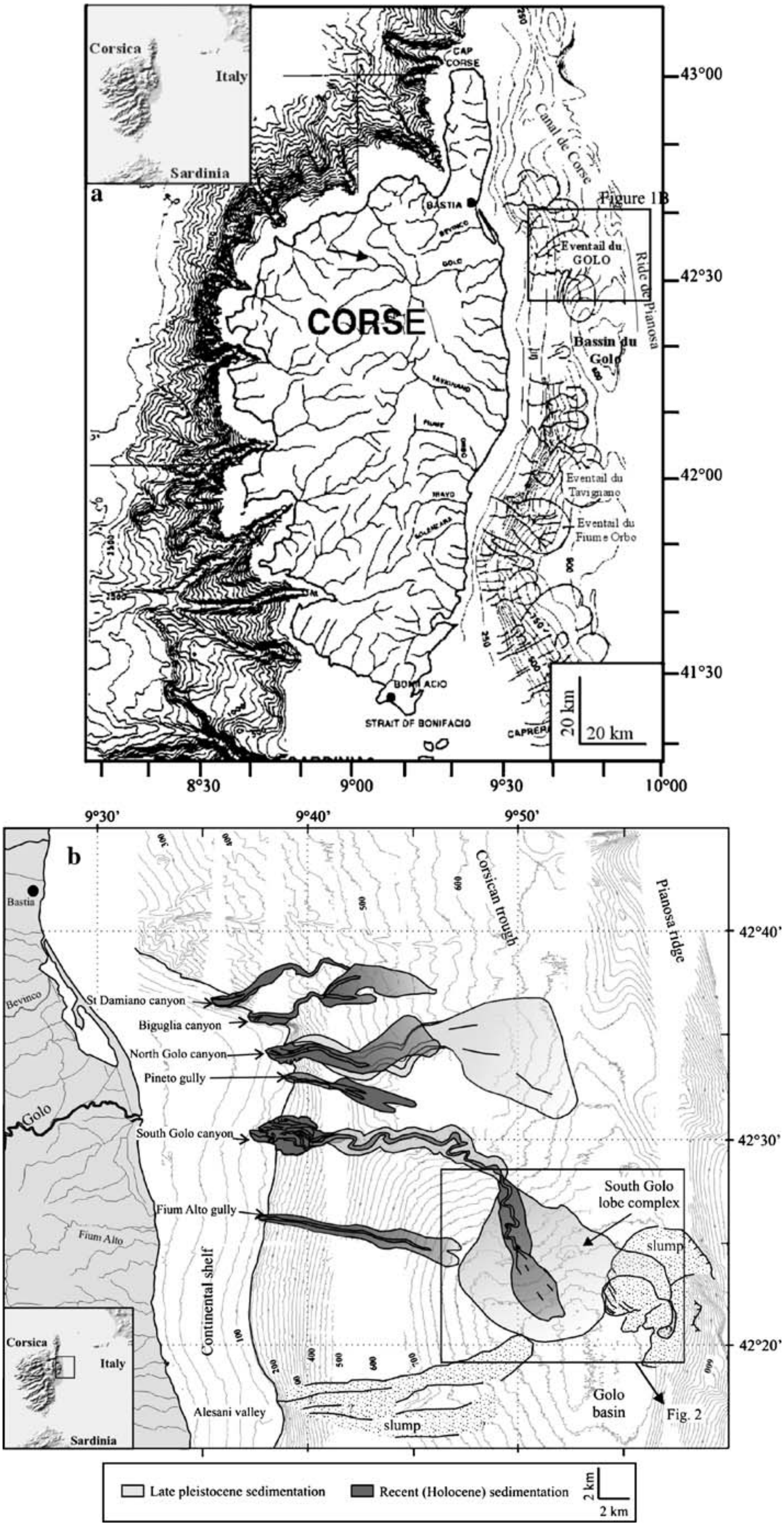

Fig. 2 **a** Map of the east Corsica deep-sea fans by Bellaiche et al. (1993). Frame by Gervais (2002). **b** Map of the Golo deep-sea fan

tion is common in sandy sediment and no coring device, easy to deploy, can be used routinely in sandy deposits. Sandy sediment can be sampled over a small length (1 m) using a box-corer or over a few metres using a hammer-core.

Recently, interface coring has been developed, allowing one to sample up to 1 m of sediment including the seawater-sediment interface. Long coring devices, such as the Calypso corer of the French RV *Marion-Dufresne*, enable the recovery of cores up to 70 m long under particularly favourable conditions.

Turbidite systems on French margins

Deep-sea clastic systems are called turbidite systems if we refer to the processes at their origin, or “fans” if we refer to their shape. No terminology is perfect. Considering the processes acting in deep-sea clastic systems, the term “turbidite system” is not completely justified because several gravity processes are active, including turbidity currents sensu stricto (see discussion in Mulder and Alexander 2001), and sediments of completely different origin (pelagite or contourite) may be interbedded in the system. The term “fan” originates from the initial description of the Navy fan by Piper and Normark (1983). However, most of the deep-sea clastic systems do not have a “fan” shape. The term deep-sea “delta”, sometimes used to describe deep-sea turbidite systems, should definitely be abandoned as it creates confusion vis-à-vis river deltas located on the continental shelf.

Deep-sea turbidite systems on French margins are mid-sized systems (Fig. 3). The largest is the Rhône deep-sea turbidite system (max. length: 300 km; max. width: 200 km; Bonnel et al. 2005). The deep-sea Armorican, Celtic and Cap-Ferret systems each have a surface area not exceeding 30,000 km^2 (Zaragosi 2001).

The Armorican system is interpreted in terms of a multiple source ramp model, according to the classification of Reading and Richards (1994). The Celtic fan is fed mainly by the Whittard and the Shamrock canyons but has several secondary canyons merging with channel-levee systems. It shares the characteristics of multiple-source and single-source deep-sea turbidite systems (Zaragosi et al. 2003a,b), including a giant right-hand levee (the Whittard Ridge). Both systems have a fan shape. Zaragosi (2001) suggested the name the “Celtic ramp” for the set of the Celtic and Armorican fan systems. The Cap-Ferret Fan is still poorly known (Crémer 1983; Mézerais 1991). It is fed by three canyons: the Cap-Ferret, the Capbreton and the Santander canyons. This turbidite system has a more-developed right-hand (north) levee.

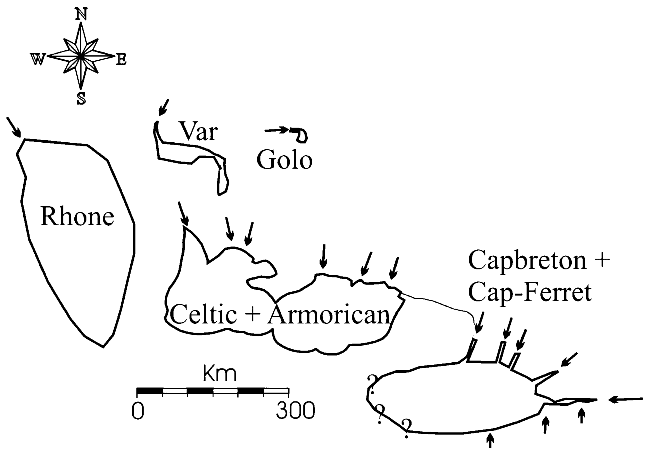

Fig. 3 Compared size of turbidite systems on French Margins

Aim of this thematic issue

This thematic issue serves as a synthesis to introduce the activity of the French working group GDR “Marges”. It reports on recent advances in the study of deep-sea clastic systems, including both siliciclastic metropolitan margins and the volcaniclastic French Antilles margins. The issue presents short papers on recent results on these systems, including a general overview of the margins (Mulder et al. and Droz et al. for the Atlantic and the Mediterranean margins respectively), general processes acting on the systems (Picard et al., French Antilles), features and processes acting on a part of a system such as the Capbreton Canyon (Gaudin et al.) or the Var sedimentary levee (Migeon et al.), processes during the late Quaternary in the Golo turbidite system (east Corsica, Mulder et al.), and climatic forcing on the recent construction of the Celtic and Armorican turbidite systems (Zaragosi et al.).

Two papers are dedicated to the general presentation of the margins: Mulder et al. present the characteristics of the Atlantic margin and deep-sea turbidite systems, and Droz et al. present the general features of the Western Mediterranean margin and related deep-sea turbidite systems.

Zaragosi et al. show how cores retrieved on the levee of a turbiditic channel can record continuous high-resolution palaeoenvironmental changes associated with exceptionally high sedimentation rates. This paper presents results from three long cores taken on the levee of the Armorican and Celtic turbidite systems, showing how the analysis of sedimentary microfacies allows one to discriminate turbidite deposits from ice-rafted load.

Gaudin et al. focus on the recent and present activity of the Capbreton Canyon. This paper shows the importance of the canyon head as both a reservoir and a receptacle for shelf sediments before their transport towards the deep sea. It points out that recent (Holocene) turbidite activity is at the origin of an intense nested levee construction, associated with alternation of turbidity current overspilling and hemipelagic deposition.

Mulder et al. focus on sedimentary processes acting during the late Quaternary in a small sandy turbidite system (Golo System, east Corsica). This paper shows how the morphology of deep-sea systems is related to sedimentary process types, and how these processes and the evolution of deep-sea turbidite systems are related to sea-level changes during the late Pleistocene and Holocene.

Migeon et al. present the structure of the giant right-hand levee of the Var turbidite system (Var Sedimentary Ridge). This paper shows that the levee is composed of superimposed sediment waves, the shape and nature of the sediment waves evolving with levee growth. The sedimentary sequences forming the sediment waves are due to either hyperpycnal flow or turbulent surge deposition.

Picard et al. present the morphology and processes on a volcaniclastic margin (French Antilles). They illustrate the importance of recognizing the continuum between subaerial and submarine processes.

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