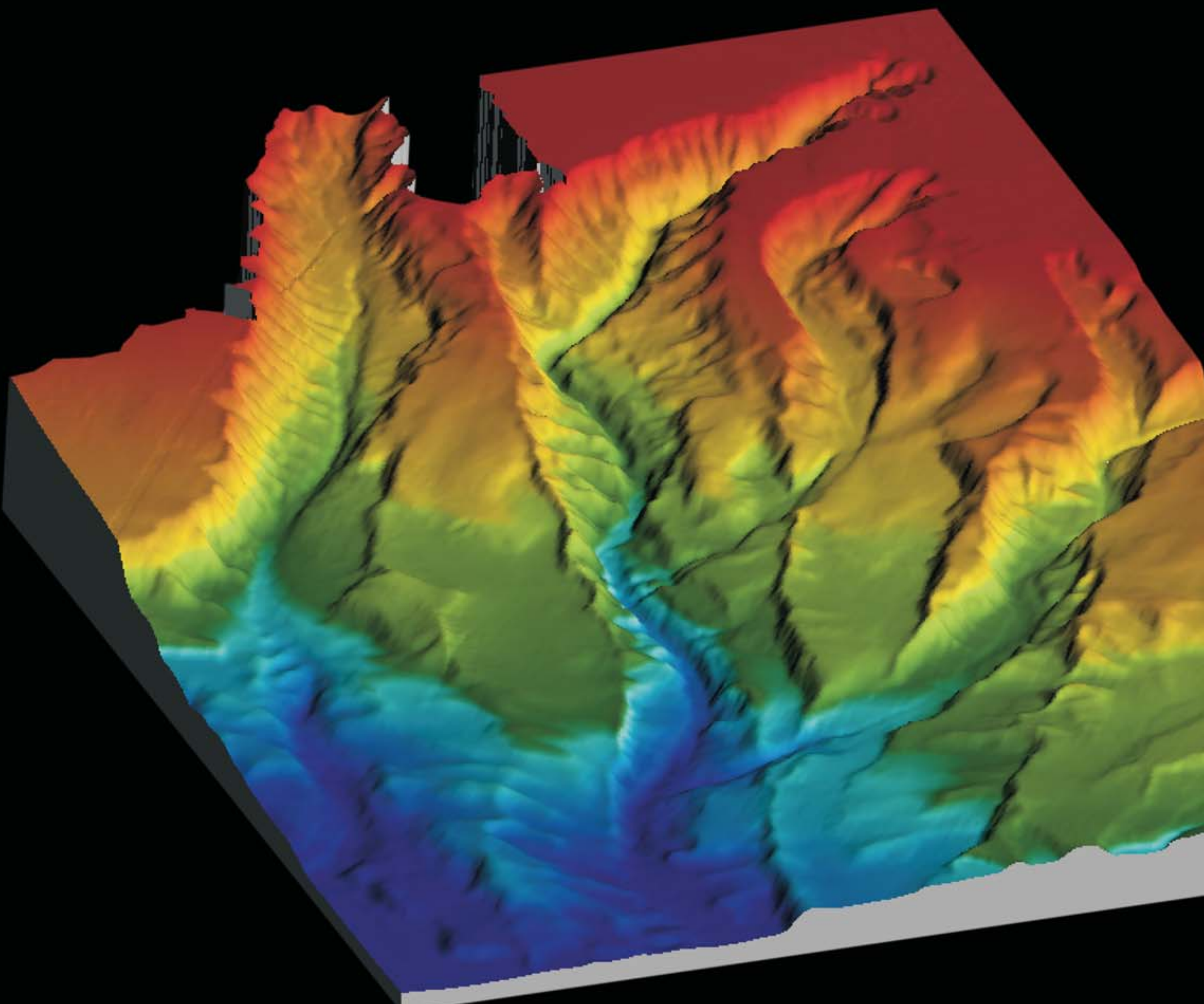
The Role of Canyons in Strata Formation



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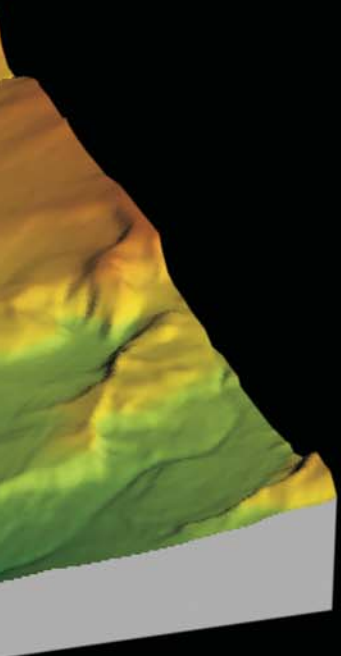

This paper provides a spatial and temporal multi-scale approach of European submarine canyons. We first present the long-term geologic view of European margins as related to controls on submarine canyon development. Then we discuss the extent to which submarine canyon systems resemble river systems because both essentially form drainage networks. Finally, we deal with the shortest-term, highest-resolution scale to get a flavor of the current functioning and health of modern submarine canyons in the northwestern Mediterranean Sea.

Submarine canyons are unique features of the seafloor whose existence was known by European fishermen centuries ago, especially for those canyons that have their heads at short distance from shoreline. Popular names given to specific canyons in the different languages spoken in European coastal communities refer to the concepts of a “deep” or “trench.” In the old times it was also common thinking that submarine canyons where so deep that nobody could measure their depth or even that they had no bottom.

Submarine canyons are just one of the seven different types of seafloor valleys identified by Shepard (1973) in his pioneering morphogenetic classification. Shepard (1973) defined submarine canyons as “steep-walled, sinuous valleys, with V-shaped cross sections, and relief comparable even to the largest of land canyons; tributaries are found in most of the canyons and rock outcrops abound on their walls.” Canyons are features typical of continental slopes with their upper reaches and heads cut into the continental shelf.

The seaward continuation of submarine canyons across deep-sea fans and channel-levee complexes at the base of the continental slope and rise is usually referred as fan valleys or turbidite channels. In fact, some authors tend to use the term "canyon-channel system" to refer to submarine canyons continued by turbidite channels.

Currently, scientists know not only that the definition above, but also the criteria used by Shepard (1973) must be adjusted and substantially refined. This is largely due to the inception of the modern multibeam mapping techniques in the 1980s, which ended the era of almost blind seafloor mapping when extrapolation among single beam distant bathymetric profiles was the rule. Prior to multibeam, the view of submarine canyons and their morphological complexities was poorly perceived from single-beam echo-sounding data. Multibeam mapping of submarine canyons has made possible the unveiling of a new landscape, often referred as a "seascape" by scientists, with about the same level of detail as onshore relief maps. What was hidden below the "great blue" of classical, land-focused maps has finally been revealed.

Other techniques have equally contributed to a new understanding of submarine canyons and continental margins in general. These include shallow water and deep-towed side-scan sonars, two- and three-dimensional seismic reflection profiling systems at various resolutions and penetrations, fast response and *in situ* moored instrumentation, an army of underwater vehicles and observatories allowing direct and remote imaging and characterization of the seafloor and the processes shaping it, improved sediment and rock sampling and drilling techniques, downhole logging tools, and *in situ* tests, among many others.

Thanks to these modern techniques, which provide improved capacity to observe the Earth system, we now know that submarine canyons are ubiquitous features of continental margins that display a large variety of lengths, widths, heights, shapes, and morphological complexities. Though some continental-margin segments may not have canyons, most continental margins display submarine canyon systems with varying degrees of development.

SETTING OF EUROPE'S SUBMARINE CANYONS: THE LONG-TERM VIEW

The ability of submarine canyons to contribute to strata formation depends very much on their geologic setting. Europe's seaboard encompasses a large variety of continental margin settings, from the glaciated margins of Scandinavia to the river-dominated margins of southern Europe, including the margins in the Mediterranean. The intensity of glacial and/or riverine conditions has changed through time following global climatic oscillations. Though the Nordic margins are much less glacially influenced today than they were during glacial epochs, the imprint of the ice is clearly visible on the seafloor and on the deposits contributing to margin's outbuilding. Weaver et al. (2000) located the glaciated margin of Europe north of 56°N. Glacial troughs hundreds of meters deep that extend to the shelf edge have been swath-mapped on the Scandinavian shelf, thus allowing the reconstruction of past ice dynamics. Submarine canyons do exist on the glaciated margins of Europe, though their relationship with the mouths of large glacial trough on the shelf edge has not been firmly established. Large sediment fans like the Bear Island Fan and the North Sea Fan consist mainly of large numbers of debris deposits of glacial origin that formed through subglacial processes, including the bulldozing action of grounded ice. Sediment dynamics and transport to the outer margin during the Holocene has been volumetrically much less than in glacial times, and only some redistribution of sediment by bottom currents and landsliding has been observed. Therefore, the role of submarine canyons in the long-term history of the glaciated margins of Europe has been largely determined by ice sheet expansion and contraction.

Although Europe's Atlantic continen-

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tal margin south of 56°N is certainly glacially influenced, this latitudinal fringe could be considered as river-dominated because most of the final transport of eroded materials to the shelf and outer margin occurred by fluvial means. On the northern margins of the Mediterranean Sea there has been no direct glacial influence. However, distant glacial influence has existed since the ice ages, when melt water from ice masses to the north substantially contributed to enhanced liquid and solid discharge of rivers opening into the Mediterranean Sea and satellite basins like the Black Sea, particularly during ice retreat. The main European rivers draining into the Mediterranean Sea originate in mountain ranges that were ice covered during glacial times, such as the Ebro (Pyrenees), Rhône, Po, and Danube (Alps). Other large rivers opening into the Black Sea, such as Dniester, Dnieper, and Don have most of their course within the formerly much colder deep heart of Eastern Europe.

Transport of sediment to the deep southern European margins was enhanced during ice ages and glacial transitions not only because river discharge and sediment supply were much greater than at present, but also because river mouths were at or close to the shelf edge due to the lowered sea level. Sediments were delivered directly to the outer shelf and upper slope, thus enhancing canyon incision and down-canyon transport. This largely contributed to the formation of deep-sea fans and to the filling of abyssal plains (Figure 1). In contrast to fans on glaciated margins, southern European deep-sea fans consist of piles of sediment left by turbidity currents, which are bottom-flowing turbulent currents laden with suspended sediment that move down subaqueous slopes and spread horizontally over the bottom. Sediment suspended in turbidity currents gives them a density greater than

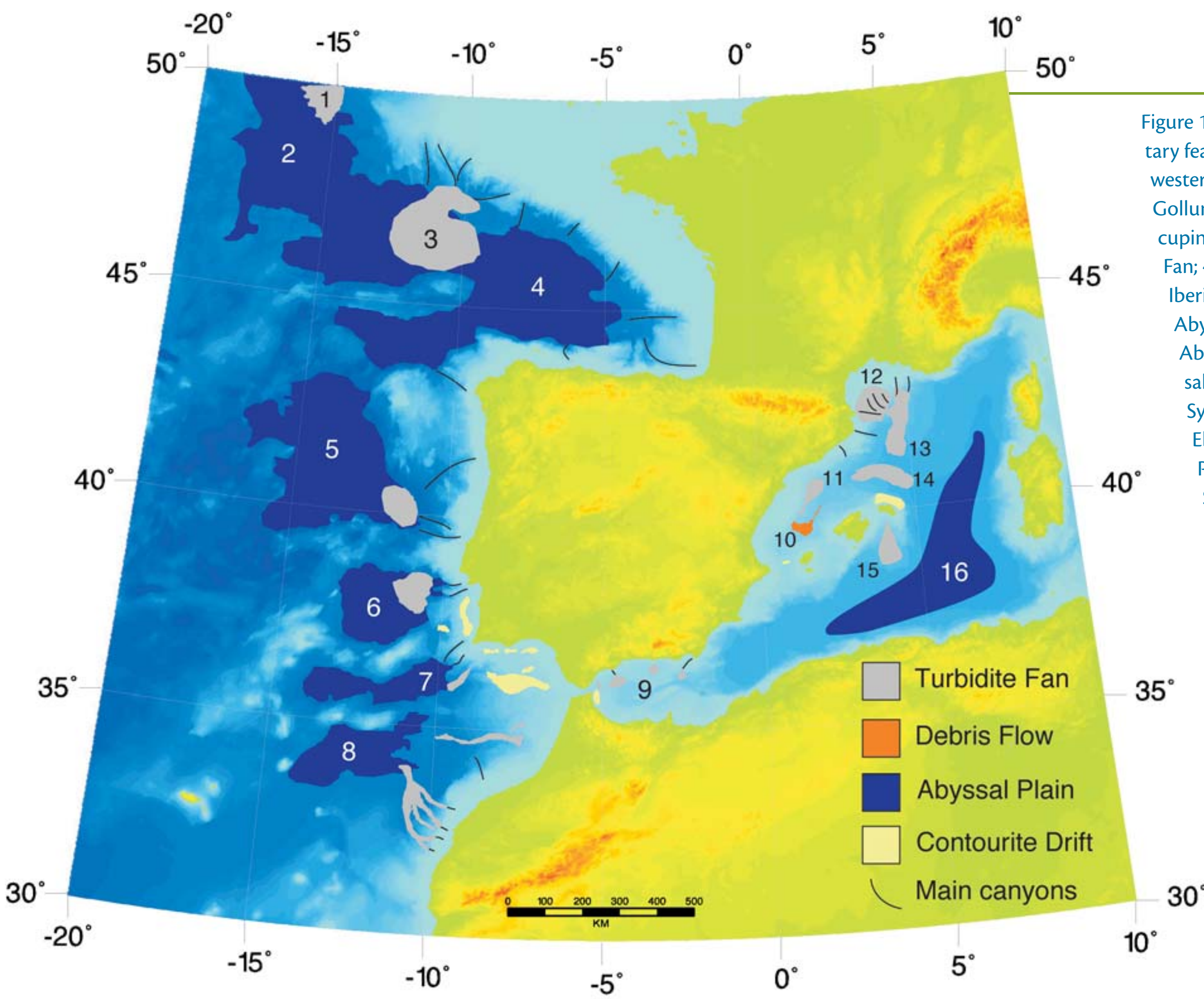


Figure 1. Main morphosedimentary features of the deep southwestern European margins. 1: Gollum Canyon System; 2: Porcupine Abyssal Plain; 3: Celtic Fan; 4: Biscay Abyssal Plain; 5: Iberia Abyssal Plain; 6: Tagus Abyssal Plain; 7: Horseshoe Abyssal Plain; 8: Seine Abyssal Plain; 9: Alboran Turbidite System; 10: BIG'95 Slide: 11: Ebro Turbidite System; 12: Pyrenean Canyons Deep-Sea Sedimentary Body: 13: Rhone Deep-Sea Fan; 14: Valencia Fan; 15: Menorca Fan; 16: Algero-Balearic Abyssal Plain.

that of surrounding waters. The resulting sediment bodies usually form lobes with a central hanging, meandering channel flanked by levees that form during channel spillover episodes. Such sediment bodies, known as channel-levee complexes, are stacked on top of each other forming hundreds-of-meters-thick sediment piles. Those channels represent the continuation of submarine canyons, which in the long term have played a major role in funnelling sediment to both the deep Atlantic and Mediterranean ocean margins off southern Europe. The southern part of the Atlantic margin of Europe is incised by hundreds of canyons, from the Gollum Canyon system southwest of Ireland to the San Vicente Canyon southwest of the southern tip of Portugal. In between, the Armorican slope west of France is cut by a large number of relatively short, basement-controlled canyons, with some of them feeding the Celtic Fan, then followed by the large Cap Breton Canyon in between France and Spain, the Cantabrian canyons of Llanes, Lastras, and Avilés off northern Spain, and the impressive canyons of Nazaré, Lisbon, and Setubal off Portugal, to cite just a few. From north to south these canyons have largely contributed to the infill of the almost coalescent Porcupine, Biscay, Iberia, Tagus, and Horseshoe abyssal plains.

A similar situation occurs in the Mediterranean Sea where many canyons incise the continental margin from one end of the basin to the other. Although a large number of relatively small channel-levee complexes develop on the base of slope as related to canyon-channel systems in the Mediterranean, some large canyon-fed deep-sea fans and turbidite systems also exist that have been explored during the last decades. The most important ones are the Nile deep-sea fan (Sardou and Mascle, 2003), whose feeding river does not directly relate to the general setting depicted above since its source area is in tropical latitudes of Africa, the Rhône deep-sea fan (Torres et al., 1997), and the Ebro turbidite system (Canals et al., 2000). Other less-conspicuous and less-studied western Mediterranean deep-sea fans are the Valencia fan and the Menorca fan. In the Black Sea, the large Danube deep-sea fan (Popescu et al., 2001) is at present being investigated extensively (Figure 1) within EU-funded research projects.

In addition, sediment transport along Mediterranean canyons has contributed to the infill of the deep plains in the western and eastern Mediterranean and in the Black Sea. It must be noted that some of the most recent and largest sedimentary units result from single events represented by megaturbidites (deposit from a mega-turbidity current) in the Balearic and Herodotus abyssal plains (Rothwell et al., 1988, 2000). These units are 300 to 600 km^3 each and the Balearic one extends over 60,000 km^2 (Figure 1), more than twice the size of the state of Maryland in the United States. Accelerator mass spectrometry (AMS) radiocarbon dating shows that the two megaturbidites have been emplaced during the last low stand of sea level at the height of the last glacial maximum. The megabed on the Balearic Abyssal Plain is derived from the southern European margin (i.e., from the strongly canyoned margins off southern France and Spain), and is the main sedimentation event over the last 120 thousand years in the region. Although the triggers for this event remain speculative, major slope destabilization following a long period of high sediment accumulation is the most plausible mechanism to explain such a "sedimentation crisis."

Sea-level rise pushes landwards shorelines and river mouths, which are the main sediment feeders of continental margins. This is why, in contrast with glacial times, the majority of canyons become inactive during high sea level stands, and are covered by blankets of pelagic fine particles. However, submarine canyons may temporarily reactivate due to events such as large storms, river floods, or earthquakes. The earthquake and tsunami that destroyed Lisbon in 1755 triggered a massive turbidity current that travelled for a few hundreds of kilometers along the Setubal Canyon and out onto the Tagus Abyssal Plain (Thomson and Weaver, 1994).

In addition to the close connection between old and modern river systems and submarine canyons in southern European margins, there are other aspects that are worth considering in relation to canyon development and functioning. One aspect is the structural control on the location and path of some European canyons. Probably the best examples are found around the Iberian Peninsula where structural lineaments known on land clearly control the emplacement of some of the largest submarine canyons, independent of the location of large river valleys. This is particularly true in the case of Cap Breton, Lastres, Avilés, Nazaré, and San Vicente canyons off the Atlantic coastlines, and the Almeria (Figure 2), Blanes, La Fonera, and Cap de Creus canyons off the Mediterranean shoreline of Iberia. In fact, it appears likely that for entire margin segments off Europe and elsewhere, the location, morphology, and spacing of canyons are controlled by a combination of sediment supply, slope angle, seafloor topography, basement topography, faulting, and history.

The long-term strata-formation potential of individual submarine canyons and their level of activity during both sea-level highstands and lowstands also relies on several, often-interrelated local factors. These factors include the incision of the canyon head into the continental shelf and its closeness to a river mouth, coastal and shelf physiography, shelf width, hydrodynamic regime and circulation, and tectonic setting, and the nature, frequency, and volume of sediment supply. On the Iberian margin, several canyons cut back to the inner shelf and feed directly or almost directly from the lower course of river valleys, including major rivers (e.g., Tagus and Sado Rivers for Setubal Canyon off Portugal), and minor rivers (e.g., Tordera River for Blanes Canyon and Ter River for La Fonera Canyon off northeast Spain). Other canyons are located so that their upper course and head interrupt the general circulation where it collides against coastal promontories, thus favoring the funnelling of particles down-canyon. This is the case of Cap de Creus and, to a lesser extent, the Lacaze-Duthiers Canyons at the western exit of the Gulf of Lions in the northwestern Mediterranean Sea. Other canyons, like those of the Ebro margin, are slightly incised on one of the widest continental shelves in the Mediterranean Sea and therefore have little chance to trap materials directly derived from the river mouth.

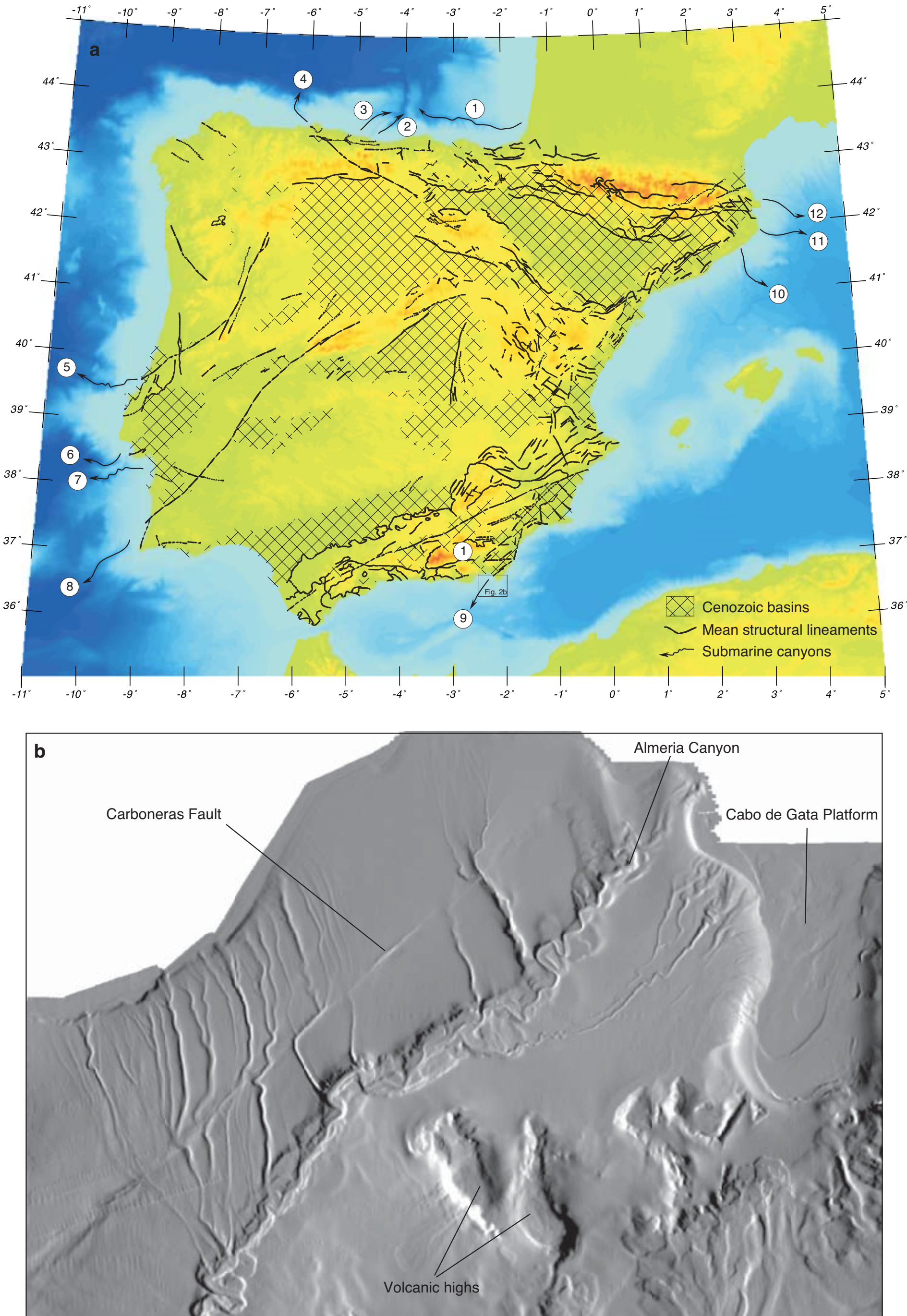


Figure 2. (a) Schematic geologic map of the Iberian Peninsula and location of some of the largest submarine canyons. 1, Cap Breton; 2, Llanes; 3, Lastres; 4, Avilés; 5, Nazaré; 6, Lisbon; 7, Setubal; 8, San Vicente; 9, Almeria; 10, Blanes; 11, La Fonera; 12, Cap de Creus. (b) Shaded-relief image of the tectonically-controlled Almeria Canyon and tributaries. Note sharp bendings of the tributaries to the north due to the Carboneras Fault.

SUBMARINE CANYONS AS SEDIMENTARY DRAINAGE SYSTEMS OF EUROPE'S MARGIN: THE DISTANT VIEW

Submarine canyons are organized in many different ways and the European margin provides a plethora of examples. Probably the area where the largest variety of submarine canyon types exists is the northwestern Mediterranean, including the margins of Sardinia and Corsica, the Ligurian Sea, the Gulf of Lions, the Gulf of Valencia, and the Balearic Promontory. Here there are (1) dozens of short (i.e., some tens of kilometers long) linear canyons with no or few tributaries, apparently disconnected from fluvial sources like those incised into the Ebro and Barcelona continental slope, (2) large (>100 km long), wide and deeply incised canyons running from short distance to coastal cliffs to depths in excess of 2,400 m like Blanes and La Fonera canyons off Northern Catalonia, (3) complex, branching canyon networks converging towards the base of slope with tributaries of different orders such as those in the Gulf of Lions (see figures in Berné et al., this issue), (4) chute-like, steep submarine canyons representing the continuation of deeply incised canyons on land such as those south of French Provence and west of Corsica, and (5) a southwest-northeast oriented deep-sea channel known as Valencia Channel that runs parallel to the Iberian and the North Balearic margins from where it collects sediment inputs.

Sediments funnelled through submarine canyons in the northwestern Mediterranean tend to converge towards the base of slope and the northern part of the Balearic Abyssal Plain where they feed the >1 km thick Plio-Quaternary (5.3 million years before present to present) sediment piles of the Rhône and Valencia fans and the Pyrenean Canyons Deep-Sea Sediment Body (PCDSB), in addition to several thinner localized channel-levee complexes (Canals, 1985; Canals et al., 2000). When it reaches the geographic longitude of the Rhône deep-sea fan sediment pile, the Valencia Channel cannot progress further eastward and is forced to turn southward to then run roughly parallel to the eastern Balearic margin. Both the feeder canyon-channel system of the Rhône deep-sea fan and the Valencia Channel progressively branch into distributary channels that finally vanish into the abyssal plain.

The canyons in the northwestern Mediterranean Sea give way downslope to channel-levee systems in which the channel is incised on top of a large sediment body, with the channel sides being built up by sediment flows that overtop the channel walls (as in river levee systems). The last turbiditic sandy layers in the Rhône neofan (the youngest fan lobe in the Rhône deep-sea fan that started growing during the last sea-level lowstand) have been dated at 6.6 to 4.4 thousand years before present, which corresponds to the present sea-level highstand. This proves that turbidite flows in the Gulf of Lions are able to reach the deep margin and basin during epochs when the shoreline is far from the shelf edge and canyon heads.

The second major feature of Mediterranean margins that has had a profound influence on the development of submarine canyons is the presence of thick evaporite layers formed 5 million years ago (Ma) during the Messinian salinity crisis, when the Mediterranean Sea dried up. Evaporite layers deform easily under the overburden of thick sediment piles such as those that have accumulated during Plio-Quaternary times on the northwestern Mediterranean margin and also on other margin segments of the Mediterranean Sea. According to Canals (1985), evaporite deformation (known as halokinesis) under the increasing load of overlying Plio-Quaternary sediments destabilized the lower slope in the Gulf of Lions, creating morphological irregularities that progressively extended to form linear conduits. These conduits evolved into submarine canyons when they reached the continental shelf edge after retrogressive erosion and upslope failure. Mass wasting also affected the walls of such conduits, thus contributing to their widening. The impact of halokinesis on the evolution and present situation of the sediment drainage pattern of northwestern Mediterranean margins has been imaged by seismic reflection profiles and multibeam maps. Several generations of subsurface evaporite pillows determine the current location of the lower course of various canyons in the Gulf of Lions. Ridges created by evaporite flowage have resulted in a field of large, parallel undulations shaping the seafloor at the PCDSB (see above). Diapirs punctuate the distal part of the Rhone deep-sea fan with distributary channels winding in between diapiric highs.

The similarity of subaerial and submarine drainage systems can be seen in the Valencia Trough/Ebro area (Figure 3). Note that both systems have a similar size and that height difference is also of the same order, about 3400 m for the Ebro Basin from the highest peaks in the

Pyrenees to sea level, and about 2700 m for the Valencia Trough from sea level to the distalmost, deepest part of the trough to the northeast. Also, both systems have a main trunk fed by tributaries coming from the sides—the Ebro River and the Valencia Channel, respectively. There are, however, marked differences. The most obvious is the relative simplicity of the submarine drainage network compared to the terrestrial one. This is not due to observational bias, nor just a matter of age (river systems tend to be older than most submarine canyons), but of contrasting sediment dynamics. It is quite common that canyon heads and upper reaches, or even entire canyons, become buried by younger sediments. While there are many examples of buried canyon heads in northwestern Mediterranean margins, the most spectacular is the total burial of the Neogene L'Escala Canyon offshore Roses Embayment on the northeast Iberian Peninsula. In contrast, continental sediment dynamics leads to the burial of river valleys only under very exceptional conditions. A second major difference is that the Ebro Basin receives tributaries from both flanks, the Pyrenees and the Iberian Massif, while the Valencia Trough is only fed from its river-dominated western slope on the Iberian margin. The lack of permanent rivers

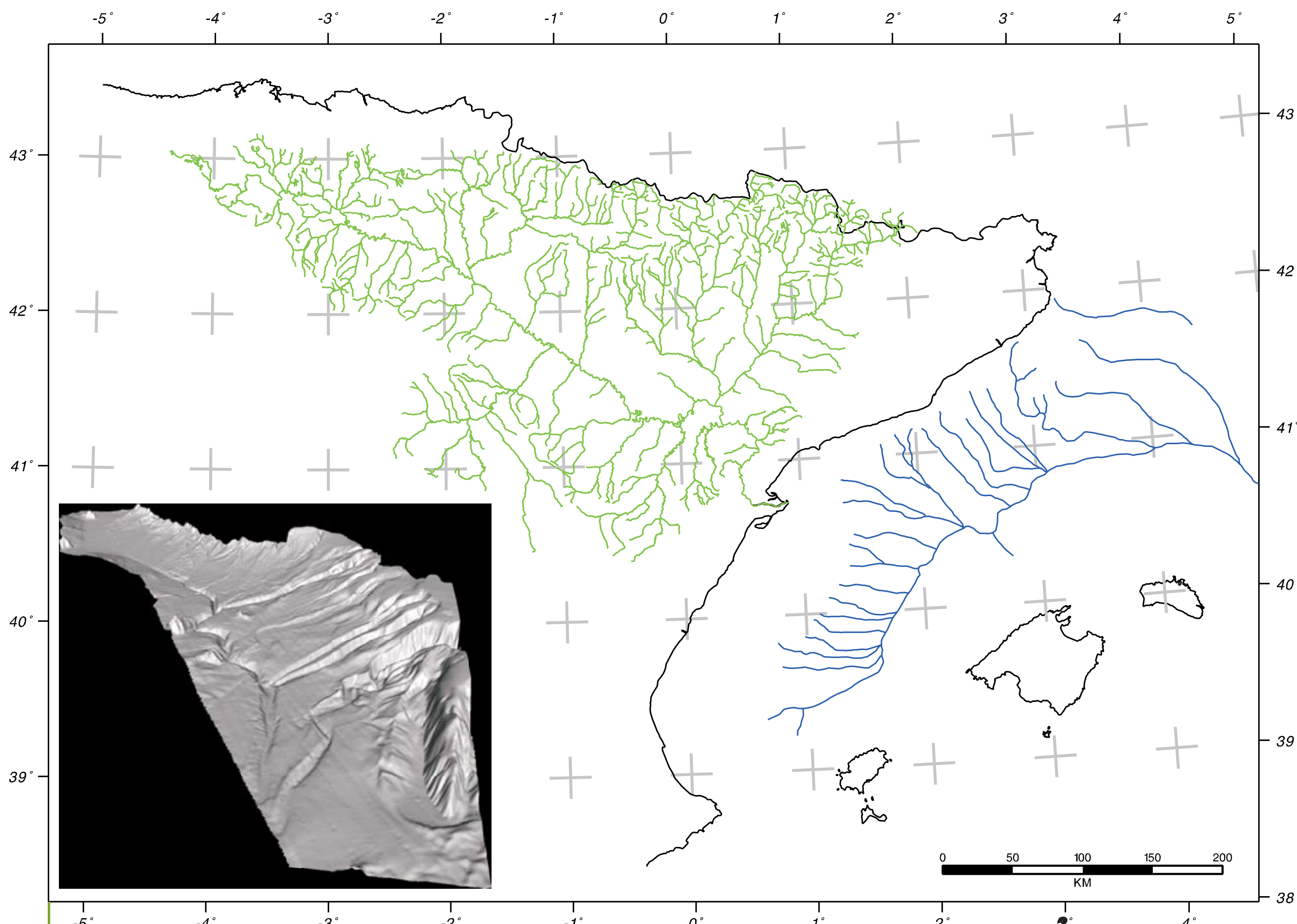


Figure 3. Comparison of the fluvial drainage network of the Ebro Basin on land (green) and the Valencia Trough offshore (blue). Similarities include roughly the same size drainage network, and both systems have a main trunk fed by tributaries coming from the sides. Differences include the relative simplicity of the Valencia drainage network compared to the terrestrial Ebro network, which is a result of contrasting sediment dynamics. Inset image is a three-dimensional view of the Valencia Trough from the northeast.

on the Balearic Islands is, jointly with a different tectonic setting, the main reason why submarine canyons did not develop on the eastern flank of the Valencia Trough. Deeply entrenched valleys of possible fluvial origin, presently filled up with sediment, have been observed only off Pollensa and Alcudia Bays, northeast of Mallorca Island (Acosta et al., 2001).

The beauty of submarine canyons also appears when looking at their detailed morphology. Canyons and canyon networks in the northwestern Mediterranean Sea display gullied walls, internal terraces, axial incisions and narrow crests atop of interfluves (Figure 4) (see also Berné et al., this issue). Hanging tributaries connected to a larger, higher-order canyon through narrow, deeply incised reaches are also observed (Figure 4). The transition from the canyon segment to the channel segment in canyon-channel systems is nicely illustrated by the development of levees along a central hanging channel feeding a channel-levee complex (Figure 5a and b). Breaching of channel flanks and levees leading to the formation of new channels and to the abandonment of previous ones that are then left hanging and starved is a relatively common phenomenon (Figure 5c). All these features prove that submarine canyons of the Mediterranean Sea have been the setting of active sedimentary processes shaping them at various space and time scales.

MODERN FUNCTIONING OF EUROPE'S SUBMARINE CANYONS: THE SHORT TERM AND CLOSER VIEW

An even closer view of Europe's submarine canyons has been achieved through (1) direct observations and *in situ* experiments by means of manned and unmanned underwater vehicles, and (2) both long-term and high-frequency monitoring of their hydrosedimentary behaviour.

Seafloor photographs offer unique opportunities to unveil submarine canyon modern sediment dynamics. A set of deep dives performed in the 1980s with the French submersible *Cyana* (Figure 6a) into several Gulf of Lions canyons

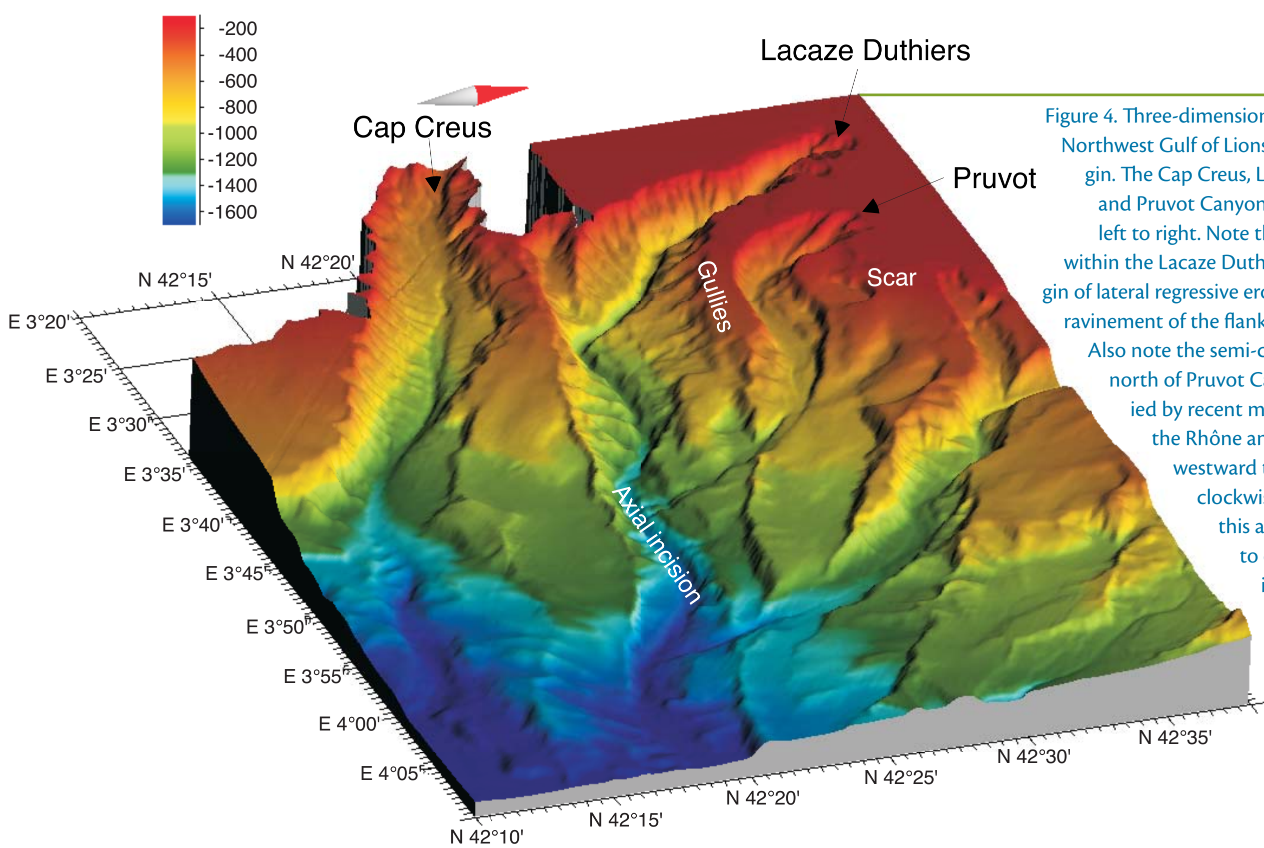


Figure 4. Three-dimensional image of the Northwest Gulf of Lions continental margin. The Cap Creus, Lacaze Duthiers, and Pruvot Canyons are seen from left to right. Note the axial incision within the Lacaze Duthiers, at the origin of lateral regressive erosion resulting in ravinement of the flanks of the canyon. Also note the semi-circular scar to the north of Pruvot Canyon, partly buried by recent muds sourced from the Rhône and transported westward through the anti-clockwise circulation in this area. For scale refer to coordinates given in the figure (1' in latitude = 1 nautical mile).

produced many interesting pictures. Some of these images are assembled in Figures 6b to 6k, together with Sediment Profiling Imagery pictures showing sections of the uppermost part of the sedimentary section. They demonstrate that at the metric and submetric scale, submarine canyons, like river valleys, are not at all uniform along their course and that the imprint of sedimentary processes, biogenic activity, and anthropogenic impacts can be easily recognized.

Living colonial cold-water corals have been found on the rims and upper flanks of some submarine canyons in the Gulf of Lions such as the Cap de Creus Canyon (Figure 6b). As in many places along the European margin, such corals are being seriously impacted by fish trawling. Note that a rope from a fishing net can be identified in the picture. Canyon heads may display amphitheatre-like shapes with locally abrupt walls where rocks and over-consolidated sediments may crop out. This has been observed in the Lacaze-Duthiers Canyon head and upper course where a small axial depression presents indications of modern bed transport down axis as suggested by the presence of gravelly sediment and accumulations of coarse grains and garbage behind large obstacles (Figure 6c). Again, rope from a fishing gear and plastic debris left behind the large boulder in the canyon axis may be observed (Figure 6c).

Compared to the generally low profile of canyon floors, canyon walls are locally steep and show clear indications of destabilisation. Creeping features and badland topography on the wall of the upper to mid-course of the Lacaze-Duthiers Canyon are presented in Figures 6g and 6h. The lack of centimeter-high biogenic

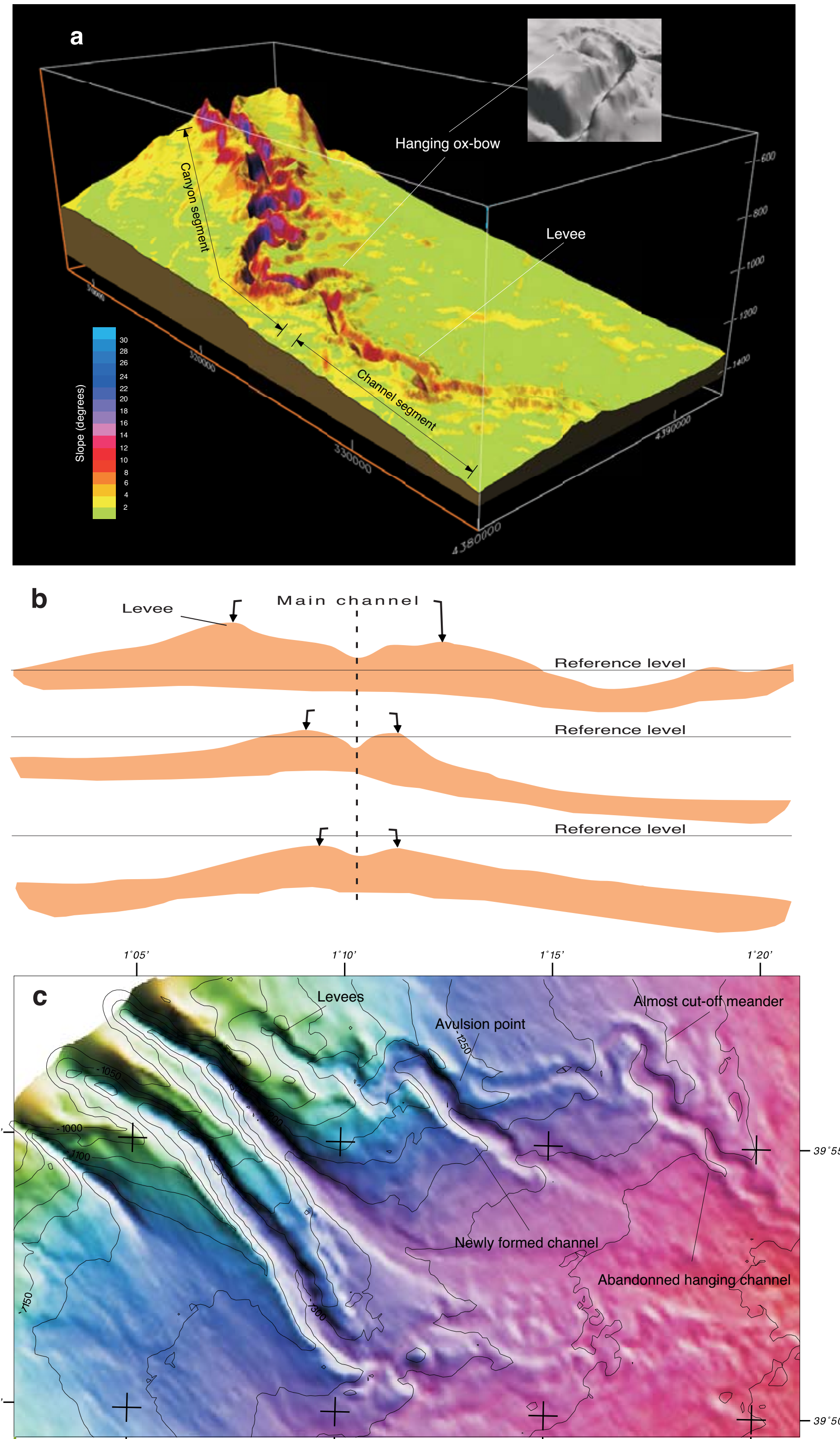
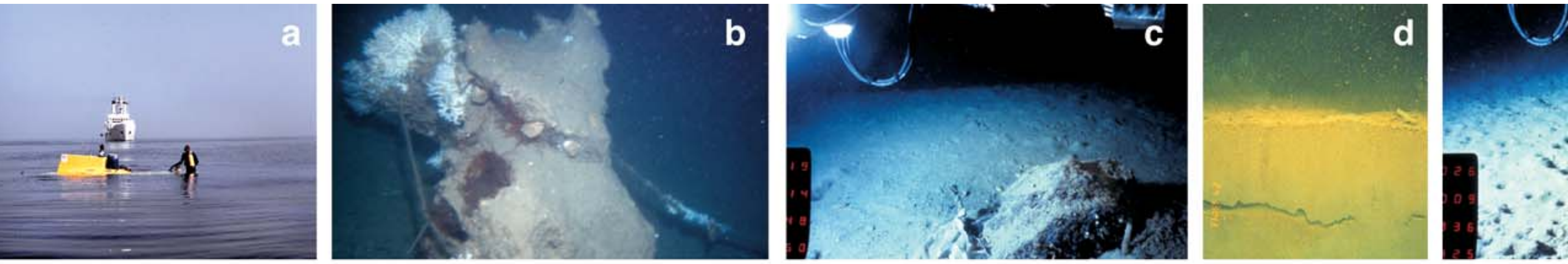


Figure 5. (a) Three-dimensional image of a channel-levee complex in the Ebro margin with a zoom detail of the hanging oxbow. Colors represent slope degrees. (b) Cross-sections through an ideal turbiditic channel showing its hanging character. (c) Image of a channel avulsion in the Ebro margin.



mounds of sediment, which are common in many other canyoned areas (Figure 6e) in the Gulf of Lions, tells us that these places are not friendly to burrowing organisms because of relatively hard substrates, frequent mass wasting events, or scarcity of food inputs.

That submarine canyons experience up- and down-canyon water movement has been known for decades. It is also known that they act as preferential conduits for fine-grained material that is then exported to the deep sea. What has been much more rarely observed is the effect of the passage of debris flows and turbidity currents on canyon walls. Figure 6j illustrates a succession of darker and lighter layers cropping out on the inner erosional wall of a meander into the Var Canyon offshore Nice. This is clearly the result of recent erosion possibly linked to the human-induced 1979 Nice slide that took away part of the Nice airport. It is thought that land filling on top of the Var River prodelta foresets to enlarge the airport of Nice caused such a catastrophic event in a landslide-prone area (Gennesseaux et al., 1980). Erosive processes are also behind the formation of extremely narrow crest-like remnants whose destination is to lower progressively through time till disappearing, thus contributing to the enlargement of submarine canyons in the Gulf of Lions (Figure 6i).

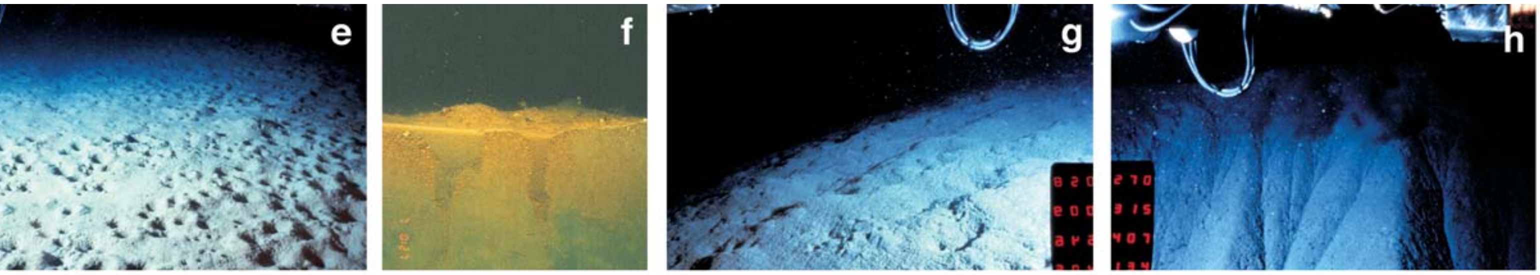
Burrowing activity leads to sediment reworking and sorting, and to the modification of their mass-physical properties including the distribution of porosity and water content. Figures 6d and 6f show a coarsening upwards sequence into the Lacaze-Duthiers Canyon, probably due to the combined action of burrowing organisms and near-bottom currents carrying away the finest grain sizes brought to suspension by bioturbation. Finally, Figure 6k shows another example of the human impact on the deep, canyoned Gulf of Lions which is a several-centimeter-thick reddish layer covering hundreds of square kilometers of seafloor that formed from mud waste released by an aluminium plant in southern France. No signs of bioturbation are observed anywhere on the reddish mud top.

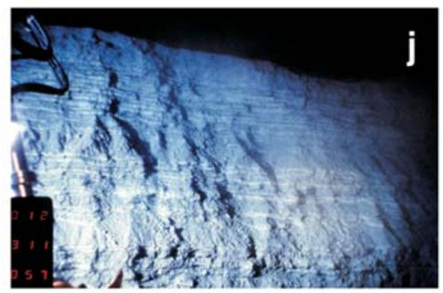
CONCLUDING REMARKS

A latitudinal and climatic control on the evolution and role of submarine canyons along Europe's continental margins has been depicted. While submarine canyons play a relatively minor role in funnelling sedimentary material down slope in glacial-dominated margins, they are extremely important in the glacially influenced, river-dominated margins of southern Europe, both in the Atlantic Ocean and the Mediterranean Sea. In fact, in terms of canyon development the entire southern European margin can be described as a "canyoned margin" showing a rough symmetry along a southwest-northeast axis extending across the Iberian Peninsula and France.

Submarine canyons form true continental margin sediment drainage networks whose efficiency is greatest during ice ages and ice retreat times when sea level is lower and melt water volumes are large. In addition to a structural control on the location of several canyons, the emplacement and development of most southern European canyons seems clearly related to river systems. Submarine canyons behave as interconnecting conduits between those rivers and the deep margin, where large turbidite deep-sea fans, myriad smaller channel-levee complexes, and sediment-filled abyssal plains develop. Altogether, they give a unique character to the southern European margin.

Although from a hydrosedimentary viewpoint most European submarine canyons are at present in a dormant





state compared to ice ages and glacial transitions, some of them at least still show signs of activity. Recent signs of human impacts are found on Europe's submarine canyons and the ecosystems they hold.

REFERENCES

Acosta, J., A. Muñoz, P. Herranz, C. Palomo, M. Ballesteros, M. Vaquero, and E. Uchupi. 2001. Geodynamics of the Emile Baudot Escarpment and the Balearic Promontory, western Mediterranean. *Marine and Petroleum Geology* 18:349-369.

Canals, M. 1985. Estructura sedimentaria y evolución morfológica del talud y el glacis continentales del Golfo de León: fenómenos de desestabilización de la cobertera sedimentaria plio-cuaternaria. Ph.D. Thesis, Univ. Barcelona, 618 pp.

Canals, M., J.L. Casamor, R. Urgeles, G. Lastras, A.M. Calafat, D. Masson, S. Berné, B. Alonso, and M. De Batist. 2000. The Ebro continental margin, Western Mediterranean Sea: Interplay between canyon-channel systems and mass wasting processes. In *Deep Water Reservoirs of the World* (CD edition), Gulf Coast Section Society of Economic Paleontologists and Mineralogists Foundation, p. 152-174.

Gennesseaux, M., A. Mauffret, and G. Pautot. 1980. Les glissements sous-marins de la pente continentale niçoise et la rupture de cables en Mer Ligure (Méditerranée occidentale). *Comptes Rendus de l'Académie des Sciences de Paris* 290 (D):959-962 (in French).

Sardou, O., and J. Mascle. 2003. *Cartography by multibeam echosounder of the Nile deep-sea fan and surrounding areas, E: 1/600 000, 2 maps*. CIESM Cartes & Atlas, Monaco.

Popescu, I., G. Lericolais, N. Panin, H.K. Wong, and L. Droz. 2001. Late Quaternary channel avulsions on the Danube deep-sea fan, Black Sea. *Marine Geology* 179 (1-2):25-37.

Rothwell, R.G., J. Thomson, and G.H. Kähler. 1998. Low-sea level emplacement of very large Late Pleistocene 'megaturbidite' in the western Mediterranean Sea. *Nature* 392:377-380.

Rothwell, R.G., M.S. Reeder, G. Anastasakis, D.A.V. Stow, J. Thomson, and G. Kähler. 2000. Low sea-level stand emplacement of megaturbidites in the western and eastern Mediterranean Sea. *Sedimentary Geology* 135 (1-4):75-88.

Thomson, J., and P.P.E.Weaver. 1994. An AMS radiocarbon method to determine the emplacement time of recent deep-sea turbidites. *Sedimentary Geology* 89:1-7.

Torres, J., L. Droz, B. Savoye, E. Terentieva, P. Cochonat, N.H. Kenyon, and M. Canals. 1997. Deep-sea avulsion and morphosedimentary evolution of the Rhone Fan Valley and Neofan during the Late Quaternary (North-western Mediterranean Sea). *Sedimentology* 44:457-477.

Weaver, P.P.E., R.B. Wynn, N.H. Kenyon, and J.M. Evans. 2000. Continental margin sedimentation, with special reference to the north-east Atlantic margin. *Sedimentology* 47 (suppl. 1):239-256.

Figure 6. Seafloor photographs showing submarine canyon modern sediment dynamics. (a) Preparing the recovery of the French submersible *Cyana* by mother vessel in flat seas after a dive in the submarine canyons of the northwestern Mediterranean. (b) Small living colony of cold water corals (*Madrepora oculata*) in an area seriously damaged by trawling (see ropes around rocky relief) in the Cap de Creus Canyon (120 m depth). (c) Axial depression in the upper course of the Lacaze-Duthiers Canyon with plastic bag and rope behind large boulder. (d) Sediment Profile Image (SPI) showing a well-preserved sub-horizontal burrow in the clayey base of a coarsening-upwards sedimentary sequence that may result from bioturbation. (e) Top of a morphological terrace close to the floor of the Lacaze-Duthiers Canyon densely covered by centimeter-sized bioturbation craters and mounds. (f) SPI showing vertical burrows filled with faecal pellets and centimeter-high sediment mounds atop of a coarsening upwards sequence. (g) Sediment creeping on the flank of the Lacaze-Duthiers Canyon. (h) Badland topography on the wall of Lacaze-Duthiers Canyon. (i) Erosional crest into the Var Canyon offshore Nice. (j) Rhythmites cropping out on the inner erosional wall of a meander into the Var Canyon. (k) SPI showing a thick reddish layer of mud waste released by an aluminium plant in southern France. Image (b) courtesy of J.M. Gili. Images (i) and (j) courtesy of IFREMER.