The long-term evolution of submarine canyons: insights from the NW Mediterranean

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ABSTRACT

A fascinating aspect of submarine canyons is that they resemble river valleys. As with fluvial systems, the study of submarine canyon and channel long profiles sheds light on the fundamental processes controlling their long-term form and dynamics (i.e. morphodynamics). In this short paper we summarize a number of recent studies, based mainly on observations and measurements from the Catalano-Balearic Basin (NW Mediterranean), that relate the long-profile form of canyons and channels to the processes that control their evolution. We briefly present a model for the long-profile curvature of submarine canyons that includes the combined effects of turbidity currents and background (i.e. hemipelagic) sedimentation, and compare the range of model profile shapes with those observed on the present-day NW Mediterranean slope. We then summarize work on a 3D seismic volume over the present-day continental slope that documents how submarine canyons and their interfluves co-evolve on constructional (i.e. prograding) margins, work that has broadened our view of canyons as purely erosive features to one in which canyons can persist through long-term margin growth. Finally, we discuss evidence from the present-day seafloor and shallow subsurface for long-profile adjustment at or near tributary junctions in the extensive Valencia deepwater channel network.

INTRODUCTION

The intriguing similarity between submarine canyons and river valleys was first recognized in early bathymetric measurements along continental margins (Daly, 1936). The apparent geomorphic similarities between fluvial and deepwater systems – similarities that are now well documented in swath sonar maps of the seafloor – has motivated numerous comparative studies (Shepard, 1981; McGregor *et al.*, 1982; Pratson and Ryan, 1996; Mitchell 2005, 2006; Straub *et al.*, 2007; Amblas *et al.*, 2011). Central to all of these studies is the question of why such similar landforms should exist in subaerial and submarine environments when (1) few continental slopes have ever been exposed to subaerial processes and (2) the surface processes that shape landscapes and seascapes differ in some important ways. Clearly these differences are in many cases less important than the similarities in the formative processes. So what can we say about these similarities?

The total relief observed in many terrestrial mountain belts is comparable to that observed along the world's continental slopes. Consider the NW Mediterranean Basin (Fig. 1). The height difference between the highest eastern Pyrenean mountain range and the coastline is nearly 2900 m, similar to the maximum depths attained in the Catalano-Balearic Basin (Fig. 1). This observation reminds us that the orogenic uplift that generates subaerial relief has a submarine analogue, where marine shelf-to-basin relief is generated by a combination of tectonics (lithospheric extension or subduction at the transition to ocean crust) and sedimentation (the characteristic clinoform of continental margin stratigraphy). To the extent that this relief provides the potential energy for fluid flow and sediment transport, it is perhaps unsurprising that both environments are characterized by drainage patterns. Figure 2 shows a comparison between the headwaters of a river (Ter River) and a submarine canyon (La Fonera Canyon). These drainage systems share similar morphologies that include a main sinuous valley surrounded by tributaries with steep flanks cut by well-developed gullies. Interestingly, at 18 km downstream in both the subaerial and submarine valleys we observe the same height difference (1300 m) and comparable contributing drainage areas (140 km^2 in the river and 120 km^2 in the canyon).

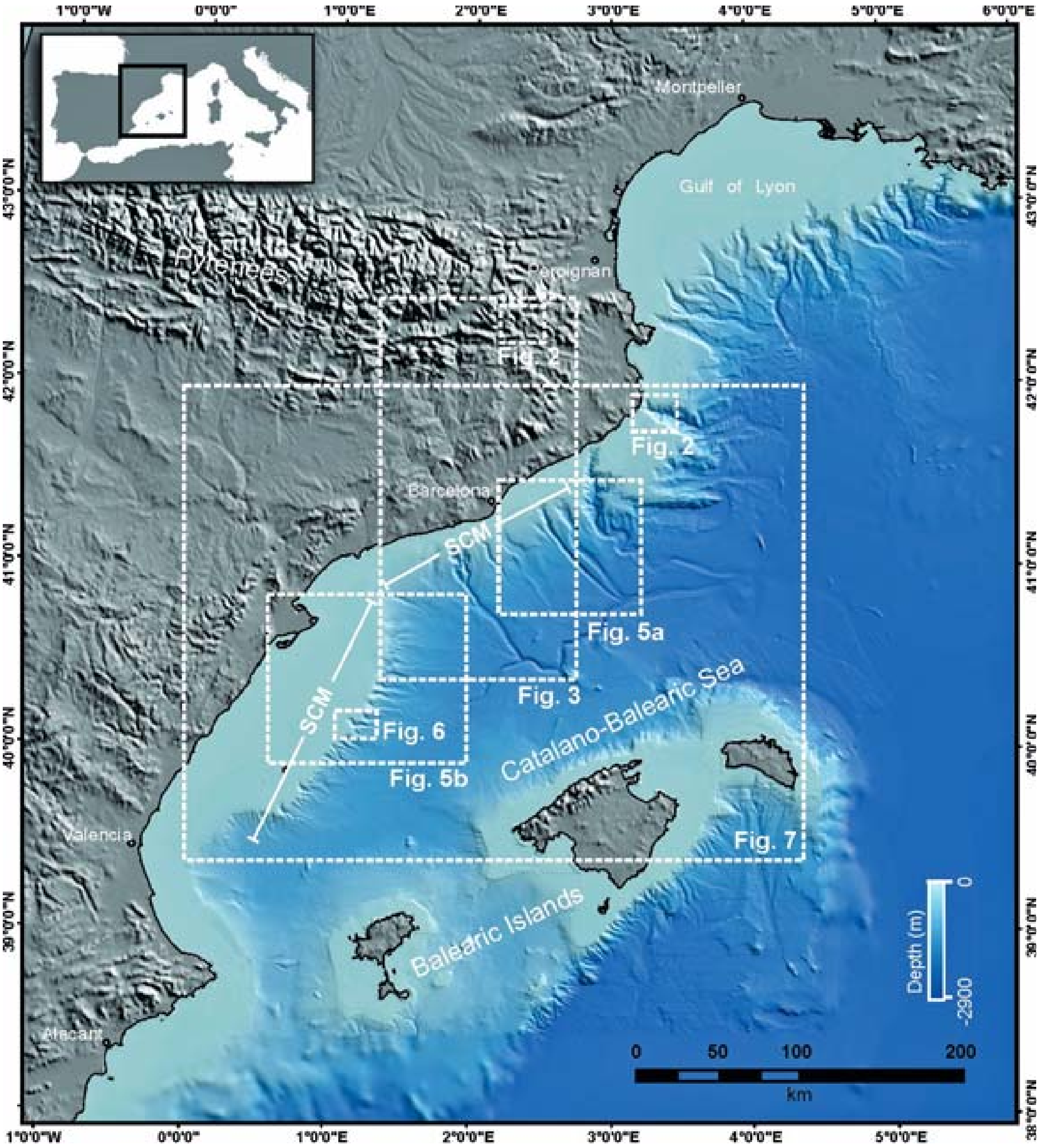

Figure 1. Shaded relief image of the NW Mediterranean Basin. The elevation data combines different multibeam bathymetry data sets from the University of Barcelona, the Spanish Institute of Oceanography, IFREMER, and global digital databases. White boxes show location of Figures 2, 3, 5, 6 and 7. SCM, South Catalan margin; EM, Ebro margin.

On land we associate these patterns with the action of rivers and debris flows (e.g. Pelletier, 2004). And we generally assume that submarine debris flows and turbidity currents generate the corresponding patterns on the seafloor (Shepard, 1981; Parker, 1982; Pratson and Coakley, 1996; Imran *et al.*, 1998; Harris and Macmillan-Lawler, this volume). As our interest is in the cumulative effect of surface processes acting over timescales of landscape evolution, we will briefly consider in what follows the geomorphic transport laws widely used to model terrestrial landscape evolution and those proposed for deepwater environments. In doing so we will focus on the long-profile (or along thalweg) shape of rivers and submarine canyons and channels, since they are easily measured and can be related directly to the predictions of process laws developed to explain them.

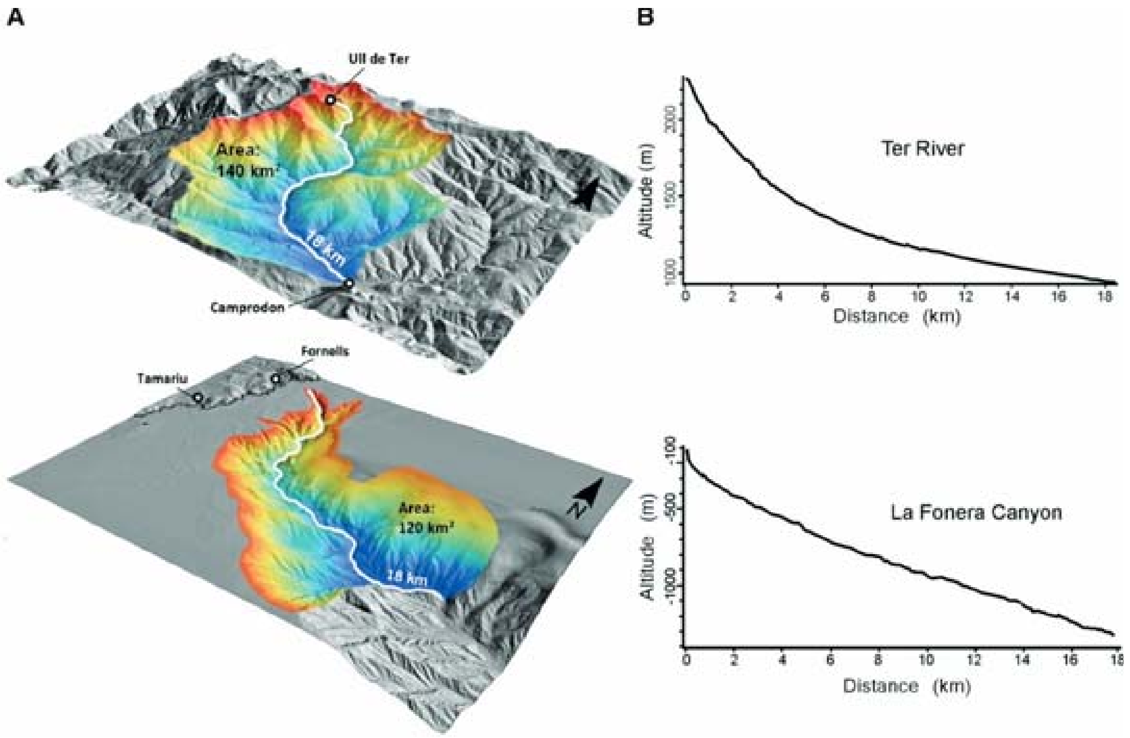

Figure 2. A) Morphometric comparison of the upper courses of Ter River and La Fonera Canyon. The resolution of the DTMs is the same in both cases (15 m). See location in Fig.1. B) Along-thalweg depth profile (i.e. canyon long-profile) of the upper course of Ter River and La Fonera submarine Canyon. Vertical exaggeration is x8 in both cases.

THE LONG-PROFILE SHAPE OF RIVERS AND SUBMARINE CANYONS

Numerous measurements of submarine canyon and channel long profiles show smooth, concave-up shapes not unlike those observed along river thalwegs (Fig. 3). Explanations for the long-profile curvature of river profiles is well-established (Snow and Slingerland, 1987; Sinha and Parker, 1996; Sklar and Dietrich, 1998), and a number of studies – either by way of fluvial analogy or analysis of sediment gravity flow mechanics – have addressed the processes that are thought to contribute to long-profile concavity in submarine settings (e.g. Pirmez *et al.*, 2000; Kneller, 2003; Pirmez and Imran, 2003; Mitchell, 2005a; Gerber *et al.*, 2009). So what are these explanations, and how do they differ?

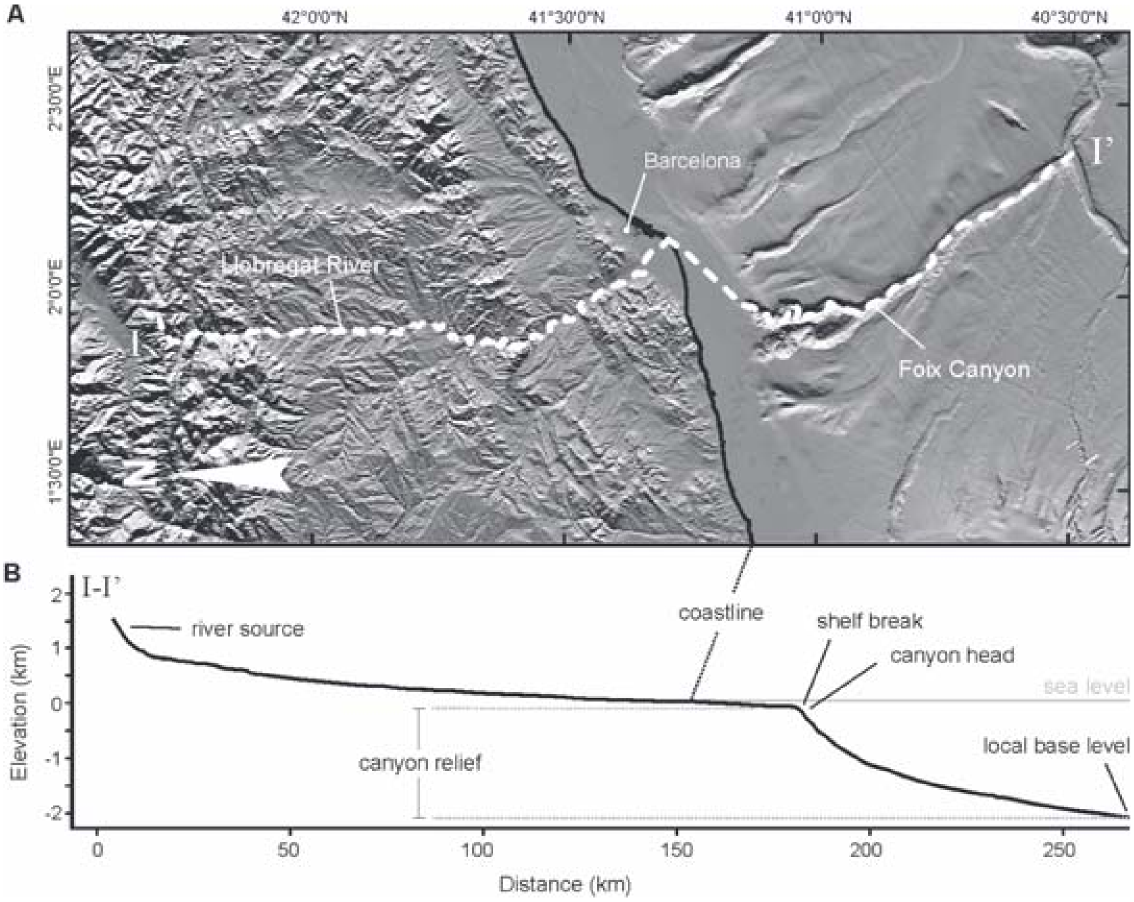

Figure 3. A) Shaded relief digital terrain model showing the thalweg trace of Llobregat River and Foix Canyon. B) Ensemble plot of Llobregat River and Foix Canyon long-profiles.

There are two primary controls on long-profile concavity in rivers: (1) increasing water discharge with downstream distance due to increasing drainage area, and (2) deposition in alluvial basins due to a divergence in bedload sediment transport. Clearly only the first of these operates in bedrock rivers, generally described using a process law of the form

$$\frac{\partial \eta}{\partial t} = U - kA^{m}S^{n} \tag{1}$$

where $\eta(x,t)$ is bed elevation, $U(x,t)$ is the tectonic uplift rate, $A(x,t)$ is the contributing drainage area, $S(x,t)$ is the bed slope, k is a (dimensional) coefficient, and x is downstream distance (Howard *et al.*,1994; Kirby and Whipple, 2001). At steady-state with constant uplift, the bed slope can be expressed as

$$S = \left(\frac{U}{k}\right)^{\frac{1}{n}} A^{-\frac{m}{n}} \tag{2}$$

where the ratio m/n (>0) sets the channel concavity for increasing drainage area (or discharge) and the coefficient U/k controls the overall slope magnitudes. Mitchell (2004, 2005) argued that a similar relationship might govern submarine canyon long-profiles. In this view, U represents the background rate of hemipelagic sediment fallout that slowly builds the continental slope, while A is the drainage area defined upslope from a point in the canyon thalweg. To make this analogy, Mitchell (2004, 2005) equated larger drainage areas to a greater frequency of sediment gravity flows initiating on the slope. Note that this definition of *A* did not include the effects of flows originating landward of canyon heads on the continental shelf.

The surface evolution of alluvial basins is generally modelled using a diffusion equation of the form

$$\frac{\partial \eta}{\partial t} = \frac{\partial}{\partial x} \upsilon \frac{\partial \eta}{\partial x} - \sigma \tag{3}$$

where σ(x,t) (>0) is the subsidence rate and υ(x,t) is a fluvial diffusivity that is linearly proportional to the stream discharge per unit width of channel q_w [L^2T^{-1}]. A detailed derivation of (3) is beyond the scope of this contribution (see Paola, 2000 for a thorough discussion). Of interest here is the long-profile form predicted by the relation. At steady state (3) can be written as

$$\frac{\partial^2 \eta}{\partial x^2} = \frac{\sigma}{\upsilon} + \left(\frac{1}{\upsilon} \frac{\partial \upsilon}{\partial x} \right) S, \; S = -\frac{\partial \eta}{\partial x} \tag{4}$$

For constant υ, the concavity of the alluvial long-profile is given by the first term on the RHS of (4). This is the depositional or ‘storage’ concavity and simply represents the decrease in slope required to for deposition to balance the subsidence. For a steady fluvial profile that progrades with constant velocity *V*, a similar term appears (*VS*/υ) representing the additional ‘storage’ concavity required to sustain progradation. The second term will increase this concavity if q_w (and hence υ) increase downstream.

Gerber *et al.* (2009) proposed a model for submarine canyon long-profiles that has analogies to both the bedrock (1) and alluvial (4) cases. They view submarine canyons on constructional margins as prograding landforms that advance basinward with the continental slope. As in the Mitchell (2004, 2005) model, a source term representing background sedimentation is included, but is defined by the average morphology (commonly sigmoidal) of the open continental slope. Sediment transport within the canyon is driven by turbidity currents, and is described by a simplified version of the 3-equation model of Parker (1986). For a steady long-profile in the traveling wave (progradational, *V*>0) coordinate $\tilde{x} = x - Vt$ the general relation is:

$$\frac{d^2 \eta}{d\tilde{x}^2} = \frac{S}{K} \left(V + \frac{dK}{d\tilde{x}} \right) - \frac{R_b}{K} \tag{5}$$

Here $R_b(\tilde{x})$ is a background sedimentation rate and $K(\tilde{x})$ is an effective diffusivity. Note that both a storage term and a term related to downstream increases in *K* favour long-profile concavity, which is offset by background sedimentation. As in the alluvial case, the diffusivity *K* increases with increasing discharge q_w (though nonlinearly). However, the dependence is unrelated to tributary input and its effect on bedload transport; rather, it arises from their representation of a suspended sediment balance for a turbidity current and an assumed relation for fluid entrainment into the flow. For a prograding, canyonized margin, (5) can be used to predict a continuum of long-profile forms with intercanyon and canyon end-members (Fig. 4). It can also be used to predict a graded (or ‘bypass’) long profile (*V*=0). Development of the model was largely inspired by – and subsequently used to explain – observations showing smooth long-profile concavity along canyons in rather different slope settings along the passive NW Mediterranean margin.

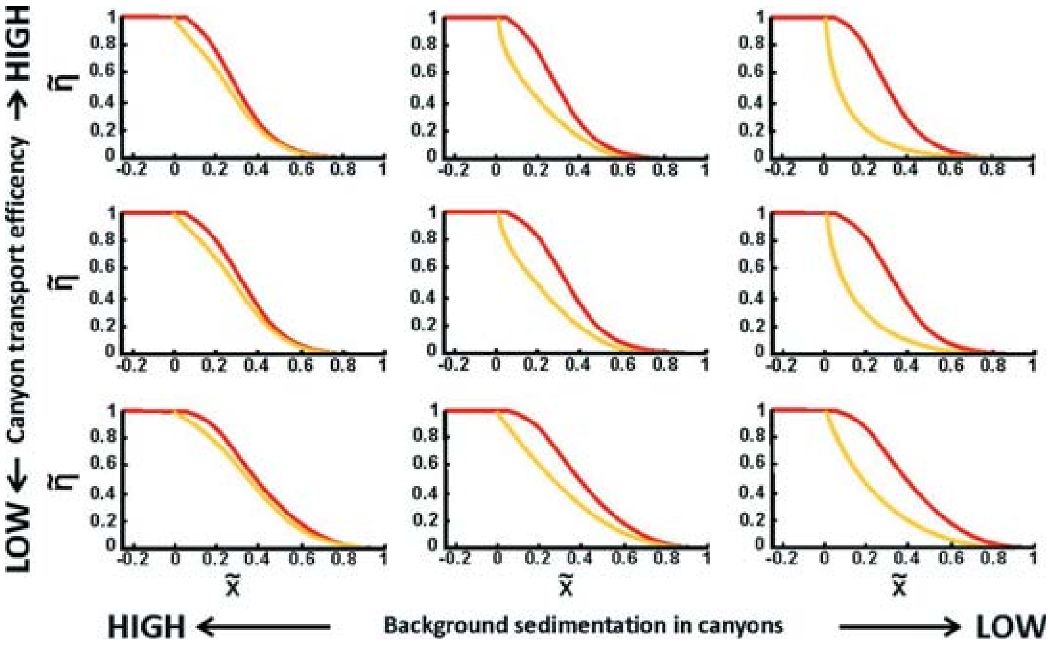

Figure 4. Matrix of canyon (yellow) and intercanyon (red) profiles for a range of canyon transport efficiency, which limits concavity, and fractions of background sediment storage, which limits convexity. Profiles are computed with analytical solution to the morphodynamic model for the long-profile shape of submarine canyons (Gerber *et al.*, 2009).
Adapted from Gerber *et al.* (2009).

On the South Catalan margin, a few large canyons are incised into a rather narrow shelf and extend across a smooth low-gradient slope (Amblas *et al.*, 2006). Arenys and Besòs canyons show a single entrenched chute with a nearly constant width and morphology from the shelf break to the canyon mouth (Fig. 5a). These canyons display a nearly constant width and morphology from the shelf break to the canyon mouth, and a single entrenched chute in seismic cross section (Gerber *et al.*, 2009). These observations suggest significant long-term sediment bypass to the contiguous Valencia Channel. The concave-up curvature displayed by the long-profiles of these canyons indicates that turbidity-current throughput exceeds background inputs to the canyons (Gerber *et al.*, 2009).

In contrast, the Ebro margin canyons are numerous and generally display low relief, most heading at or near the edge of the wide Ebro continental shelf (Fig. 5b). The long-profile of these canyons generally displays a concave-up curvature, similar to those observed along the South Catalan margin (Amblas *et al.*, 2011). However, a recent subsurface study based on a 3D seismic cube in the vicinity of Orpesa Canyon shows a convex-concave (sigmoidal) long-profile curvature on its mid-Pleistocene ancestor (Amblas *et al.*, 2012; see next section). This change in long-profile curvature has been interpreted as a shift to a canyon dominated by turbidity currents from one strongly influenced by the pattern of sedimentation that built the open-slope canyon interfluves (Amblas *et al.*, 2012). The progressive steepening of the Ebro margin from mid-Pleistocene to present (Kertznus and Kneller, 2009; Amblas *et al.*, 2012), and the effect of canyon capture and piracy (Lai *et al.*, 2013) would have determined the observed change in sedimentation style. It is relevant to note that in tectonically active margins, like the Sicilian margin, the convex-up curvature of the long-profile of submarine canyons has been interpreted as a consequence of tectonic uplift (Lo Iacono *et al.*, this volume).

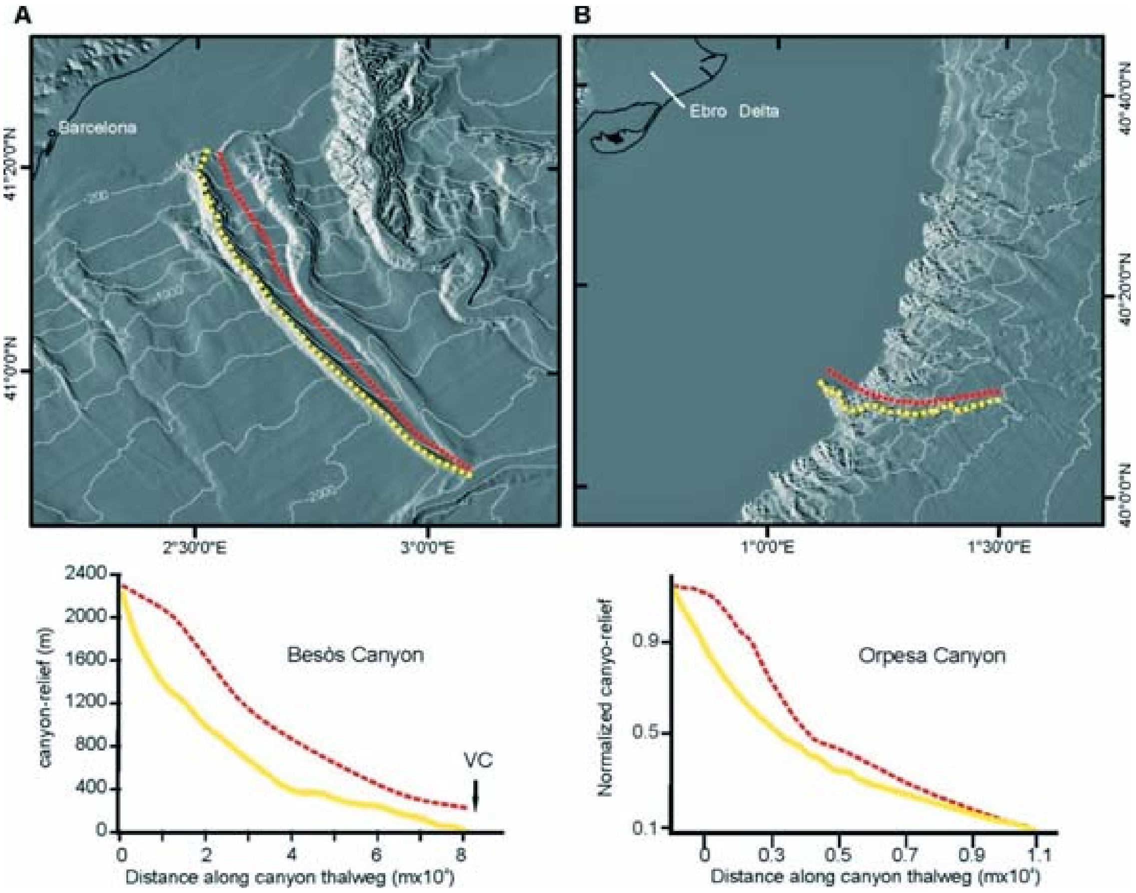

Figure 5. (a) Shaded relief image of the Southern Catalan margin and the Ebro margin. See Fig.1 for location. (b) Long-profiles of Besòs and Orpesa canyons (yellow) and their nearby interfluves (red). 'VC' denotes junction with Valencia Channel.

SUBMARINE CANYONS IN NET DEPOSITIONAL MARGINS

Increasingly available 3D seismic data sets show that many modern submarine canyons have coevolved together with their interfluves during outbuilding of the continental margin (e.g., Wonham *et al.*, 2000; Deptuck *et al.*, 2007; Straub and Mohrig, 2009; Amblas *et al.*, 2012). The predominant view of canyons as purely erosive features (Shepard, 1981) implies that buried canyons represent submarine landforms that are rapidly cut and then passively filled. The Danube Canyon in the Black Sea (Popescu *et al.*, this volume) and the Rosetta Canyon in the Egyptian continental margin (Mascle *et al.*, this volume) show good examples in this regard. An alternative view is that some long-lived canyons can persist (i.e., maintain their overall morphology) over timescale during which significant margin progradation occurs. For this to occur there must be net sediment storage, both within the canyon and along the open slope. The model summarized above (Eqn. 5) has been used to represent this case (Fig. 4), and in essence treats canyons on constructional margins as clinoforms which, together with intercanyon slopes, define the strike-averaged long profile shape of the margin.

The aforementioned 3D seismic cube, provided by BG Group through the Spanish project EDINSED3D (CTM2007-64880/MAR), shows prograding and aggrading shelf-margin clinoforms with the canyon incising the outer shelf and slope near Orpesa Canyon, on the Ebro margin (Amblas *et al.*, 2012). A seismic profile coupling the modern Orpesa thalweg with its underlying mid-Pleistocene surface reveals a general subparallel stacking pattern of moderate- to high-amplitude seismic reflections, similar to the prograding clinoform architecture observed in the same chronostratigraphic interval outside the canyon (Fig. 6). This seismic architecture indicates long-term net sediment storage in the canyon, despite the likely occurrence of periods of erosion and transient disequilibrium that could be associated with sea-level lowstands. This pattern of nested canyon strata beneath the Ebro shelf and slope has been observed elsewhere on the margin (Field and Gardner, 1990; Bertoni and Cartwright, 2005).

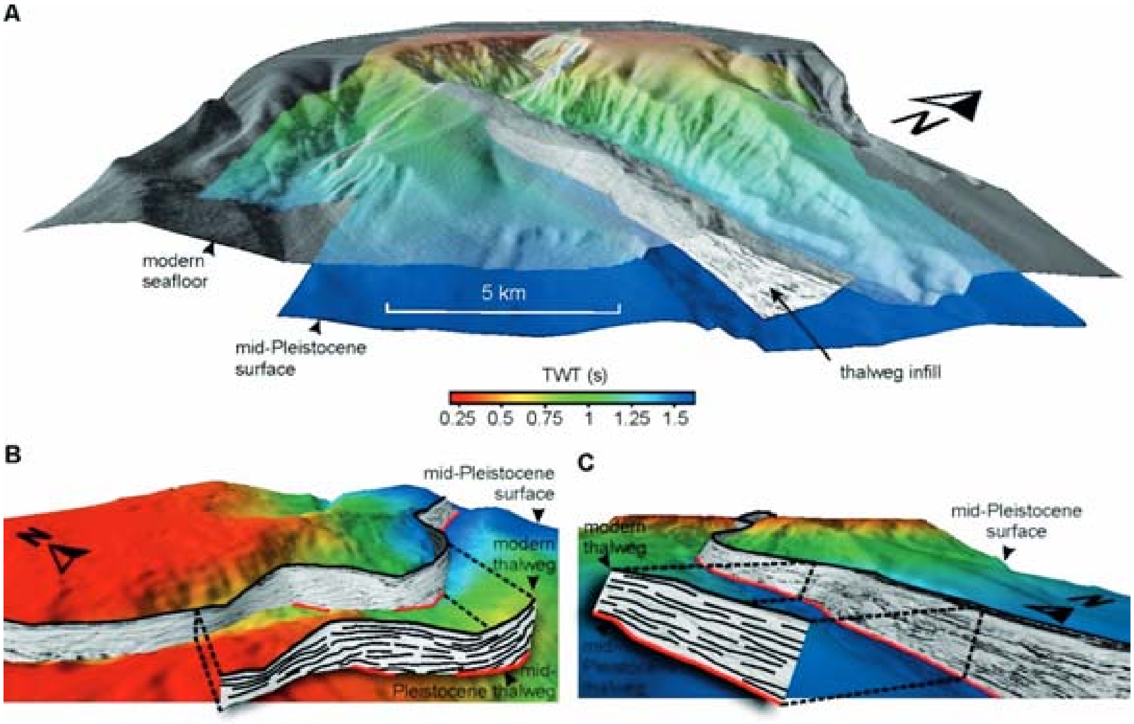

Figure 6. A) 3-D view of stacked modern and mid-Pleistocene surfaces around Orpesa Canyon (see Fig. 1 for location) along with the seismic profile showing the thalweg infill. TWT, two-way traveltime. B and C) 3-D view of mid-Pleistocene surface around Orpesa canyon with the seismic profile coupling the modern and the mid-Pleistocene thalweg.

EQUILIBRIUM AND TRANSIENCE OF SUBMARINE CANYONS

Submarine canyons and channels show discontinuities in their long profile which resemble widely observed subaerial knickpoints. In river basins, knickpoints are generally interpreted as evidence for downstream base level fall, and their form has been used to infer erosion laws governing upstream migration (Howard *et al.*, 1994; Whipple and Tucker, 2002). Submarine knickpoints have been shown to initiate where tectonic motion displaces the seafloor (e.g. Mitchell, 2006), where channel levees are breached (e.g. Pirmez *et al.*, 2000; Gamberi, this volume) or following submarine base level changes (e.g. Adeogba *et al.*, 2005). It is worth mentioning that, though not addressed here, the modeling framework summarized above can be used to investigate transient long-profile evolution.

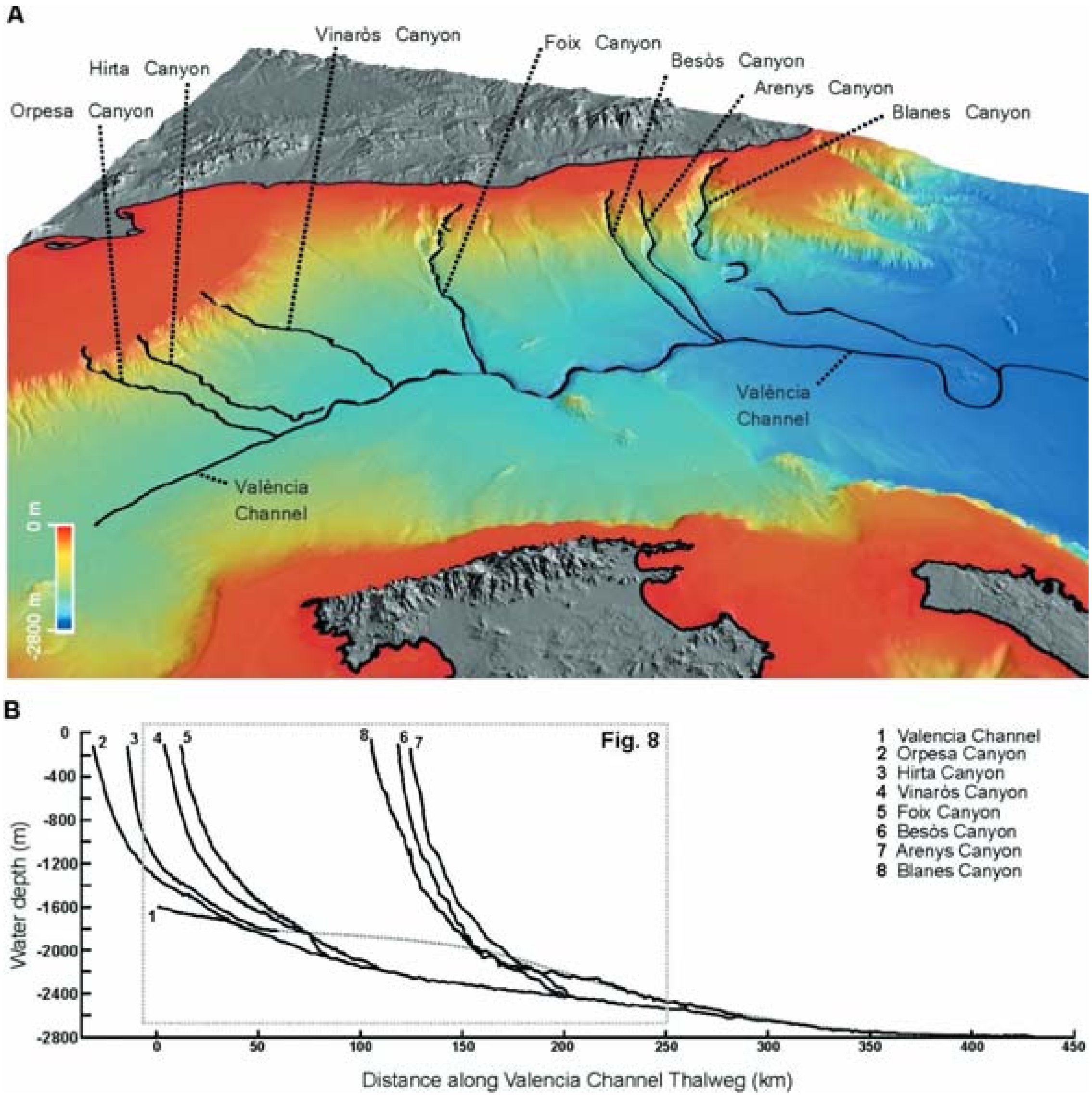

Figure 7. A) 3-D view of the Valencia Trough area showing the Valencia Trough turbidite system (black lines). See location in Fig.1. B) Longitudinal profiles of the main submarine valleys feeding the Valencia Channel from the southernmost modern tributary (Orpesa) to the Valencia Fan (distal end of plot) extracted from swath bathymetry (50 m grid resolution). Gray dotted curve is the smoothed bathymetric profile of the Valencia Channel margin parallel to its thalweg. Gray dotted box shows location of Fig. 8. Adapted from Amblas *et al.* (2011).

Discontinuities in canyon and channel long-profiles can provide clues about previous equilibrium conditions in single canyons or in submarine valley networks. One of the largest submarine valley networks in the Mediterranean is the Valencia Trough turbidite system (VTTS). The VTTS is located in the Catalano-Balearic Basin and routes sediment from a network of more than 1100 linear kilometres of submarine canyons and canyon-channel systems that share a common final conduit in the Valencia Channel (Fig. 7). The integrated analysis of channel thalweg bathymetry in the VTTS shows contiguous long-profiles through most of the submarine drainage network, although evidence for transient incision in the form of knickpoints is observed in two of its tributaries: Vinaròs and Hirta canyons (Fig. 8). By reconstructing the adjusted long profiles downstream of the knickpoints, it is possible to estimate the magnitude of channel adjustment in the drainage network. Based on the location and form of the unadjusted profiles upstream of the knickpoints, Amblas *et al.* (2011) suggested two possible triggering mechanisms for knickpoint initiation: (a) a change in sediment routing forced by a large debris flow at 11,500 yr BP (i.e. BIG'95 debris flow) that disrupted the upper reaches of the VTTS (Lastras *et al.*, 2002), and (b) a change in downcutting rates along the Valencia Channel middle course due to shifting sediment input during glacio-eustatic lowstands. Based on the timing of these, long-term average incision rates in the Valencia Channel have been estimated to be between 7.7 to 12.1 m kyr^{-1} near the Vinaròs junction and 3.3 to 5.2 m kyr^{-1} near the Hirta junction. These values should be taken as rough estimates for maximum entrenchment rates in the submarine channel.

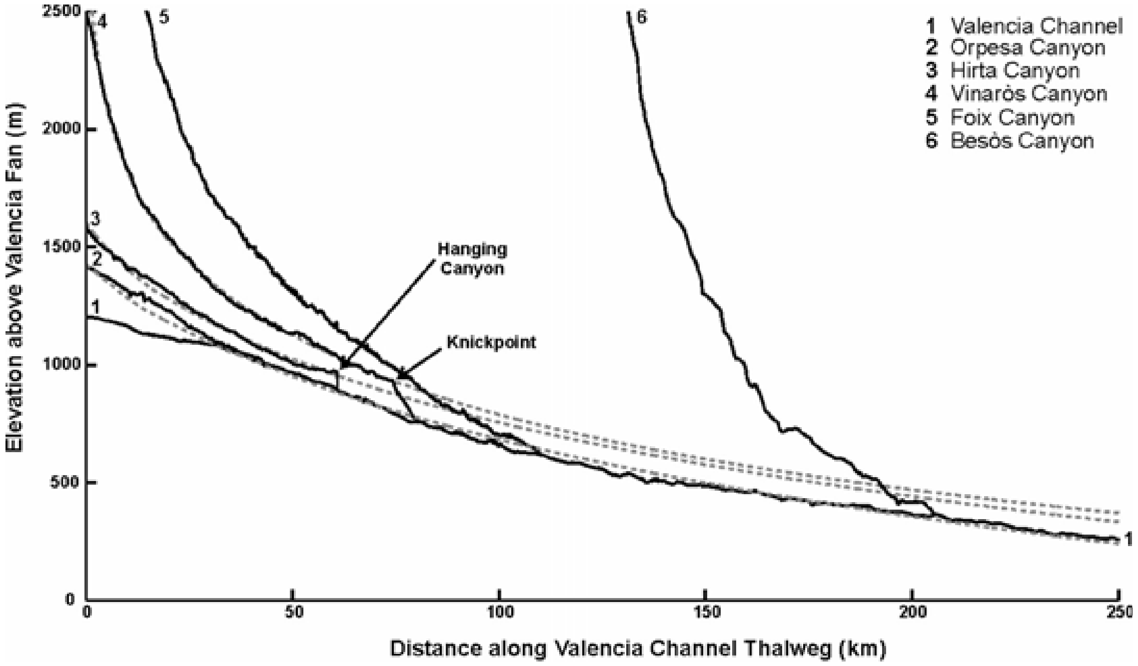

Figure 8. Zoom of the upper and middle course of the Valencia drainage network (see Fig. 6 for location) showing interpreted features of canyon-channel long-profiles. For Hirta and Vinaròs canyons, dashed lines show power-law fits to profiles above knickpoints that are projected below the knickpoints and down the Valencia axis. Also shown is a power-law fit to the Orpesa and Valencia combined long-profile. Modified from Amblas *et al.* (2011).

CONCLUSIONS

Advances in geophysical mapping of the seafloor and subsurface have provided new opportunities to understand Earth-surface processes along continental margin seascapes. We have adopted the approach of terrestrial geomorphologists in using the long-profiles of canyon and channel thalwegs to identify the signature of processes that sculpt the seafloor and build margin strata. Our natural laboratory has been the Catalano-Balearic Basin in the NW Mediterranean, where after decades of imaging we have documented in detail an extensive submarine drainage network that routes sediment from margins with contrasting morphologies through a single "trunk" conduit to an ultimate sink on the Valencia Deep Sea Fan. Observations from this margin have led to detailed field-based comparisons (Amblas *et al.*, 2006, 2011, 2012) and motivated and informed the development of morphodynamic models of submarine canyon long-profiles (Gerber *et al.*, 2009).

Acknowledgments

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