34 Bedforms in the Southern Submarine Canyons of the Balearic Islands (Western Mediterranean) Interpreted as Cyclic Steps

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Abstract

Multibeam bathymetric data collected along the Menorca Channel (Balearic Islands) for a depth range of 70–850 m revealed the occurrence of bedforms along some of the submarine canyons of the Balearic southern slope. The four main canyons presented in this study display a linear to sinuous geometry, incising the slope for up to 170 m and carving the shelf-edge at a depth of 110 m. Bedforms along these canyons are more developed along the two northernmost canyons, particularly within the 300–700 m depth range. The crescentic shape of the bedforms and their wavelengths of between 120 and 210 m resemble the morphology of bedforms found in other submarine channels and canyons. In line with these previously observed bedforms, we here explore the possibility that the bedforms in the canyons could be interpreted as cyclic steps formed by supercritical turbidity currents. Assuming this interpretation holds, then some simple modelling would

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allow us to give rough estimates of velocity and thickness of the flows that formed the cyclic steps.

Keywords
Cyclic steps • Supercritical-flow bedforms • Menorca channel • Western mediterranean

34.1 Introduction

Trains of bedforms have been mapped along the southern canyons of the Menorca Channel (Balearic Islands, western Mediterranean; Fig. 34.1). The bedforms are several hundred meters long and have a distinct crescentic shape (Fig. 34.2). In geometry and size these bedforms resemble trains of sediment waves as observed on the floor of many other submarine canyons and channels (Smith et al. 2005; Paull et al. 2010; Hughes Clarke et al. 2012; Conway et al. 2012; Casalbore et al. 2014; Normandeau et al. 2014). Monitoring studies have shown that these sediment waves are migrating upslope in response to downslope-moving turbidity currents (Hughes Clarke et al. 2012, 2014). Recently a review of ocean floor sediment waves has shown that these upstream migrating bedforms are very abundant and occur over a large range of sizes (Symons et al. 2016). In general upslope migrating bedforms such as antidunes (Kennedy 1963) and cyclic steps (Taki and Parker 2005) are characteristic of Froude supercritical flows (Simons 1960; Cartigny et al. 2014). Supercritical-flow conditions are likely to occur in turbidity currents as a result of the low density differences between these flows and the ambient water (Cartigny and Postma 2016). Numerical and experimental studies have shown that cyclic steps are controlled by alternating subcritical and supercritical conditions within turbidity currents (Kostic and Parke 2006; Fildani et al. 2006; Spinewine et al. 2009; Postma and Cartigny 2014).

If such canyon floor bedforms can be confidently interpreted as supercritical-flow features, then they can be used to estimate the size of the flows that controlled their evolution. This link would then in turn allows to roughly estimate the

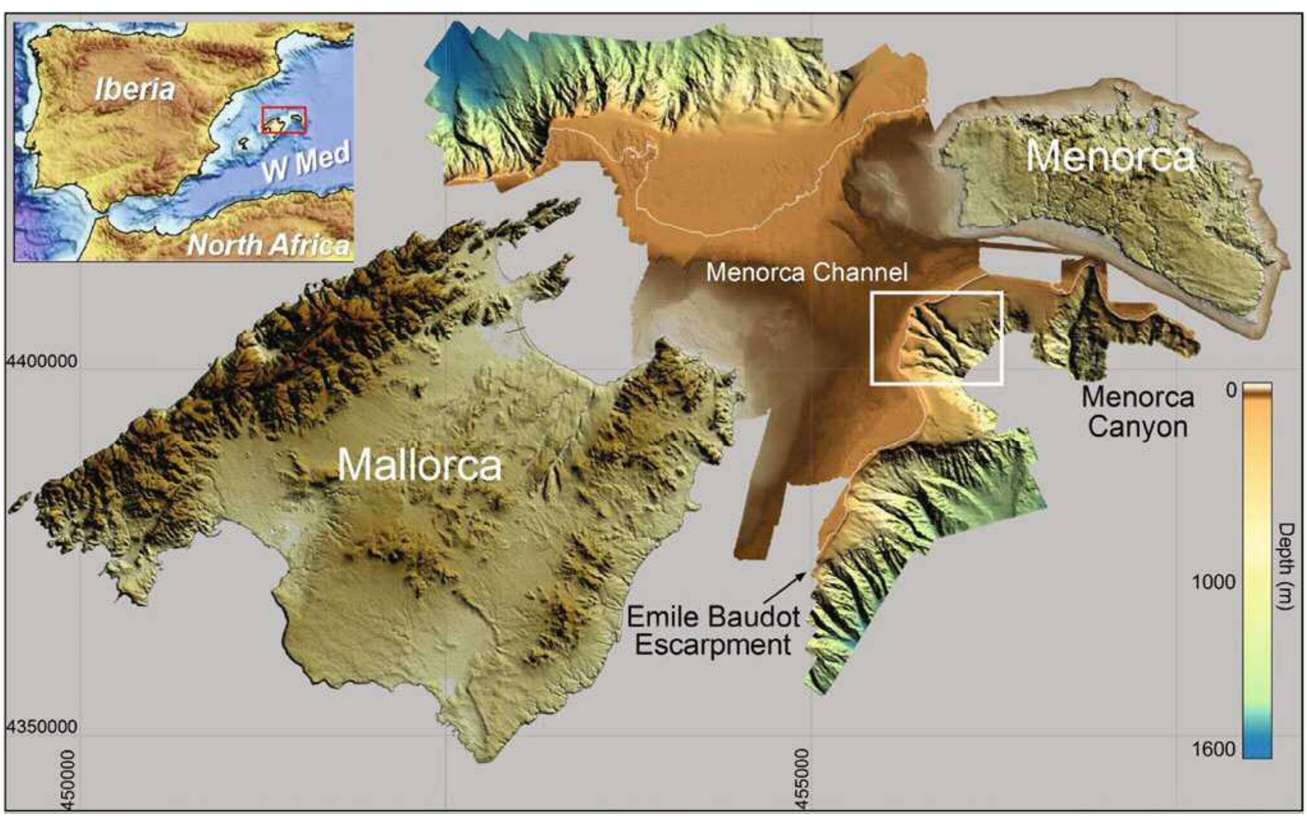

Fig. 34.1 Bathymetric model of the Menorca Channel. The *white rectangle* corresponds to the area under study

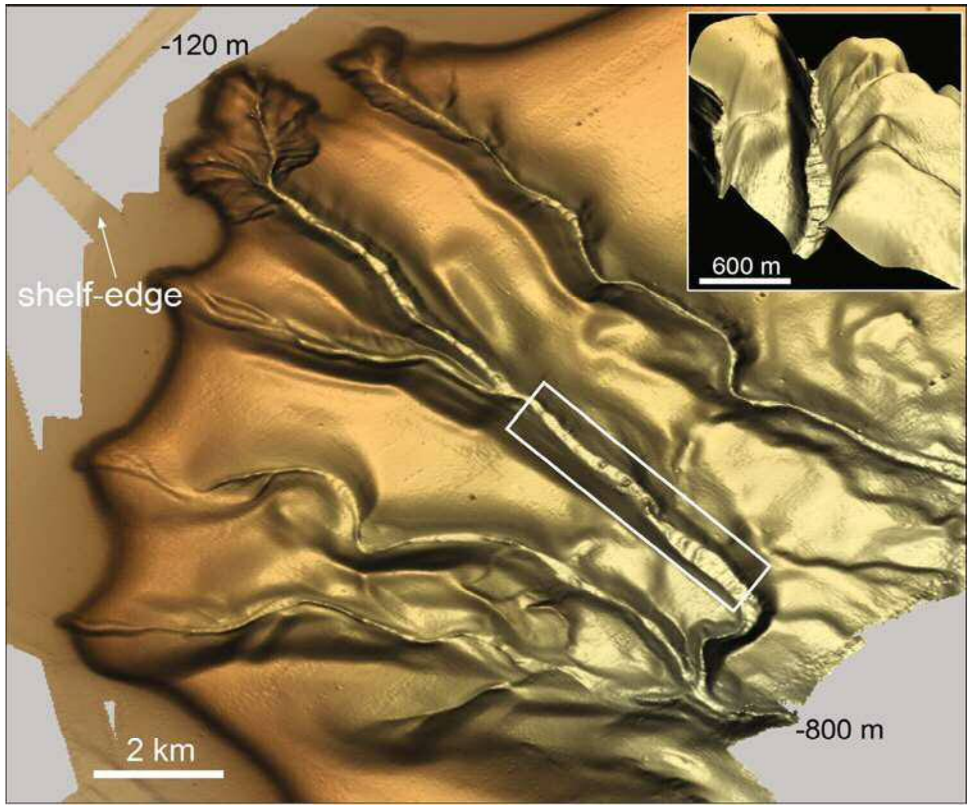

Fig. 34.2 The four submarine canyons where the studied bedforms were mapped. The *white rectangle* corresponds to the area illustrated in the 3D bathymetric model in the *top-left inset* and to the cyclic steps where numerical models were applied to reconstruct their genetic turbidity currents (Fig. 34.3)

dynamics of turbidity currents down submarine canyon systems just on the basis of the bedform morphologies, representing then a big step forward in our understanding of turbidity currents, which are otherwise so difficult to measure. However, to confidently interpret these bedforms as cyclic steps it would be desirable to confirm the upslope migration of the bedform over time, either by repeat mapping (Smith et al. 2005; Conway et al. 2012; Hughes Clarke et al. 2014) or by recognizing upslope migrating backsets patterns (Ventra et al. 2015) in the subsurface expression (Covault et al. 2014; Zhong et al. 2015). As such data is lacking for the canyons of the Balearic Islands, we have to base our cyclic step interpretation solely on the typical crescentic shape and common wavelength of the bedforms.

Here we aim to describe the main morphological characteristics of the mapped bedforms in the submarine canyons of the Balearic Islands. Based on this morphological character we interpret these bedforms as cyclic steps, and we use some basic numerical modelling to estimate the flow characteristics that could have formed cyclic steps of this geometry and scale.

34.2 Methods

Multibeam bathymetry data were acquired in 2012 onboard the RV *Miguel Oliver* using a Simrad EM302, in the framework of the INDEMARES-LIFE Project (www.indemares.es) of the Instituto Español de Oceanografía (IEO). Digital Terrain Models were produced with a footprint resolution of 20 m. Global Mapper and Golden Software Surfer9 were used to map the train of bedforms and calculate their main morphometric characteristics. For further details, see Lo Iacono et al. (2013). Assuming the bedforms were formed by supercritical turbidity currents, then rough estimations of the flow characteristics of the flows in the canyons can be made by comparing the bedform geometries on the canyon floor with bedform geometries predicted by a numerical model for a given range of flow characteristics (Cartigny et al. 2011). The numerical model strongly simplifies the flows by averaging all flow parameters over the depth, by excluding any exchange of sediment in between the flow and the bed, and by limiting the downstream evolution of the flow to only include small variations as described by gradual varying flow theory. More details on the model and its assumptions can be found in Cartigny et al. (2011). The model input consist of an average stoss and lee side slope of the bedforms (Table 34.1) and an average grain size, which is here set at 1 mm (Lo Iacono et al. 2013). Based on these inputs the model then runs several thousands of simulations for flows with different combinations of discharges, Froude numbers and sediment concentration, and calculates the bedform wavelength and amplitude that would result from the combination of flow parameters and the observed canyon floor bedform slopes.

Table 34.1 Morphometric characteristics of the cyclic steps of Fig. 34.3

	Slope stoss side (–)	Slope lee side (–)	Length (m)	Amplitude (m)
Step 1	0.049	0.043	215	4.5
Step 2	0.064	0.066	230	7.2
Step 3	0.013	0.046	269	4.0
Step 4	0.031	0.052	189	3.0
Step 5	0.027	0.061	199	3.4
Step 6	0.044	0.051	235	4.0
Average	0.038	0.053	223	4.3

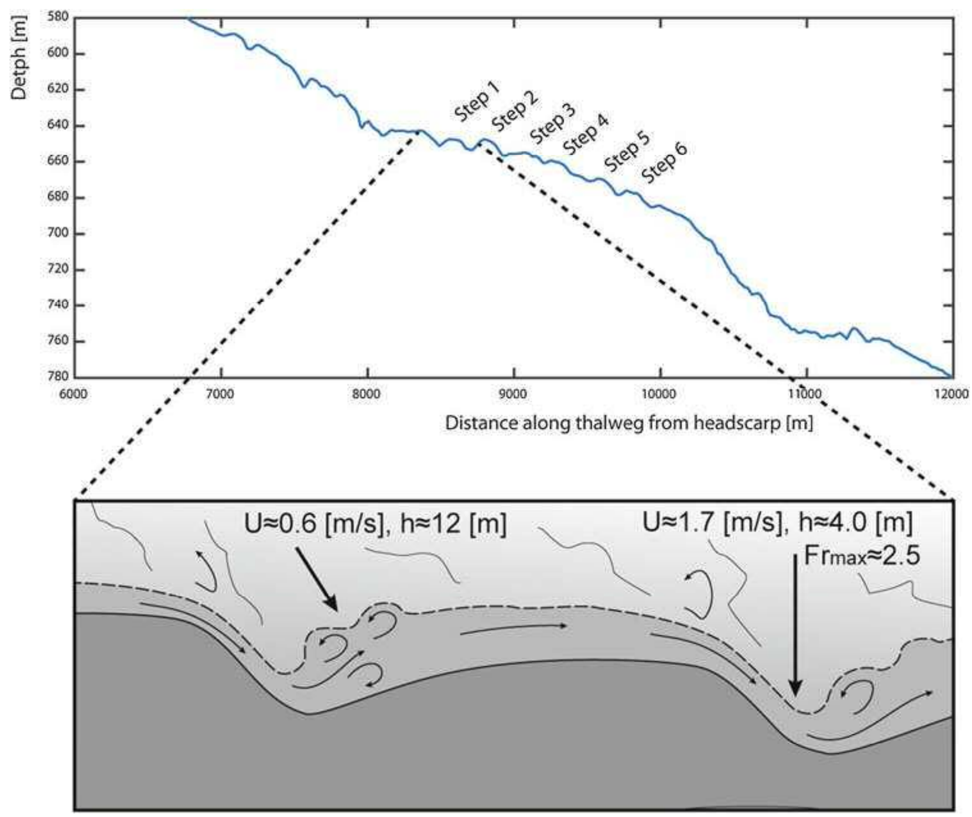

Fig. 34.3 Longitudinal bathymetric transect of the most pronounced cyclic steps in the study area (see Fig. 34.2 for location) and estimation of intensity (*U*) and thickness (*h*) of the corresponding genetic currents based on numerical modelling on an idealised cyclic step drawing

By comparing the predicted bedform wavelength and amplitude with the observed wavelength and amplitude, the most appropriate flow characteristics can be selected.

34.3 Results-Discussion

The studied bedforms were observed along four linear canyons of the southern Balearic slope. These canyons develop east of the Emile Baudot Escarpment (EBE), a passive tectonic feature which bounds the slope region offshore of Mallorca. The canyons breach the paleo/coastal sandy deposits of the southern edge of the Menorca Channel at an average depth of 130 m, and do not presently have a direct connection with the coastal environment (Lo Iacono et al. 2013) (Fig. 34.1). The two northernmost canyons breach the shelf margin the furthest, corresponding to an increase in their width and incision and suggesting a more mature evolutionary stage compared with the two southernmost canyons, which barely incise the shelf (Lo Iacono et al. 2013). The canyons have been mapped to a maximum depth of ~800 m. The bedforms within the canyons display wavelengths ranging from 120 to 300 m and amplitudes ranging from 4 to 7 m. The largest and most pronounced bedforms mapped along the downstream part of the northernmost canyons occur along a thalweg stretch with an average gradient of 2° (Fig. 34.2).

Given the crescentic shape and the scale bedforms on the canyon floor we here interpret these bedforms as cyclic steps. Assuming this interpretation holds then we can estimate the velocity and depth of the flows that have formed the cyclic steps. As input for the model, we used the most prominent bedforms, which are observed at depths of 600–780 m (Figs. 34.2 and 34.3). The average characteristics for the bedforms are summarized in Table 34.1. The model indicates that the flows in the canyon might have had average velocities of 1.3 m/s and a flow depth of around 7 m. The maximum velocity at the toe of the steep lee sides of the steps attains higher values of ~1.7 m/s, while on the flatter stoss sides the flow thickness reaches a maximum value of about 12 m combined with a minimum velocity of ~0.6 m/s. These flows are likely related to periods of strong hydrodynamics during the winter storms occurring in the area. These storms enhance the sediment transport processes along the outer shelf and trigger sandy turbidity currents flowing from the shelf-edge down the canyon (Lo Iacono et al. 2013).

As stated before these velocity and flow thickness estimates are only valid if our cyclic steps interpretation holds. Additionally, it should be kept in mind that the modelling results are only rough estimations due to the assumption that are made in the model.

34.4 Conclusions

Recent multibeam mapping along the Menorca Channel has revealed the occurrence of trains of bedforms along four submarine canyons incising the southern slope of the Balearic Margin. Observed bedforms display maximum lengths of 300 m. If we interpret these bedforms as cyclic steps, then some basic numerical modelling shows that these bedforms might have formed by roughly 10 m thick turbidity currents whose velocities can be estimated in the range of ~0.5–2 m/s.

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