The Malta-Sicily Escarpment: Mass movement dynamics in a sediment-undersupplied margin.

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Abstract

The Malta-Sicily Escarpment (MSE) is a steep carbonate escarpment that appears to have largely remained isolated from inputs of fluvial and littoral sediments since the Messinian Salinity Crisis. Mass movement activity has so far only been inferred from sediment cores at the base of the MSE. In this study we use geophysical and sedimentological data acquired from the upper MSE and outer Malta Plateau to: (i) map and characterise the dominant forms of mass movements, and (ii) determine the nature and origin of these mass movements, and their role in the evolution of the MSE. We document 67 mass movement scars across 370 km^2 of seafloor. Slope instability entailed translational slides, spreads and debris flows that mobilised Plio-Pleistocene outer shelf hemipelagic/pelagic sediments or carbonate sequences across the upper continental slope. Slope failure events are caused by loss of support associated with the formation of channels, gullies, canyon heads and fault-related escarpments. Mass movements play a key role in eroding the seafloor and transferring material to the lower MSE. In particular, they control the extent of headward and lateral extension of submarine canyons, facilitate tributary development, remove material from the continental shelf and slope, and feed sediment and drive its transport across the submarine canyon system.

Keywords: submarine mass movement, submarine canyon, sediment-undersupplied margin, Malta-Sicily Escarpment, Mediterranean.

1. Introduction

The Malta-Sicily Escarpment (MSE) is one of the principal physiographic elements of the central Mediterranean (Fig. 1). Consisting of a steep, NNW-SSE trending slope that extends southwards from the east coast of Sicily, the escarpment is 250 km long and has a vertical relief of almost 3 km. The MSE is the expression of a passive margin separating the continental crust of the Malta Plateau from the oceanic crust of the Ionian Basin (Argnani and Bonazzi 2005). Triassic-Neogene sedimentary and volcanic sequences outcrop along the escarpment (Casero et al. 1984; Scandone et al. 1981). Reconstructions of past sea level changes (Imbrie et al. 1989) and stratigraphic analyses (Max et al. 1993; Osler and Algan 1999) suggest that, following the Messinian Salinity Crisis (~5.9 Ma), the majority of the MSE has largely remained isolated from inputs of fluvial and littoral sediments, and that it has experienced low sedimentation rates; the escarpment may thus be classified as a sediment-undersupplied margin. The MSE is also located at the convergence between the eastward flowing Atlantic Ionian Stream and the westward passage of the denser Levantine Intermediate Water. Sediment drift accumulations, indicative of bottom current activity, have been reported at the foot of the MSE (Marani et al. 1993)

The role of slope instability in the overall evolution of the MSE is not well-understood. Mass movement activity has mainly been inferred from sediment cores. Volcaniclastic and terrigenous turbidites and debrites have been reported from the lower reaches of a submarine canyon system that incises the MSE (Casero et al. 1984; Scandone et al. 1981). Slumping across the MSE itself has only been reported from seismic reflection profiles (Jongsma et al. 1985). In this study we use geophysical and sedimentological data recently acquired from the outer Malta Plateau and upper MSE to: (i) map and characterise the dominant forms of mass movements, and (ii) determine the nature and origin of these mass movements, and their role in the evolution of the MSE.

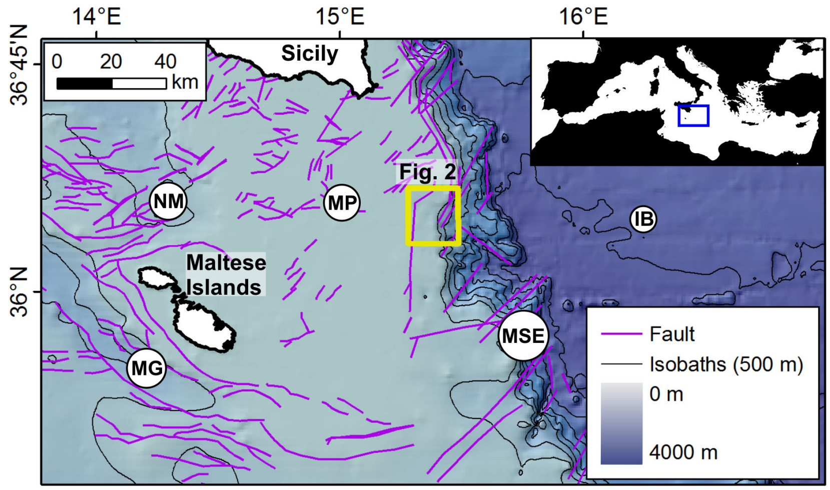

Fig. 1. Bathymetric map of the MSE, central Mediterranean Sea, showing the principal morphological features of the region (IB = Ionian Basin; MG = Malta Graben; MP = Malta Plateau; MSE = Malta-Sicily Escarpment; NM = North Malta Basin) (Source: IOC et al. (2003)). Faults are mapped from published seismic reflection data; some of them have been reactivated in the early Pliocene (Casero et al. 1984; Gardiner et al. 1995).

2. Data and methods

Our study is based on four types of data acquired from the MSE during the CUMECS research cruise (2012).

i. Multibeam echosounder (MBES) data: An area of ~370 km^2 of seabed was surveyed using a Kongsberg-Simrad EM-710 system (70-100 kHz) (Fig. 1). Both bathymetry and backscatter grids with 10 m × 10 m bin size were derived (Fig. 2). These grids were visually interpreted and standard morphometric attributes (gradient, aspect, curvature) were extracted.

ii. Sub-bottom profiles: 500 km of high resolution seismic reflection profiles were acquired simultaneously with the MBES data. The profiles were collected using a hull-mounted CHIRP-II profiler with operating frequencies of 2-7 kHz. For conversion of two-way travel time to depth we used a standard seismic p-wave velocity of 1600 m s^{-1}.

iii. Gravity cores: A total of 28 m of sediment cores were obtained from nine sites using a 6-m gravity corer (Fig. 2a). The cores were visually logged, photographed, and analysed in terms of sediment colour, magnetic susceptibility, p-wave velocity, and gamma density using a Geotek® Multi-Sensor Core Logger.

iv. Dredge samples: Samples were acquired with a cylindrical metallic dredge from one selected site at a depth of 320 m (Fig. 2a).

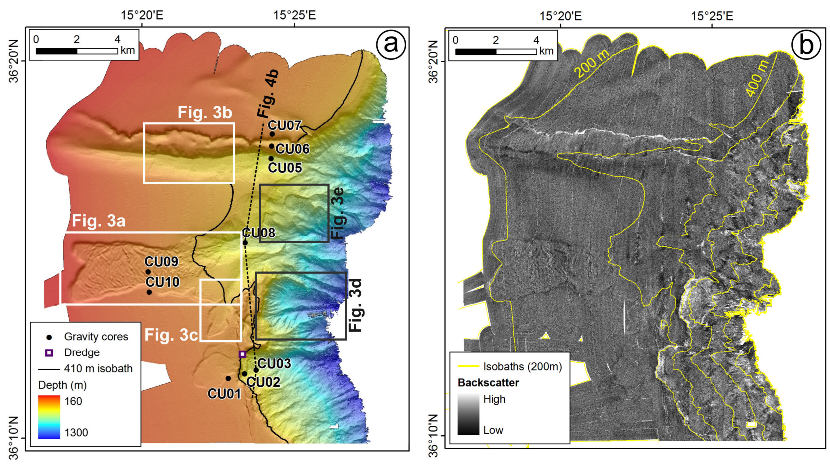

Fig. 2. (a) Bathymetric data draped on a shaded relief map and (b) backscatter map of the study area (isobaths at 200 m intervals). Location in Fig. 1.

3. Results

3.1 Seafloor morphology and composition

The study area comprises two morphologically diverse provinces (outer Malta Plateau and MSE) that are divided by the 410 m isobath (Fig. 2a).

3.1.1 Outer Malta Plateau

The seafloor between 160 m and 410 m depth is predominantly smooth, very gently sloping (0.8° - 1.8°) towards the east, and characterised by low backscatter response. Across the Outer Malta Plateau we identify three morphological elements of interest:

(i) Escarpments

Steep breaks of slope, up to 12.5 km long and 60 m high, occur in three orientations: W-E, N-S and SW-NE. They are straight to non-linear, and they generally correspond to high backscatter (Figs. 2; 3b).

(ii) Scars

Located just upslope of the 410 m isobath are four scars that range from 1 to 18 km^2 in area. The scars have ellipsoidal to elongated plan-form shapes oriented east to north-eastwards; their lateral and upslope limits are characterised by escarpments with gradients of up to 15° and heights of up to 50 m. The largest scar comprises a series of sub-parallel linear ridges and troughs (Fig. 3a). The other three scars, on the other hand, are intersected by gently-sloping escarpments (Fig. 3c). The downslope section of these scars consists of smooth, near-planar seafloor whereas the upslope section comprises a ridge and trough pattern (Figs. 3a,c). The downslope limit of all the scars is contiguous with another scar, a channel or an escarpment.

(iii) Channels

The deepest part of the Outer Malta Plateau is incised by four channels. Two other channels connect scars with the upper MSE (Figs. 3a, c). The longest channel (12 km long) dominates the northern part of the study area (Fig. 3b). Its steeper northern wall is characterised by an elongated mounded morphology, up to 1 km wide, which extends along the foot of a 70 m high escarpment. Two 90 m wide circular depressions are also observed in that location. The walls of the long channel are affected by sixteen small scars (0.03 – 0.4 km^2 in area), all of which slope towards and connect to the channel bed. The scars are shallow (maximum depth of 5 m), smooth, planar and have low aspect ratios.

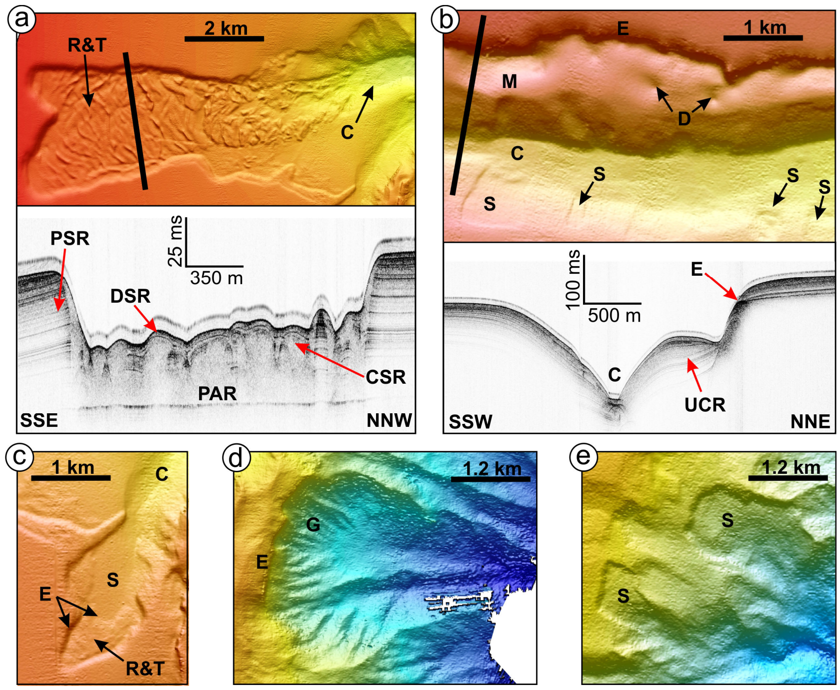

Fig. 3. Bathymetric map and sub-seafloor image of the: (a) Largest scar in the Outer Malta Plateau; (b) Longest channel in the Outer Malta Plateau, the elongated morphology and escarpment across its northern wall. Bathymetric map of (c) Small scar in Outer Malta Plateau; (d) Amphitheatre-shaped depression in the upper MSE; (e) Shallow scars in the upper MSE. Depth legend in Fig. 2. Abbreviations: C = channel; CSR = chaotic seismic reflections; D = circular depressions; DSR = draping seismic reflections; E = escarpment; G = gullies; M= mounded morphology; PAR = planar high amplitude reflector; PSR = parallel seismic reflections; R&T = ridges & troughs; S = scar; UCR = upwardly-convex high amplitude reflectors.

3.1.2 Upper MSE

The seafloor deeper than 410 m is considerably different from that upslope. The slope is steeper (mean gradient of 11°) and is heavily incised by a dense network of gullies and distinct larger and wider channels that extend all the way from the shelf break to the limit of data coverage (Fig. 2). The gullies have steep sidewalls and sharp interfluves, whilst their beds generally coincide with high backscatter values. Some gullies are carved into large amphitheatre-shaped depressions (Fig. 3d), the upslope limits of which are high escarpments (up to 150 m in height) that have a very high backscatter response (Fig. 2b). The southernmost of these depressions intersects a N-S trending ridge; dredged material from this ridge consists of hard carbonate rocks. A large proportion of the gullied slope is affected by numerous, shallow scars (Fig. 3e). These are oriented downslope with a predominantly elongate plan shape, and they have upslope limits that are generally linear, steep and have a high backscatter character. The lower limit is difficult to identify from the bathymetric data. The scars are mostly located upslope or adjacent to gullies and channels.

3.2 Sub-seafloor architecture

The seismic expression of the sub-seafloor in most of the shallow province comprises a sequence of continuous, parallel, high amplitude seismic reflections that is at least 50 m thick in places. At abrupt changes in slope, the sequence thins and seismic reflections converge. Sub-bottom profiles across scars in the shallow province show that this parallel seismic reflection pattern is truncated at escarpments (Fig. 3a). At the downslope limit of the scars, the seismic signature is predominantly chaotic. Where ridge and trough morphology occurs, the seismic pattern is predominantly represented by an irregular, chaotic, low reflectivity unit, which has variable thickness and is draped by an up to 5 m thick unit of coherent, moderate reflectors (Fig. 3a). The base of the irregular unit is a planar, high amplitude reflector.

The internal stratigraphy of the elongated mound on the long channel's northern wall is characterised by an asymmetric package of sub-parallel, upwardly-convex, high-amplitude reflectors (Fig. 3b). This sequence is also draped by a coherent, moderately reflective, 5 m thick unit.

3.3 Sub-surface sedimentology

The sediment in all nine gravity cores is predominantly clay to silty clay of homogeneous lithology and physical properties, and punctuated by infrequent variations (Fig. 4). These include:

i. Between 60 and 75 cm downcore in most cores, there is a layer of volcanic ash that generates a characteristic high peak in the magnetic susceptibility curve, which is used to correlate cores. This peak is found deeper downcore in core CU05, at about 120 cm.
ii. The last 60 cm of core CU03 shows inclined laminae, sand clasts and erratic variability of the physical properties. Similar characteristics are found between 70 and 120 cm downcore in core CU05, 10 cm above the ash layer.

iii. Between 260 and 290 cm downcore in CU05 there is a sequence of silty clay containing medium sand laminae alternating with clay laminae, characterised by relatively higher gamma ray density and p-wave velocity.

iv. A 1 m thick sequence of unsorted, roughly-graded, medium to fine sand intermixed with clay occurs in core CU07. This sequence is characterised by relatively higher gamma ray density and p-wave velocity than the rest of the core, which correlates with the layer described above in core CU05.

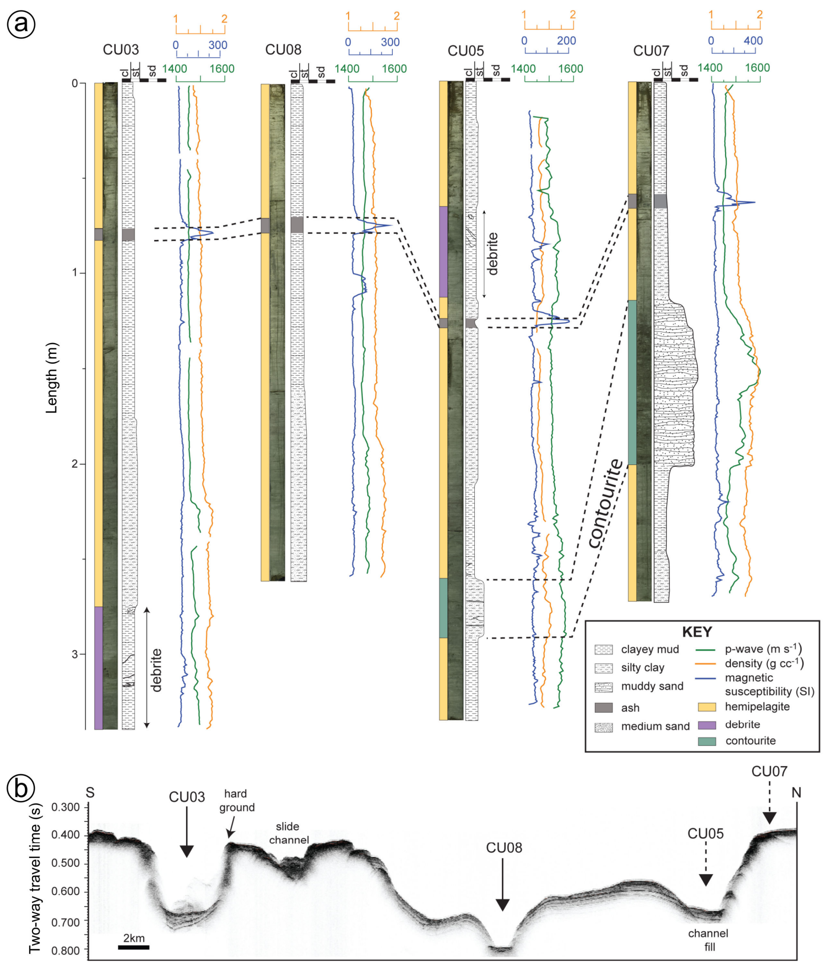

Fig. 4. (a) Data and interpretation of sediment cores from sites CU03, CU08, CU05 and CU07, and (b) their location on a sub-seafloor transect. The coloured bar to the left of the core photographs represents lithological interpretation. Location of cores and transect in Fig. 2a.

4. Discussion and conclusions

4.1 Nature of mass movements and sediment transport

We interpret the scars documented across the study area as evidence of widespread slope instability. The 67 mass movements identified can be divided into two classes - shelf mass movements that affect the outer Malta Plateau, and slope mass movements that occur across the MSE. Their areal extents range across three orders of magnitude and display up to three levels of retrogression.

On the outer Malta Plateau, mass movements have occurred on very gentle slopes of stratified fine sediments, which is likely of hemipelagic and pelagic origin and deposited during the Plio-Pleistocene (Micallef et al. 2011; Tonarelli et al. 1993). The style of deformation observed is indicative of both translational slides and debris flows. The ridge and trough morphology is the signature of spreading, which involves extension of a sediment unit and its break up into blocks that slide above a planar failure surface (Micallef et al. 2007). Spreading occurs in the largest scar as well as in the upslope sections of the smaller scars located at the shelf break. The chaotic seismic signature of the downslope limit of the scars is indicative of internal deformation, most likely caused by the occurrence of debris flows. The core retrieved from the long channel thalweg (CU05) has a sequence with the deformed sediments and erratic physical properties (Fig. 4), which we interpret as a debrite.

On the upper part of the MSE, slope instability has taken place in carbonate sequences with a steeply inclined exposure (Scandone et al. 1981). Due to the composition of the failed material, the chaotic seismic signature of the deposits, and their linear to arcuate steep headwalls, we infer that the style of failure was either a translational slide or debris avalanche (e.g. ten Brink et al. 2006). The amphitheatre-shaped depressions are likely canyon heads that result from coalescing, arcuate scars (Mulder et al. 2012). Mass movements associated with the upslope development of the southernmost of these canyon heads were powerful enough to erode a structurally-controlled bedrock ridge at its headwall (Fig. 5).

From the geophysical and sediment core data in Figs. 3b and 4, we interpret the elongated mounded morphology along the northern wall of the long channel as a contourite (Rebesco and Stow 2001; Stow et al. 2002).

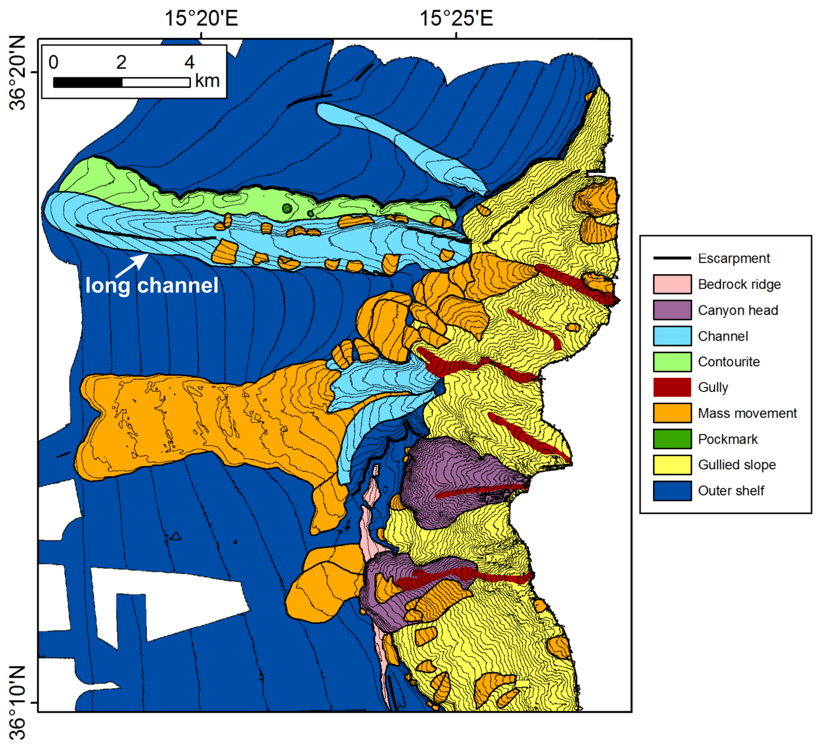

Fig. 5. Interpretation map of the study area (isobaths at 25 m intervals).

4.2 Causes of slope instability

We propose four potential causes of slope instability across the outer Malta Plateau and upper MSE:

i. **Loss of support**: The retrogressive nature of the mass movements – with their location upslope of other mass movements, escarpments, channel/gully beds or canyon heads - indicates that loss of support plays an important role in triggering slope instability in the study area. Across the MSE, the incision of gullies and channels triggers slope failures across their walls due to oversteepening and loss of support (e.g. Micallef et al. 2012). These flank failures are responsible for widening and extending the gullies and channels upslope. The same dynamics characterise the long channel in the outer Malta Plateau. In this case, the formation of a contouritic drift on the northern wall indicates that bottom currents may play a role in channel incision. Otherwise, loss of support is the result of a mass movement taking place downslope or associated with the upslope development of a submarine canyon head.

ii. **Sedimentation**: Hemipelagic and pelagic sedimentation, as well as contouritic deposition along the northern wall of the long channel, provide the material that fails across the outer Malta Plateau. Sedimentation rates across the Malta Plateau in the last 5 Ma are reported to be low, in the range of ~6 cm per 1000 yr on the Malta Plateau (Max et al. 1993; Osler and Algan 1999). Thus, we believe that sediment loading and associated excess pore pressure development are not a pre-conditioning factor for slope instability in the region.

iii. **Faulting and seismicity**: Faults, linked to the different rates of underthrusting between the buoyant Malta Plateau and the Ionian crust (Adam et al. 2000; Grasso 1993), are common across the study area (as shown in Fig. 1 and inferred from the escarpments in Fig. 5) and likely to have exerted a predominant control on the physiography and, indirectly, on the location of mass movements (e.g. occurrence of steep slope gradients, seafloor deformation, escarpments, and channels). Seismic activity has mostly been restricted to the northern section of the MSE (Argnani and Bonazzi 2005). Ground shaking associated with distal earthquakes could thus have played a minor role in triggering slope instability across the study area.

iv. **Fluid flow**: Deep fluid flow systems, sourced by Late Mesozoic sedimentary units, have been reported in parts of the outer Malta Plateau (Micallef et al. 2011). Fluid, likely transferred to the surface by faults in the Tertiary carbonate sequences, may thus play a role in reducing the stability of the outer Malta Plateau by elevating pore pressures in the sediments. The circular depressions identified on the northern wall of the long channel may be evidence of fluid escape at the seabed.

4.3 Role of mass movements in the evolution of the MSE

The evolution of the MSE in the study area appears to have been determined by the interaction of: (i) fault activity associated with the tectonic regime of the central Mediterranean, (ii) sedimentary activity, driven by hemipelagic, pelagic and contouritic sedimentation, (iii) seafloor incision, related to bottom current activity and, possibly, to oceanographic and terrestrial processes that could have been active during sea level lowstands (e.g. Messinian Salinity Crisis). In this framework, the role of mass movements across the MSE and outer Malta Plateau was to erode the seafloor and transfer material to the lower MSE. What is interesting about our study area is that it presents a very good example of how mass movements and canyon processes are interrelated. Submarine mass movements control the extent of lateral and headward extension of the canyons across the continental slope and shelf, as well as facilitate tributary development. They also remove material from the continental shelf and slope, feeding sediment and driving its transport down-canyon. Because of their size and position in the stratigraphic record, we believe that the mapped submarine mass movements do not constitute a significant geo-hazard to the central Mediterranean region.

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