Chapter 26
Submarine Mass-Movements Along the Slopes of the Active Ionian Continental Margins and Their Consequences for Marine Geohazards (Mediterranean Sea)

Silvia Ceramicola, Daniel Praeg, Marianne Coste, Edy Forlin, Andrea Cova, Ester Colizza, and Salvatore Critelli

Abstract The Ionian margins of Calabria and Apulia (IMCA) have been affected by mass movements of varying style, scale and age. Here we present examples of seabed and subsurface features identified along more than 400 km of the IMCA from multibeam seabed imagery and subbottom profiles acquired by OGS since 2005. Four different types of mass movement phenomena are recognized with expression at seabed and in the shallow subsurface: (1) mass transport complexes (MTCs) within intra-slope basins, (2) isolated slide scars (ISS) along open slopes, (3) slope-parallel sediment undulations (SPSU) recording block-rotations linked to fluid migration, and (4) headwall and sidewall scarps (HSC) in submarine canyons. Preliminary analyses of sedimentary processes suggest that both open-slope failures capable of triggering tsunamis and retrogression of canyon headwalls within 1–3 km of the Calabrian coast represent potential geohazards for coastal populations and offshore infrastructures.

Keywords Slope failures • Morpho-bathymetry • Seismics • Marine geohazards • Calabrian and Apulian margins

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26.1 Introduction

Gravity-driven submarine processes on continental margins are important geomorphic agents for transporting sediments downslope into deep-marine environments. Advances in shallow geophysical surveying methods have significantly improved our ability to map and describe the morpho-sedimentary features that record submarine mass movements over time (Chiocci and Ridente 2011). Any activity that affects the seabed represents a potential geohazard. An improved understanding of the spatial distribution and timing of geomorphic features related to mass movement is relevant both to understanding triggering factors (e.g. seismicity, faulting, fluid migration), and to assessing potential hazards for offshore infrastructures and adjacent coastal areas (e.g. tsunamis).

The Ionian margins of Calabria and Apulia (IMCA) provide an interesting laboratory to study active sedimentary processes related to submarine failures (Fig. 26.1). The two tectonically-active margins lie on opposite sides of the suture due to the subduction of the African and Adrian plates beneath southern Italy, and contain a variety of slope settings related to different tectonic activity (Rossi and Sartori 1981; Sartori 2003). The seabed dynamics of the IMCA and its linkages to deeper structures are currently being examined at OGS in the context of the Italian projects MAGIC and RITMARE, with the overall aim of defining and mapping geological features and processes that may constitute geological risks for surrounding coastal areas.

In this paper, we present examples of seabed and subsurface features identified from multibeam and subbottom data acquired over the last several years from the IMCA, supplemented by public seismic data held by OGS. The objective is to describe the variety of features related to mass movements, and to assess their potential hazard for coastal areas and offshore infrastructures.

26.2 Geological Setting

The IMCA includes two margins affected by subduction and accretionary tectonism. The Ionian Calabrian margin (ICM) records two main processes: compression and fore-arc extension during the SE advance of the Calabrian accretionary prism since the late Miocene (Sartori 2003), and rapid uplift (up to 1 mm/year) of onshore and shallow shelf areas since the mid-Pleistocene (Westaway 1993). This has resulted in steep slopes (3–8°) in the south, landward of the deep-water Crotone and Spartivento forearc basins, and irregular slopes (2–4°) in the north across the offshore extension of the southern Apennine thrust-fold belt, where intraslope basins of the western Gulf of Taranto correspond to piggy-back structural highs and lows (Fig. 26.1). The passive Ionian Apulian margin (IAM) is the result of westward subduction of the Adria plate under the southern Apennines, resulting in a steep (4–6°) slope characterised by several morphological steps resulting from the uneven structural setting of the underling Mesozoic carbonate platform. The seismicity of the IMCA

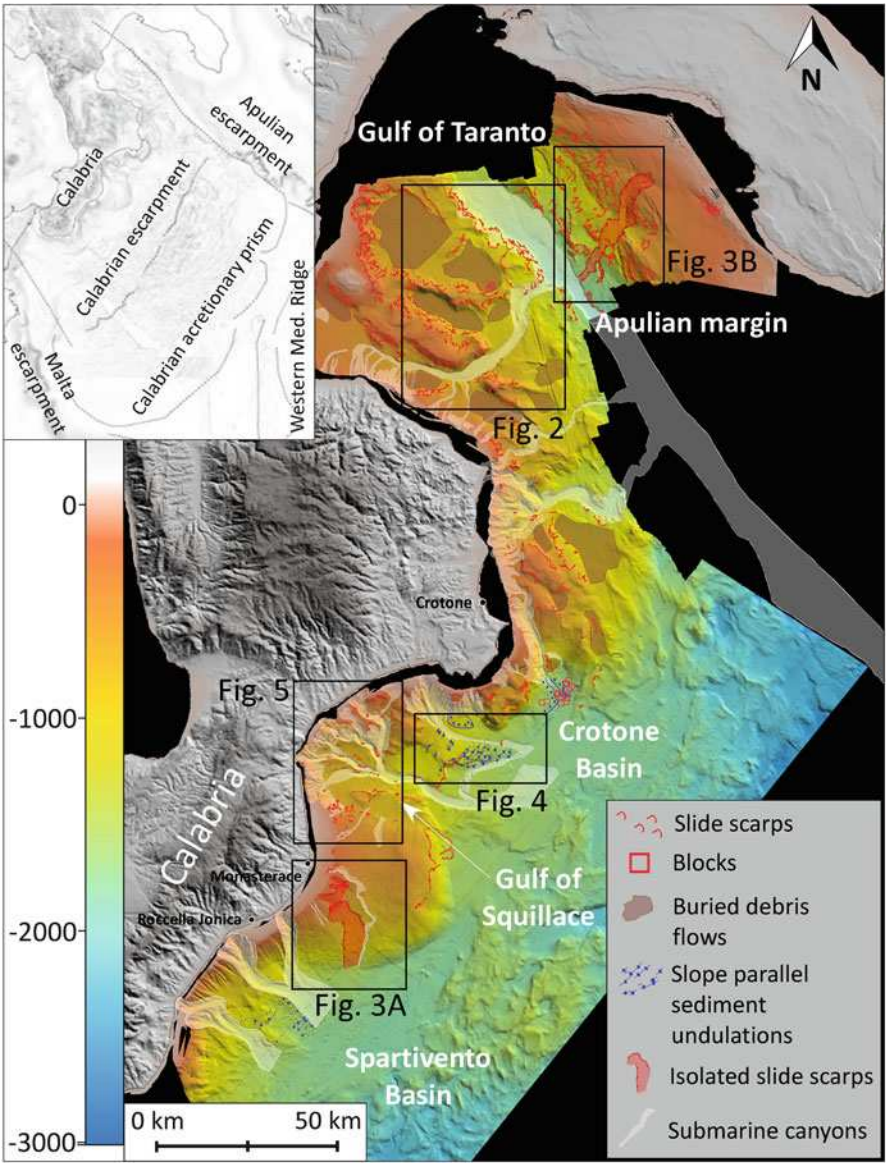

Fig. 26.1 Location of the IMCA study area and the main seabed morpho-sedimentary features related to downslope sediment movements. Offshore bathymetry based on DTMs of variable resolution (5–50 m grids, shaded relief illuminated from NE)

during the last century is mainly located along the onshore to nearshore parts of the Apennine-Calabrian accretionary system and decreases in foreland areas (DISS Working Group 2010). However, in 1743 an earthquake of estimated magnitude 7.0 affected a large area of the Ionian Sea from the Salento peninsula to the Greek island of Lefkas (Boschi et al. 2000).

26.3 Data and Methods

This study is primarily based on high-resolution geophysical data (multibeam and subbottom profiles) acquired by the RV OGS Explora during campaigns in 2009 and 2005. Swath bathymetric data were acquired over an area of about 30,000 km^2 using Reson 8150 (12 kHz) and 8111 (100 kHz) multibeam systems to obtain DTMs of variable cell size (5–50 m). Subbottom data consist of ca. 10,000 line-km of Chirp profiles (2–7 kHz). Our interpretive method consists of mapping seabed morpho-bathymetric elements in relation to acoustic facies identified on the sub-bottom profiles, in order to identify the principal tectonic and sedimentary features of the margin. Linkages to deeper structures are made using public multichannel seismic datasets (Videpi Project), held in a digital database at OGS.

26.4 Results

The seabed morphology and subsurface data together allow the recognition of four main types of mass movement phenomena along the slopes of the IMCA: mass transport complexes (MTCs) within intra-slope basins, isolated slide-scars (ISS) and slope-parallel sediment undulations (SPSU) on open slopes, and headwall and sidewall scarps in submarine canyons (HSC).

26.4.1 Mass Transport Complexes (MTCs) Within Intra-slope Basins

MTCs are recognised within piggy-back basins on the Calabrian slope of the Gulf of Taranto, in water depths of 600–900 m, as features including both seabed slide scarps and buried failure deposits together extending over areas of 30–200 km^2 (Fig. 26.1). Slide scarps are observed around the steep (up to 5–9°) flanks of the intra-slope basins as linear to crescentic features, some showing "*fresh*" sharp morphologies in contrast to others showing more rounded ruptures, that record multiple failure events. Blocks of various sizes are observed both along runoff and at the base of the slopes (Fig. 26.2). Sub-bottom profiles show the adjacent basins to contain unstratified (acoustically transparent) bodies up to tens of meters thick beneath thinner acoustically stratified units, interpreted as buried debris flows (Fig. 26.2). In places, stacked debris flows are observed, indicating that the MTCs record multiple episodes of failure along the intra-slope basin margins.

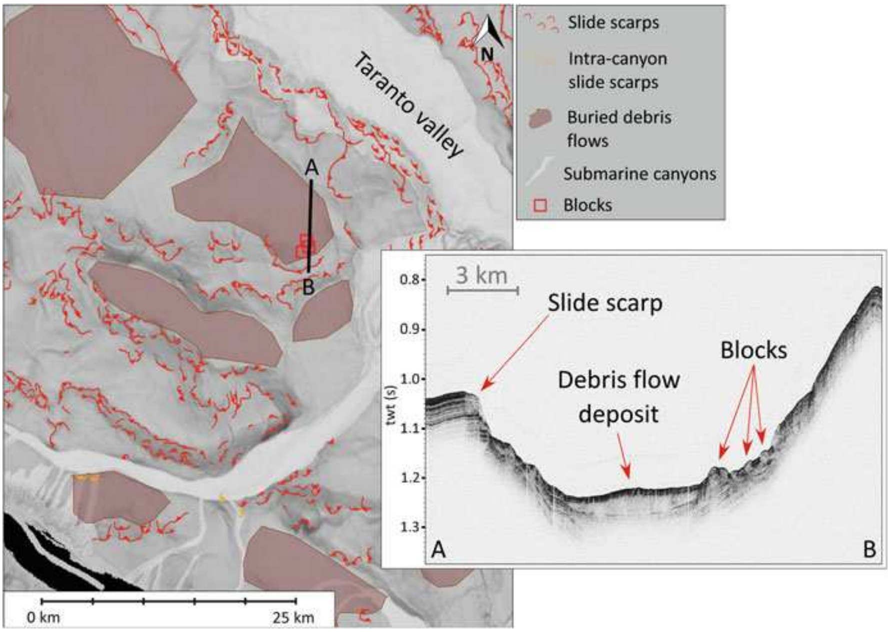

Fig. 26.2 Examples of mass transport complexes (MTCs) within intra-slope piggy-back basins of the Ionian Calabrian margin. Location is indicated in Fig. 26.1. Chirp sonar profile AB across a basin shows slide scarps and blocks above an unstratified debris flow deposit

26.4.2 Isolated Slide Scars on Open Slopes (ISS)

The steep (3–8°) open slopes offshore southern Calabria and western Apulia contain evidence of repeated failures, recorded by multiple slide scars at seabed and, in places, stacked slide deposits (Fig. 26.1). On both slopes larger isolated slide scars are observed: the Assi and Manduria failures (Fig. 26.3).

The Assi failure lies 8 km offshore Calabria on slopes of ca. 3° and in water depths of 400–1,400 m, where seabed scarps up to 50 m high define an elongate slide scar up to 6 km wide and at least 18 km long (Fig. 26.3A). Sub-bottom profiles show the slide deposits to include both acoustically stratified sediments and unstratified bodies and blocks (Fig. 26.3a). The profiles also show the slide to cut older debris flow deposits, linked to seabed scarps observed upslope (Fig. 26.3a). We infer the Assi to be the most recent isolated failure to affect this slope, and estimate that it mobilized in total ca. 2 km^3 of sediment, in one or more events.

The Manduria failure lies 30 km offshore Apulia on slopes of 4–5° and is an elongate depression up to 250 m deep and 34 km long, extending across water depths of 400–1,800 m to join the Taranto canyon (Fig. 26.3B). The feature resembles

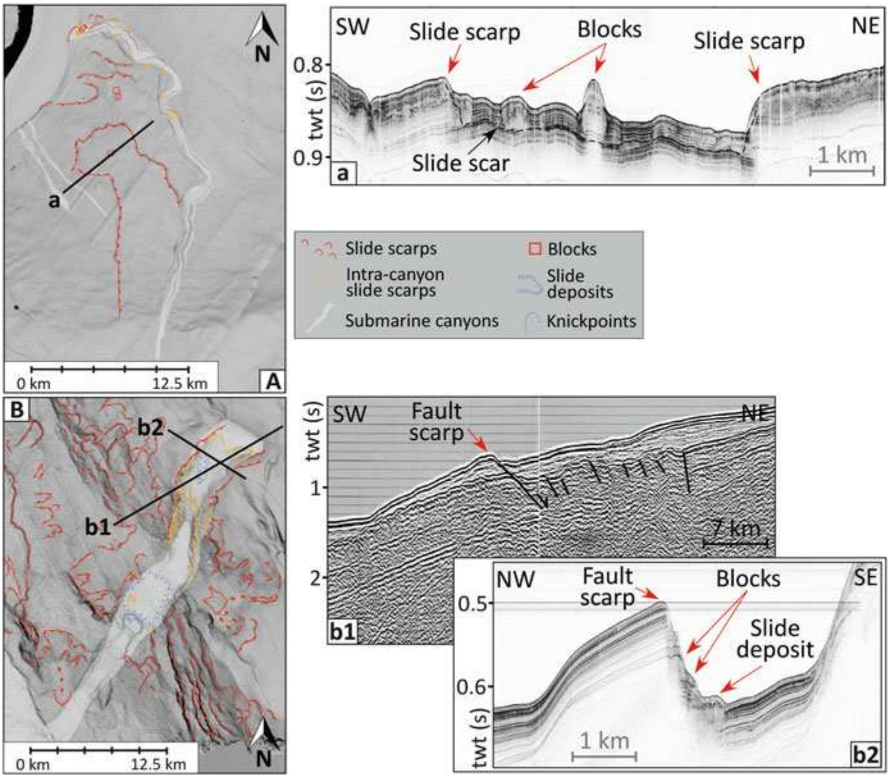

Fig. 26.3 Isolated slide scars on the Calabrian and Apulian open slopes (locations in Fig. 26.1). (**A**) Assi failure, the Chirp profile (*a*) shows the upper failure to include stratified and unstratified sediments, and to cut older debris flow deposits; (**B**) Manduria failure, the Chirp profile (*b2*) shows slide scarps and deposits, while the multichannel profile (*b2*) suggests a link to faults

a canyon, but is in part bounded by seabed slide scarps that are linked to seabed blocks and subsurface slide deposits on subbottom profiles (Fig. 26.3b). A concave axial profile includes two knick-points at 900 m and at 1,190 m depths, suggesting retrogressive failure activity. The total volume of the feature is estimated at 13 km^3. No deposits are observed at the base of the slide as they have probably been redistributed into the Ionian abyssal plain via the Taranto canyon. Seismic lines show that the Manduria failure coincides with faults in the Mesozoic carbonate platform (Fig. 26.3) suggesting a possible tectonic control on the localization of failures.

26.4.3 Slope-Parallel Sediment Undulations (SPSU)

In two areas south of Calabria, each on slopes of ca. 2°, multibeam data reveal distinctive slope-parallel sediment undulations, with lengths up to 12 km and

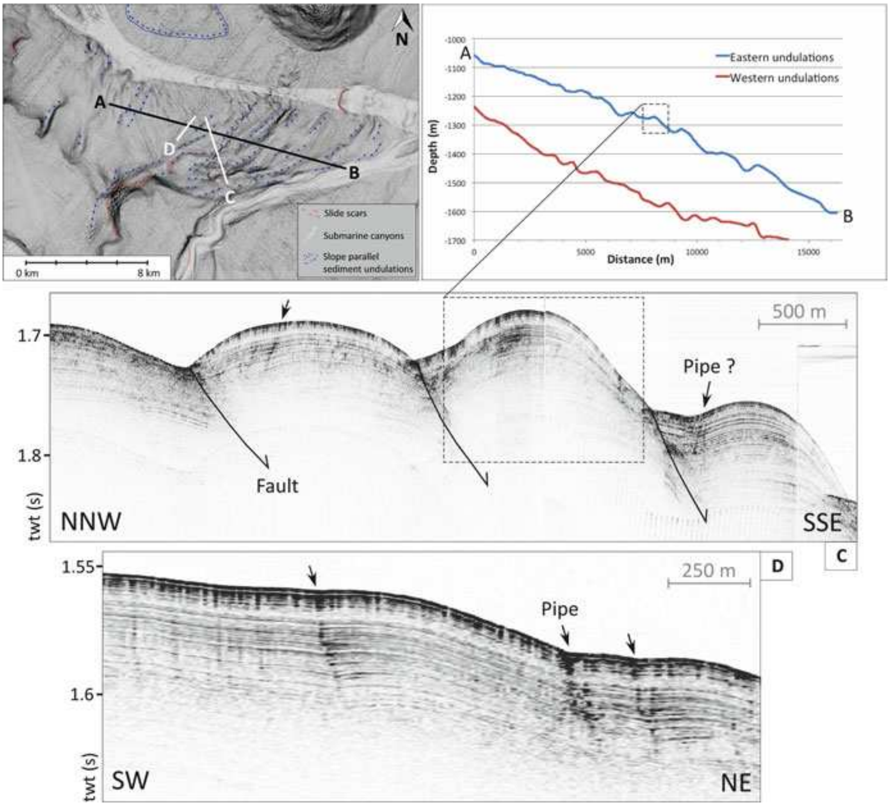

Fig. 26.4 Slope-parallel seabed undulations (SPSU) of the southern Calabrian margin (see Fig. 26.1). *Top right*: bathymetric profiles across the two areas of asymmetric SPSU, location of profile *A–B* shown at *left*. *C* and *D* are Chirp profiles showing interpreted faults and fluid escape pipes

spacing of 0.6–1.4 km (Fig. 26.1). The undulations are up to 100 m in relief and asymmetric in profile, with steeper upslope-facing flanks (Fig. 26.4 top-right). On subbottom profiles they consist of stratified sediments, mainly conformable with seabed to form anticline-like structures, but laterally discontinuous across seaward-dipping surfaces beneath their troughs interpreted as fault planes (Fig. 26.4c, d). The stratified sediments also contain inclined zones of high amplitudes near seabed, resembling fluid escape pipes (Andresen 2012). The SPSU are interpreted as fault-bounded sediment blocks recording downslope rotation in association with fluid migration, comparable to slope-parallel undulations observed elsewhere, notably on the Nile fan (Loncke et al. 2004; Migeon et al. 2013; Praeg et al. 2013).

The undulations provide evidence of a linkage between seabed sediment deformation and subsurface fluid flow. An interpretation of rotated sediment-blocks is consistent with evidence from deeper seismic profiles across the eastern area, showing the SPSU to form part of a folded/faulted Pleistocene interval developed

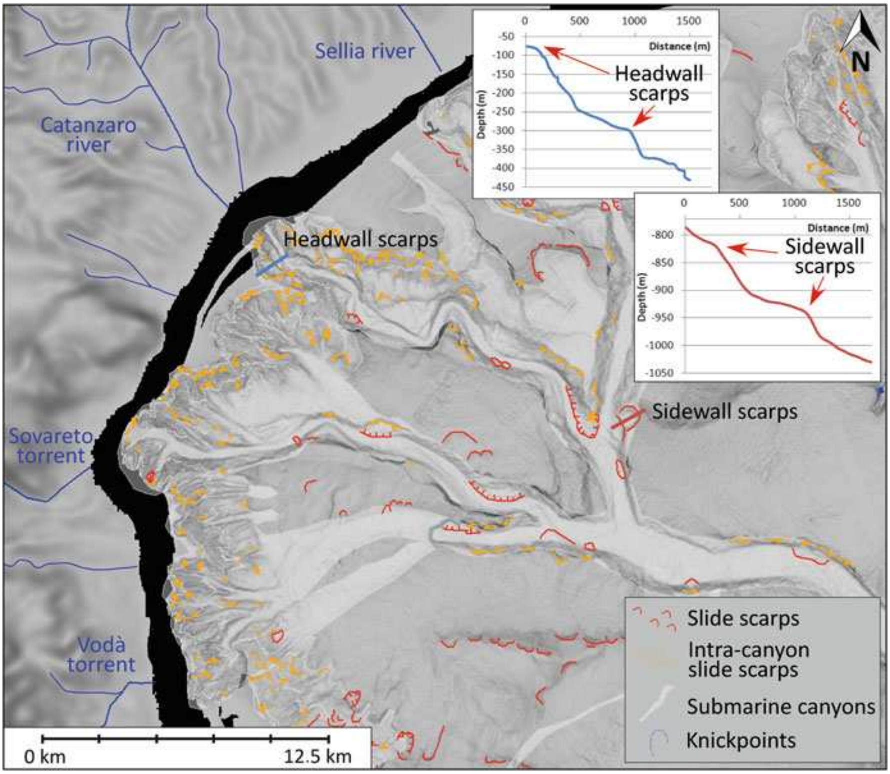

Fig. 26.5 Headwall and sidewall scarps in the Squillace canyon system (location in Fig. 26.1). The cauliform headwall lies 1–3 km from the coast, not all branches of the dendritic network connect with the hydrographic system onshore (in *blue*)

above diapiric structures affecting thick Pliocene sediments (Capozzi et al. 2012). The diapiric structures were originally suggested to be halokinetic (Rossi and Sartori 1981), but recently to be mud mobilized by upward fluid migration along normal faults (Capozzi et al. 2012). Our results indicate that the diapric structures are associated with fluids and show that their buried crests coincide with slope-parallel sediment blocks bounded by normal faults. We infer that overpressured fluids continue to facilitate progressive downslope rotation of sediment blocks along faults rooted in the diapiric structures. It is notable that the fluids have not resulted in mud volcanism, in contrast to adjacent areas (Praeg et al. 2009; Morelli et al. 2011).

26.4.4 Headwall and Sidewall Scarps in Submarine Canyons (HSC)

The Calabrian slopes are incised by numerous submarine canyons, of varying sizes and morphometries, not all connected to onshore drainage systems (Fig. 26.5). In the

Gulf of Taranto, the canyons extend 50–70 km offshore to join the Taranto canyon, which drains 250 km to the Ionian abyssal plain. South of Calabria canyons extend up to 70 km into the Crotone-Spartivento fore-arc basins (Morelli et al. 2011). Seismic profiles across the Squillace canyon in the Crotone basin show incision of relatively young (Pleistocene) sediments (Capozzi et al. 2012). All of the canyons are marked by semi-circular scarps, overlapping along their headwalls and isolated along sidewalls (Fig. 26.1), recording smaller-scale failures. The largest canyon system is located in the Gulf of Squillace (Fig. 26.1), where the headwall has a total perimeter of 62 km and an area of ca. 630 km^2. The canyon system is highly dendritic, the first-order branches of the cauliform headwall extending to within 1–3 km of the coastline. Headwall scarps are on average 30 m high and 60 m long, with a density of occurrence of ca. 50/km^2. Sidewall scarps are bigger in size (50–150 m high and 50–500 m long on average) with a lower density of occurrence (12/km^2).

Headwall and sidewall scarps show that failures of the canyon walls represents an important mechanism for their retrogressive growth. Considering only headwall scarps in the first-order canyon branches of the Squillace system, we estimate the volume of sediment removed by failure to be of the order of 6 km^3. Retrogressive scars are observed to be larger where canyons cut structural highs (e.g. Squillace), suggesting ongoing adjustment to tectonically-created topography.

26.5 Discussion – Mass Movements and Geohazards in the IMCA

The four types of mass movement described above constitute different degrees of marine geohazard for the Ionian coastal and deep-sea areas.

The slopes of the IMCA are marked by seabed slide scarps, which are particularly abundant along the Calabrian and Apulian margins of the Gulf of Taranto (Fig. 26.1). MTCs of the western Gulf of Taranto are located away from the coasts in water depths of $\geq$600 m and confined in intra-slope basins, and so do not represent a significant hazard for coastal areas. Nonetheless, they record a history of recurrent failure that is likely to be linked to seismogenic activity along the Apenninic belt, thus reflecting a wider potential for seismically-triggered failures. The Apulian slope is dissected by slide scars (Fig. 26.1), some of which appear to be linked to faults (Fig. 26.3B). This is interesting as this area has been considered seismically quiet, and raises the question of to what extent the observed failures may reflect distal versus proximal effects of seismicity. In our opinion, seismicity represents a significant potential trigger for geohazards along the IMCA in the Gulf of Taranto.

Isolated slide scars (ISS) on the Calabrian and Apulian open slopes also reflect a potential for larger submarine failures that may be capable of triggering tsunamis or anomalous waves. Tsunami modelling has been performed for the Assi slide, one scenario showing the area most affected to be the adjacent coast between Roccella Jonica and Monasterace (Fig. 26.1), where waves up to 1 m high could cause damage to coastal infrastructures (Zaniboni et al. 2012). Thus future open-slope failures similar to Assi could constitute geohazards for adjacent coastal areas, as well as for deep-sea infrastructures (pipelines, cables etc.). A better understanding of failures on the IMCA is relevant to the monitoring of tsunamigenic failures in the Mediterranean Sea, where tsunami early-warning systems are less effective than in open oceans. This is an important issue as, in contrast to earthquakes, tsunamigenic failures can be monitored.

Slope-parallel seabed undulations (SPSU) represent a low potential hazard because they record slow gravity-driven deformation of slope sediments. However, the SPSU are associated with fluid pipes that we infer to reflect fluid overpressures associated with underlying mud diapirs. A sudden release of fluid overpressures could present a hazard for deep-sea infrastructures, as reflected in near-by mud volcanoes (Praeg et al. 2009).

Retrogressing canyon headwalls represent an important geohazard along the southern Calabrian margin, where they are located within 1–3 km of the coastline (see also Morelli et al. 2011). Headwall regression can lead to coastal erosion, with risks for coastal infrastructures (highways, harbours, railways). Retrogressive canyon erosion has caused of the repeated collapse of the pier of the harbour of Cirò Marina (Casalbore et al. 2012), which could have been avoided with more efficient geohazard assessment and coastal management. We recommend monitoring and higher sensibility of national and regional stakeholders to this important issue.

26.6 Conclusions

The Ionian margins of Calabria and Apulia, including the Gulf of Taranto, provide a natural laboratory to study submarine geohazards, due to ongoing convergent tectonism and a wide range of mass failure phenomena. Mapping of over 400 km of the IMCA show the seabed and shallow subsurface to contain four main types of sedimentary record of failure over time: (1) mass transport complexes within intra-slope basins, (2) isolated slide scars along open slopes, (3) slope-parallel sediment undulations recording gravity-driven block rotations linked to over pressured fluids, and (4) headwall and sidewall scarps in submarine canyons. Preliminary analyses of sedimentary processes occurring along the IMCA indicates that open-slope failures capable of triggering tsunamis represent potential geohazards both for coastal populations and for deep-sea infrastructures, whereas retrogression of canyon headwalls lying <1–3 km off the Calabrian coast represents an important geohazard that requires regular monitoring. Seismic hazard remains a major issue to be addressed in the IMCA.

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