Submarine instability processes on the continental slopes off the Campania region (southern Tyrrhenian Sea, Italy): the case history of Ischia Island (Naples Bay)

G. Aiello, E. Marsella and S. Passaro

Istituto per l'Ambiente Marino Costiero, Consiglio Nazionale delle Ricerche (CNR), Napoli, Italy

(Received: March 12, 2008; accepted: July 31, 2008)

ABSTRACT The continental slope off the Campania region (southern Tyrrhenian Sea, Italy) represents a natural laboratory for the study of geological events and processes related to submarine gravity instabilities in deep waters, as a base to evaluate geological and environmental hazards triggered by earthquakes, volcanic eruptions and tectonic activity in correspondence to regional faults. The identification of submarine instabilities on continental slopes shows important implications in terms of applied research for the coastal zone knowledge and management, also in terms of geological and environmental hazard. This study is carried out by using marine geophysical data collected by the CNR-IAMC Institute, in particular Multibeam bathymetry and reflection seismics (Sparker Multitip seismic source). The submerged sectors of Ischia Island are the site of submarine gravity instability processes, having both catastrophic (instantaneous) and continuous characteristics (accelerated erosion along submarine canyons or channels, debris fluxes along channels and creeping). The geological interpretation of the marine DEM (Digital Elevation Model) of Ischia Island has put in evidence an articulated topography of the sea bottom. A complex stratigraphic architecture, with intercalations between volcanic and sedimentary units is revealed by the interpretation of high-resolution seismic-reflection profiles. The Ischia Debris Avalanche (IDA) has a southern dispersal axis with a transport of blocks of up to 40-50 kilometres from the island. The interpretation of Multibeam bathymetry has shown that IDA is bounded northwards by a large scar, coincident with the Mount Epomeo block; its emplacement is probably younger than the eruption of the Green Tuffs of the Mount Epomeo volcano (55 ky B.P.). Piston cores, sampled on the southern, submerged flank of Ischia Island along the IDA, recovered blocks of Mount Epomeo Green Tuff Ignimbrites enclosed in a sandy-to-muddy matrix, constituting the main bulk of the avalanche deposit. These products are covered by tephra layers, correlatable to Ischia $\leq$ 10 ky eruptions based on major and trace element chemistry. Other important debris avalanches occur in the northern and western sectors of the island, as put in evidence by Side Scan Sonar profiles recorded on the same navigation lines as the Multibeam bathymetry.

1. Introduction

On submarine slopes, offshore the Campania region, gravity instability processes occur both on the submerged flanks of volcanic edifices (i.e. Ischia Island) and/or on volcanic relic morphologies (Banchi di Pentapalummo, Nisida and Miseno in the Naples Bay; Banco di Forio and Banco d'Ischia on Ischia Island) and along tectonically-controlled steep sedimentary slopes (i.e. southern slope of the Sorrento Peninsula, slope of Policastro Gulf) or in correspondence to slightly inclined ramps, surrounding extended areas of continental shelf (i.e. Salerno Gulf). Significant processes of rock slides and gravity-mass collapses are often concentrated in correspondence to steep coastal cliffs, both volcanic (i.e. Naples Bay, Ischia and Procida Islands) and sedimentary (i.e. Sorrento Peninsula, Capri Island). Such processes allow the continuous modification of the coastal relief, giving rise to coarsely-grained deposits at the toe of the cliffs, which grades seawards, towards sands and shales. Moreover, abrupt slopes, irregularly articulated in channel-levee areas cropping out at the sea bottom are controlled by the development of tributary channels, which drain sedimentary inputs at the edge of extended continental shelves, influenced both by volcanic and sedimentary processes (i.e. Cuma canyon).

The aim of this paper is to investigate submarine instabilities on the continental slope off the Campania region, discussing, in particular, the example of Ischia Island (Naples Bay).

The recent realization of Multibeam bathymetric surveys in the Tyrrhenian Sea (Marani and Gamberi, 2004) has produced new geological data in areas surrounding both emerged (Aeolian Islands, Ischia and Ustica) and submerged volcanic edifices (Vavilov, Marsili, Palinuro and submerged volcanoes of the Aeolian arc), collecting morpho-bathymetric evidence on volcanic, tectonic and gravitational processes at various scales.

The gravitational collapses of the flanks of volcanic edifices are complex phenomena, giving rise to the formation of debris avalanches, debris fluxes and turbidity currents, as verified for example for the Canary Islands (Watts and Masson, 1995; Carracedo, 1999). Sea-bottom morphologies interpreted as gravity instabilities have been recently recognised in the southern Tyrrhenian Sea (Marani and Gamberi, 2004), on the flanks of the submerged portion of Ischia (Chiocci *et al*., 1998a) and Stromboli Islands (Kokelaar and Romagnoli, 1995; Chiocci *et al*., 1998b). The study of submarine instability processes is relevant also if related to the possibility of development of tsunamis related to submarine slides (Saxov and Niewenhuis, 1982; Ward, 2000; Maramai *et al*., 2005).

The morpho-bathymetry of the continental slopes off the Campania region varies depending on the geological framework of the adjacent emerged areas, conditioning the nature (sedimentary and/or volcanoclastic), and, consequently, the type of instability at the sea bottom. The use of typical techniques and methodologies of marine geology and geophysics has important implications for the definition of geological and environmental hazard.

Regional control factors for such processes include seismic activity, volcanic eruptions and tectonic activity in correspondence to significant normal faults. Local control factors trigger submarine instabilities in slope areas, i.e. the increase of steepness of the slope topographic profile (due to high volcanic and/or sedimentary supply), the increase of water content in the sediments, the processes of emersion/erosion and consequent flooding in correspondence to significant sea-level fluctuations during the Late Quaternary, the occurrence of unconformities and shallow gas pockets in the stratigraphic succession (Correggiari *et al*., 2001; Lee *et al*., 2002; Aiello *et al*., 2004b; Cattaneo *et al*., 2004; Sultan *et al*., 2004; Trincardi *et al*., 2004).

Three sketch tables of the geologic interpretation of selected Subbottom Chirp profiles in Naples Bay are reported in order to show significant instability processes occurring in Naples

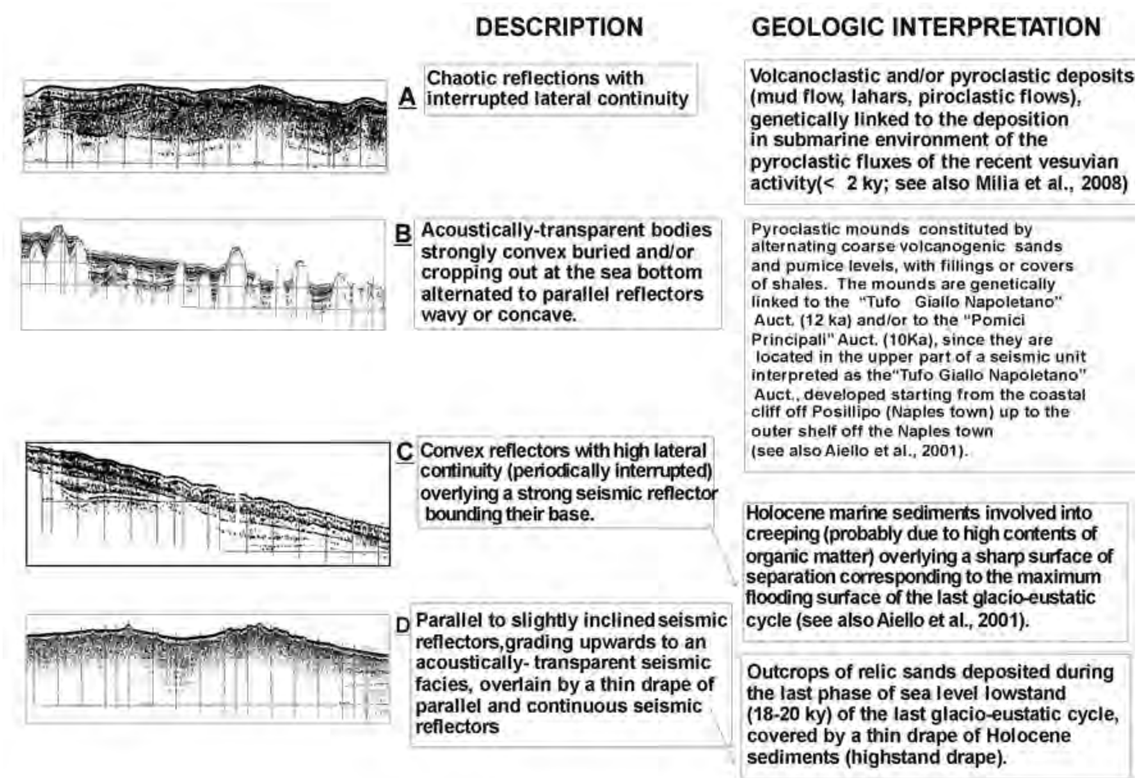


Fig. 1 - Sketched table showing significant acoustic facies on the continental shelf of Naples Bay, recognized by the geological interpretation of Subbottom Chirp profiles. Some of them (A, B, C) appear to be related to submarine gravity instabilities. Volcanoclastic and/or pyroclastic deposits (mud flow, lahars, piroclastic flows; label A) are genetically linked to the deposition in the submarine environment of the pyroclastic fluxes of the recent Vesuvian activity (see also Milia *et al.*, 2008). Pyroclastic mounds constituted by alternating coarse volcanogenic sands and pumice levels (label B) have been identified on the outer shelf of Naples Bay and are interpreted here as a submarine slide, controlled by volcano-tectonics during the Late Quaternary (see also Aiello *et al.*, 2001; D'Argenio *et al.*, 2004). Holocene marine sediments involved in the creeping (label C) crop out at the sea bottom and are bounded downwards by a strong seismic reflector interpreted as the maximum flooding surface of the last glacio-eustatic cycle. Outcrops of relic sands (label D) have been deposited during the last phase of the sea-level lowstand of the last glacio-eustatic cycle.

Bay [Figs. 1 and 3; Aiello *et al.* (2001), D'Argenio *et al.* (2004)]. The stratigraphic labels of interpreted acoustic reflectors are based on regional geological and geophysical detailed knowledge of the area and on piston cores collected in the frame of research projects of marine geological cartography of Naples and Salerno Bays (Aiello *et al.*, 2001; D'Argenio *et al.*, 2004; Aiello *et al.*, 2004a; 2005; Ruggieri *et al.*, 2007; Milia *et al.*, 2008). On the continental shelf, volcanoclastic and or pyroclastic deposits form mud flows, lahars and pyroclastic flows occurring in the eastern part of Naples Bay and are related to the last eruptive phases of the Vesuvius volcano (A in Fig. 1). A complex submarine slide is composed of pyroclastic mounds exposed at the sea bottom or partly buried; they are constituted by alternating coarse volcanogenic sands and pumice levels, with fillings and covers of shales off the city of Naples (B in Fig. 1). The mounds are genetically linked to the eruption of the deposits of the "Tufo Giallo Napoletano" (12 ky) and of "Pomici Principali" (10 ky). Offshore the northern Sorrento Peninsula, Holocene marine

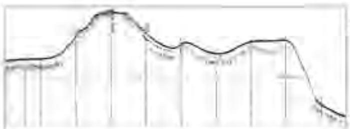
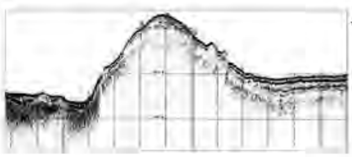
		DESCRIPTION	GEOLOGIC INTERPRETATION
	E1	Body having a mounded external geometry, characterized by a sharp echo in correspondence to the surface of separation,overlain by highly continuous inclined and wavy to parallel seismic reflectors	Buried volcanic unit interpreted as the "Ignimbrite Campana"Auct. (35 ky), related to the Phlegrean Fields caldera (see also Orsi et al., 1991) overlain by Holocene marine sediments.
	E2	Body with an external morphology of bank, characterized by a strong echo in correspondence to the surface of separation; its top is locally covered by an acoustically transparent sediment drape; its flanks are onlapped by inclined seismic reflectors	Volcanic acoustic basement, cropping out at the sea bottom in correspondence to the "Pentapalummo", "Nisida" and "Miseno" relic volcanic edifices, located on the outer shelf off the Gulf of Pozzuoli (see also Aiello et al., 2004a; 2005; Ruggieri et al., 2007)
	E3	Body with a mounded external morphology, characterized by a strong echo in correspondence to the surface of separation, overlain by a thin drape of parallel and continuous seismic reflectors; its flanks are onlapped by inclined to parallel seismic reflectors.	Volcanic acoustic basement cropping out at the sea bottom, interpreted as lavas deposited in correspondence to parasitic vents genetically linked to the Somma-Vesuvius volcanic complex (see also Aiello et al., 2004a; 2005; Ruggieri et al., 2007).

Fig. 2 - Sketched table showing volcanic acoustic basements in Naples Bay based on the geological interpretation of Subbottom Chirp profiles. Based on regional seismo-stratigraphic evidence the facies labelled E1 are interpreted as the "Ignimbrite Campana" Auct. erupted from the Phlegrean Fields caldera about 35 ky B.P. and widely occurring in the eastern sector of Naples Bay, up to Dohrn canyon. The facies labelled E2 correspond to volcanic acoustic basements cropping out at the sea bottom on the outer shelf, off Pozzuoli, in correspondence to relic volcanic edifices ("Pentapalummo", "Nisida" and "Miseno" banks; see also Aiello *et al*., 2004a, 2005; Ruggieri *et al*., 2007). The facies labelled E3 are interpreted as volcanic acoustic basements cropping out in correspondence to parasitic vents located on the continental shelf offshore the Somma-Vesuvius volcanic complex and genetically related to the last eruptive phases of the volcano (see also Aiello *et al*., 2004a, 2005).

sediments are involved in creeping over a sharp surface of separation corresponding to the maximum flooding surface of the last glacio-eustatic cycle (C in Fig. 1).

Volcanic morphologies are extensively present in Naples Bay (Fig. 2). Mounded volcanic units interpreted as outcrops of the "Ignimbrite Campana" pyroclastic deposits (35 ky) are overlain by recent marine sediments (E1 in Fig. 2). A volcanic acoustic basement crops out at the sea bottom, in correspondence to the Pentapalummo, Nisida and Miseno banks (E2 in Fig. 2), representing relic volcanic edifices and marking the submerged border of the Phlegrean caldera (Aiello *et al*., 2004a, 2005; Ruggieri *et al*., 2007). Mound-shaped, acoustically-transparent bodies overlain by a thin drape of parallel and continuous seismic reflectors (E3 in Fig. 2) are interpreted as lavas emplaced in correspondence to parasitic vents genetically related to the Somma-Vesuvius volcanic complex (Aiello *et al*., 2004a, 2005; Ruggieri *et al*., 2007).

At the foot of the volcanic slopes of the banks, slide deposits occur as wedge-shaped bodies with chaotic reflectors without lateral continuity and cloudy acoustic aspects, underlain and overlain by highly-continuous, inclined and wavy reflectors (F in Fig. 3). Successions of highly-continuous, convex and parallel or inclined reflectors form morphologies of channel-levee

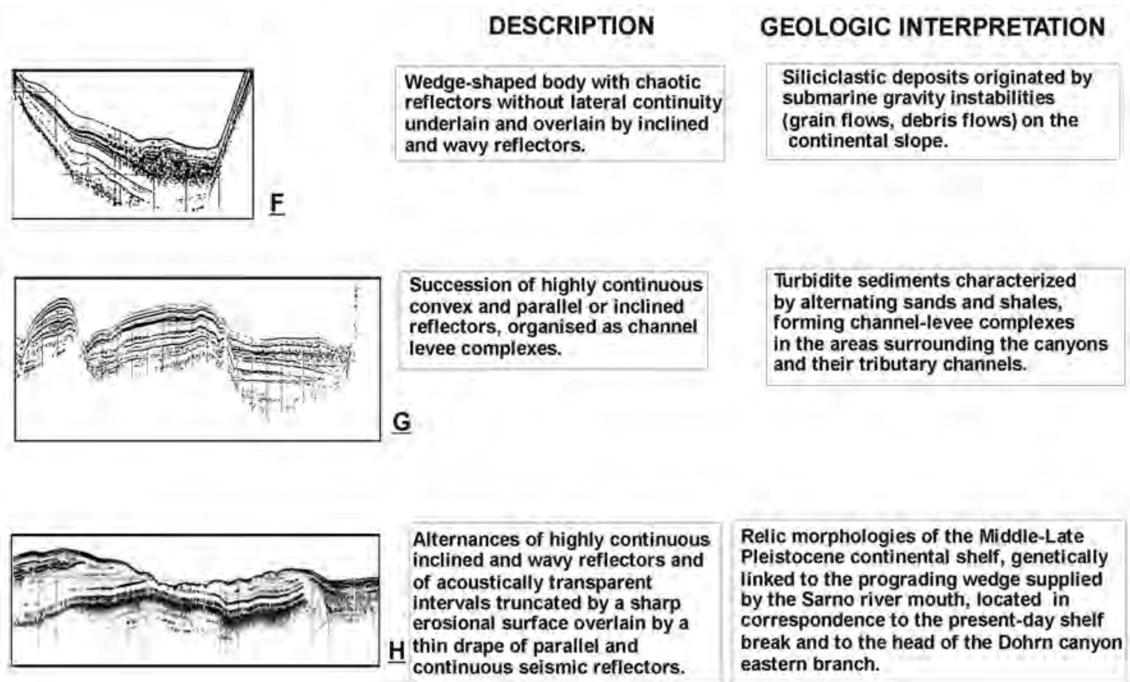


Fig. 3 - Sketched table showing significant acoustic facies on the continental slope of Naples Bay based on the geological interpretation of Subbottom Chirp profiles. Wedge-shaped bodies, characterized by chaotic reflectors (label F), underlain and overlain by inclined and wavy reflectors, have been recognised on the continental slope and interpreted as submarine slides fossilised by Holocene marine sediments. Channel levee complexes located around the canyons correspond to successions of highly continuous convex and parallel or inclined reflectors (label G). Relic morphologies of the Middle-Late Pleistocene continental shelf, located in correspondence to the present-day shelf break and to the head of Dohrn Canyon's eastern branch, are characterized by highly continuous inclined and wavy reflectors alternated by acoustically transparent intervals truncated by a sharp erosional surface (label H).

complexes, especially in the areas surrounding the Dohrn and Magnaghi canyons (G in Fig. 3). Successions of highly-continuous, inclined and wavy reflectors closing towards a sharp erosional surface, overlain by acoustically clear, parallel reflectors, are interpreted as relic morphologies of the Middle-Late Pleistocene continental shelf located in correspondence to the present-day shelf break (H in Fig. 3).

2. Geological setting

The Campania Tyrrhenian margin is characterized by the occurrence of marine areas, strongly subsident during the Plio-Quaternary, sites of thick sedimentation, as the Capri basin, Naples Bay, Salerno Valley and the Sapri and Paola basins. Several stratigraphic-structural papers have given a geological interpretation to the seismic stratigraphy of the basin filling based on single-channel and multichannel seismics (Aiello *et al*., 1997a, 1997b, 2001, 2004a; Secomandi *et al*., 2003). Under the Plio-Quaternary sedimentary cover, the Campania continental margin is characterized by the occurrence of tectonic units of the Apenninic chain, resulting from the seaward prolongation of corresponding units cropping out on the coastal belt of the southern Apennines.

The main structural trends of the Campania margin are NNW-SSE and are characterized, on the continental slope and in the bathyal plain, by the occurrence of intra-slope basins and structural highs, showing hints of intense synsedimentary tectonics. Two main NE-SW trending lineaments, i.e. the Phlegrean Fields-Ischia fault and the Capri-Sorrento Peninsula fault, control the structural setting of Naples Bay. These lineaments have controlled the emplacement of main morphostructures on the continental slope and in the bathyal plain. In the Bays of Naples and Salerno the synsedimentary tectonics played a major role in triggering submarine gravity instabilities from the Middle-Late Pleistocene up to recent times.

Ischia Island represents an alkali-trachytic volcanic complex, whose eruptive activity lasted from the Late Pleistocene up to historical times (Vezzoli, 1988). The oldest rocks date back to about 150 ky and crop out in several sectors of the coastal belt of the island, with particular abundance in correspondence to the "Scarrupata di Barano", a steep slope located south-eastwards of the island. This evidence suggested the occurrence of a resurgent caldera, about 10 km wide, where the eruptive activity and tectonics gave rise to the uplift along faults of the Mount Epomeo block (Orsi *et al*., 1991). The main eruptive events of the Ischia-Procida-Phlegrean Fields system suggest at least five eruptive cycles, ranging in age from 135 ky to prehistorical and historical times. The most important recent eruption originated the "Arso" lava flow and occurred in 1302 A.D.

For Ischia Island, the extensional tectonics associated to the tectonic uplift of the Mount Epomeo block and interpreted as intra-calderic resurgence (Acocella and Funiciello, 1999) is related to a relatively confined shallow seismicity, triggering gravity instabilities on the Epomeo relief. Most of the landslides occurring on Ischia Island, as rock falls in tuff coastal cliffs, roto-translational slidings and debris flows (Mele and Del Prete, 1998) are associated to the dynamics of Mount Epomeo. Moreover, significant slides are related to the dynamics of erosion of the littorals, particularly efficient on the volcanic islands, as observed during marine geophysical surveys carried out in the Maronti Bay (Marsella *et al*., 2001).

3. Ischia Island: interpretation of Multibeam bathymetry and high-resolution reflection seismics

Ischia Island lies on a volcanic ridge showing a mainly E-W trending elongment. On the western offshore of the island, a strong field of magnetic anomalies suggests the occurrence of a magmatic system, now inactive. Two main structural trends exist in the E-W trending volcanic ridge of Ischia Island: one E-W trending and another ENE-WSW trending, which has been recognised especially at western offshore part of the island. At a regional scale, the comparison between the distribution of magnetic sources and the morphostructures, indicate a poor correlation for the E-W trending morphostructures, and a high correlation for the ENE-WSW (Bruno *et al*., 2002; Passaro, 2005).

A Digital Elevation Model (DEM) of Ischia Island, based on Multibeam bathymetric surveys, recorded by the CNR-IAMC Institute and integrated by onshore topography is shown in Fig. 4. The geological interpretation of the marine DEM of the island allows the identification of the main morphostructural features of the sea bottom. Spectacular features characterize the continental slope off south-western Ischia Island, incised by a dense network of canyons and

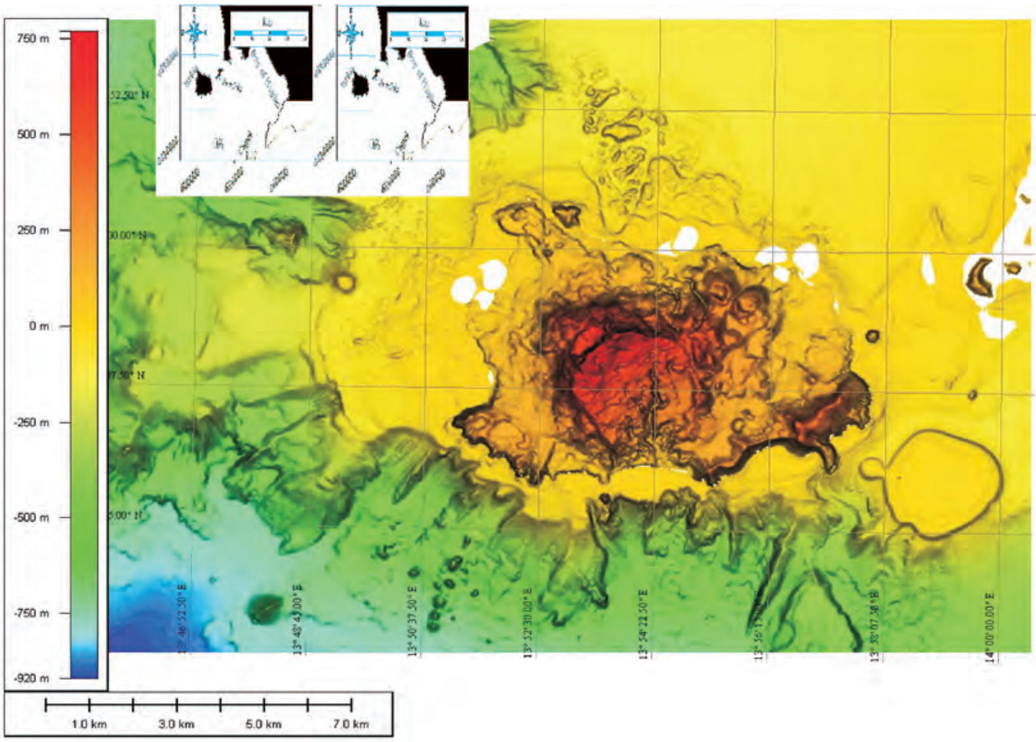


Fig. 4 - DEM of Ischia Island resulting from the merging of different data sets of Multibeam bathymetry recorded by the CNR-IAMC Institute during several oceanographic cruises. The DEM is based on regularly spaced soundings arranged in symmetrical x, y, z matrices called grids. Each grid is characterized by an elementary square cell unit and the adopted cell size must take into account the limits imposed by the average footprint. The DEM results from the integration of different grids, each characterized by a variable cell size, ranging from 2.5x2.5 m at water depths reaching up to – 50 m to 25x25 m at greater depths. The marine DEM has been merged with a Digital Terrain Model of the coastal area, derived from topographic maps having the same cell size.

tributary channels, starting from a retreating shelf break, parallel to the coastline and located at varying depths. Large scars characterize the platform margin off south-western Ischia Island, in particular the scar of the southern flank of the island, corresponding, onshore, to the Mount Epomeo block and probably at the origin of the Ischia debris avalanche. Volcanic banks, having irregular morphologies, are identifiable on the south-western flanks of the island, as the "Banco di Capo Grosso", a complex morphostructural high located on the southern continental slope.

The marine DEM shows the relic morphology of the "Banco di Ischia", a wide-terraced volcanic bank located on the south-eastern flank of the island (Fig. 4). Swath bathymetric surveys recorded by the CNR-IAMC Institute (de Alteriis *et al.*, 2004; Passaro, 2005), coupled with side scan sonar imagery and seismic profiles put in evidence a large field of hummocky deposits south of Ischia Island (the Ischia debris avalanche). Based on detailed piston coring and tephrostratigraphy, Chiocci and de Alteriis (2006) suggested that the volcano-tectonic collapse originating the avalanche occurred during prehistorical times.

The geological interpretation of the DEM reveals, several volcanic highs, disposed along two main ridges. The first ridge, NE-SW trending, is about 10 kilometres long and includes several morphological highs located in the south-western Ischia offshore at water depths ranging from -800 m and -100 m ("Banco Rittmann", "Banco P. Buchner", "Banco G. Buchner", "Banco di Forio"). The top of the "Banco di Forio" tuff cone occurs at water depths of about -30 m. The second ridge, E-W trending, starts in north-western offshore Ischia, at water depths of about -600 m (from the "Banco Pithecusa" and the "Banco Mazzella") and continues up to the coastal sectors of the island.

The submerged sectors of Ischia Island are the site of submarine gravity instability processes, having catastrophic (instantaneous) character (debris avalanches) or continuous character (i.e. accelerated erosion along submarine canyons or channels, debris fluxes along channels and creeping).

The first category of submarine instabilities includes debris avalanches all originated from the volcano-tectonic uplift of the Mount Epomeo block during the last 30 ky.

The most important debris avalanche of Ischia Island is the IDA (Ischia debris avalanche), having a southern dispersal axis with a transport of blocks up to 40-50 kilometres from the island. The origin of the catastrophic collapse of the IDA has to be attributed to a land-sea collapse involving all the southern sector of the island. This is suggested by the large scar of the southern flank of the island, well evident on Multibeam bathymetry and coincident to the Mount Epomeo block (Figs. 4 to 6).

A morphological sketch map, based on the geological interpretation of Multibeam bathymetry, was drafted to show the main morphostructural lineaments occurring around the island. In particular, three important areas of accumulation of debris, avalanche deposits are located in north, west and south offshore Ischia (Fig. 5). The main heads of the canyons are located in the north-western sector of offshore Ischia ("Testata di Punta Cornacchia", "Canalone di Forio"; Fig. 5). Strong erosion along canyons and channels occurs in the southern offshore part, characterized by abrupt slopes, mainly incised in volcanic deposits. In particular, several channels erode the slope between Punta Imperatore and Punta Sant'Angelo, starting from the retreating shelf break, located at water depths of about -100 m. The preferential NE-SW trend of the channels indicates a possible structural control over their development. The canyons off the Maronti Bay, exhibit a dominant N-S azimuth and start in correspondence to embayments of the shelf break, more retreated than in the adjacent sectors of the southern offshore part (Fig. 5). The promontories of the platform margin are located in correspondence to the promontories of Punta Imperatore, Punta Sant'Angelo, Capo Grosso and Punta San Pancrazio, where the continental shelf is very reduced or absent (Figs. 5 and 6).

In the southern part of offshore Ischia the geological interpretation of the DEM has revealed the reduced extension of the continental shelf, the lobate heads of the canyons off Maronti, Capo Grosso and Barano and the linear heads of the canyons off Cava Grado and Punta San Pancrazio. The continental slope off Maronti Bay appears to be further retreated and steeper than in the adjacent sectors; this is probably due to the development, to the south, of the large scar corresponding to the IDA (Fig. 6).

The estimated volume of the IDA, based on Multibeam bathymetry, is in the order of 1.5 cubic kilometres (Fig. 6). Such a value is coherent with the values estimated on the basis of seismic reflection profiles and piston cores (Chiocci and de Alteriis, 2006).

In northern and western offshore Ischia Island, hummocky topographies occur, not correlated

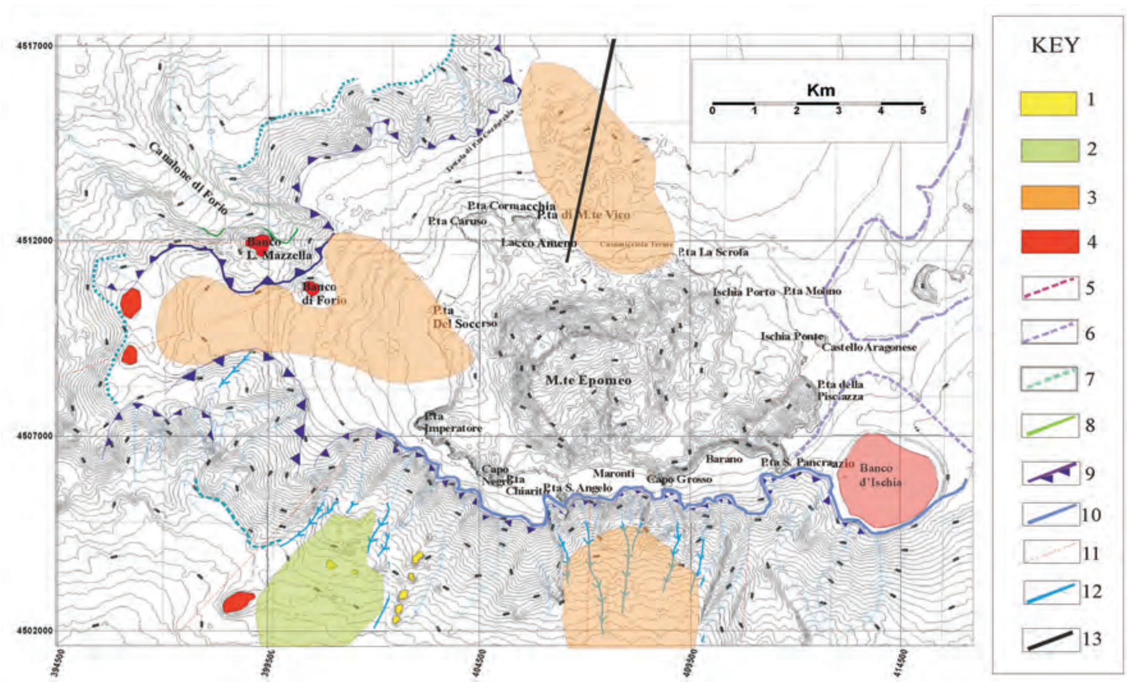


Fig. 5 - Sketched morphological map of Ischia Island, based on the geological interpretation of Multibeam bathymetry. Main morphostructural features have been represented: 1) slope fan; 2) creeping; 3) hummocky facies corresponding to debris avalanche deposits; 4) volcanic edifice; 5) calderic rim; 6) depositional terrace rim; 7) slope break; 8) channel levee; 9) retreating canyon head; 10) retreating shelf break; 11) buried normal fault; 12) drainage axis; 13) location of seismic profile.

with evident slide scars (Figs. 4 and 5). In particular, Side Scan Sonar profiles recorded in offshore western Ischia between Punta del Soccorso and Punta Imperatore show extended hummocky, chaotic facies at the sea bottom, having a kilometric extension at water depths ranging between about -30 m and more than -100 m. In the hummocky topographies, heterometric blocks are buried and inglobated by pelitic sediments. The deposits reach the tuff cone of the "Banco di Forio" and are interposed between a submerged depositional terrace and a more recent coastal wedge of marine sediments (Budillon *et al.*, 2003). In northern offshore Ischia hummocky deposits, composed of large blocks, have a fan-shaped topography in plan view and cover a large erosional area offshore Punta della Cornacchia to the west and offshore Casamicciola to the east (Figs. 4 and 5).

The hummocky area off northern Ischia is evident on shaded relief maps of Multibeam bathymetry (Fig. 4). The extension of the deposit is also shown in Fig. 5. The hummocky topographies are located in water depths ranging from -20 m to -180 m and show large blocks, having average dimensions in the order of hundreds of meters, cropping out at the sea bottom or partly covered by Holocene sediments. The deposits form a large field having sub-circular shape in plan view, which is bounded by depositional levees; a network of erosional gullies develops in the portion of the sea bottom occupied by the hummocks. As suggested by the interpretation of seismic profiles (Fig. 7), the hummocky deposits (H1 and H2 in Fig. 7) are interpreted as the

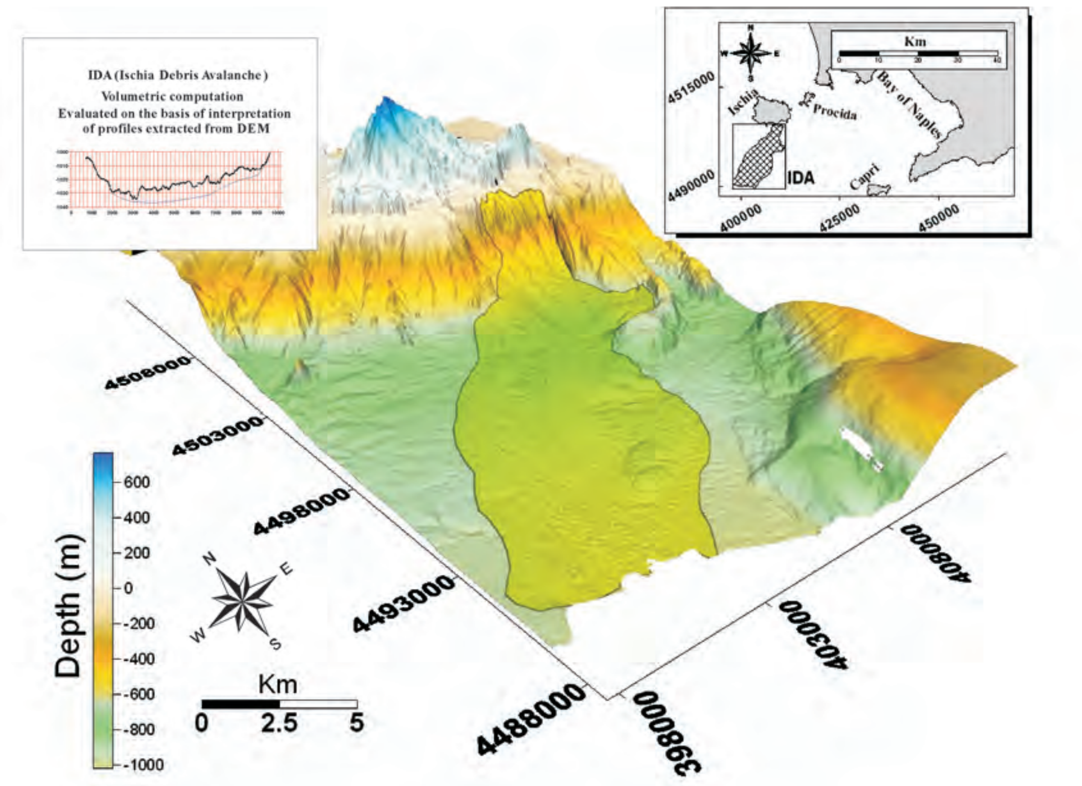


Fig. 6 - Three-dimensional shaded relief map of the Multibeam bathymetry of the southern flank of Ischia Island. Note the occurrence of the large scar of the southern flank of Ischia Island, corresponding to the Mount Epomeo block and at the origin of the IDA. A continuous line indicates the extension of the deposit, propagating on the continental slope up to 40-50 kilometres from the island. The location of the shaded relief map in Naples Bay is shown in the inset reported at the right-hand side of the map. In the same inset, the extension of the IDA is also reported. On the left, in the figure, the bathymetric profile reported in the inset allows for a volumetric computation of the IDA evaluated on the basis of interpretation of profiles extracted from DEM.

result of two events of debris avalanches, partly superimposed.

A sketch stratigraphic scheme has been constructed in northern offshore Ischia based on the interpretation of high-resolution seismic profiles acquired by using the Sparker Multitip seismic source (Fig. 7). Forced regression prograding wedges (FST), pertaining to the Late Quaternary depositional sequence, appear on the continental shelf off the northern Ischia Island. Debris avalanche deposits, having wedge-shaped external geometry and chaotic facies are arranged in two distinct, superimposed bodies (H1 and H2 in Fig. 7). The two wedges are characterized by facies hetheropy with the upper seismic unit of the basin filling (unit 5 in Fig. 7). The lower seismic unit of the basin filling (unit 3 in Fig. 7) is characterized by reflectors having a parallel seismic facies and shows bidirectional onlaps in correspondence to depressions eroding the top of the underlying seismic unit. The intermediate seismic unit of northern offshore Ischia (unit 4 in Fig. 7) is characterized by parallel-to-subparallel seismic reflectors. The unit shows a strong wedging in correspondence to a normal fault (fossilised by the erosional unconformity located at the top of the unit) and facies hetheropy with the upper part of dome-shaped, buried volcanic

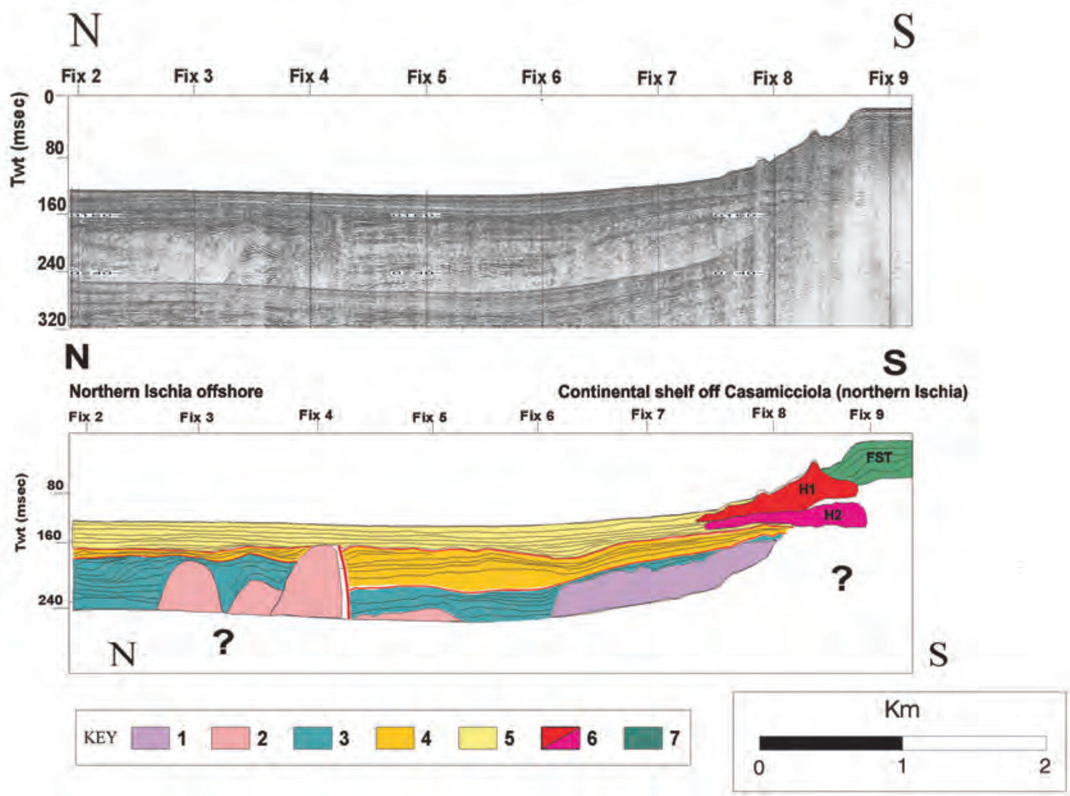


Fig. 7 - Seismic profile L27 recorded offshore northern Ischia by Sparker Multitip seismic source (see Fig. 5 for the location). The line runs from the continental shelf, off Casamicciola (northern Ischia), towards northern offshore Ischia. Qualitative sketched stratigraphic diagram of northern offshore Ischia based on the geological interpretation of seismic profile L27. Forced regression prograding wedges characterize the stratigraphic architecture of the continental shelf (FST). Two superimposed wedges of chaotic deposits suggest a multi-phase event for the evolution of the debris avalanche off Casamicciola (H1 and H2). Three seismic units, separated by regional unconformities occur in the basin filling (respectively units 3, 4 and 5; see the key for the description).
Key: 1) Volcanic unit of Casamicciola. Undetermined volcanic unit, probably corresponding to a volcanic acoustic substratum, eroded at its top by an unconformity, probably subaerial. 2) Volcanic domes of Casamicciola. Dome-shaped volcanic edifices, characterized by transparent acoustic facies and dome-shaped external geometry, interstratified in the lowest seismic units of the basin filling (unit 3 and 4). 3) Lower seismic unit of the basin filling, characterized by parallel-to-subparallel seismic reflectors and, locally, by prograding clinoforms (on the left in the profile). The unit is strongly downthrown in correspondence to a normal fault. 4) Intermediate seismic unit of the basin filling, characterized by parallel to subparallel seismic reflectors. The unit shows a strong wedging in correspondence to a normal fault, which is fossilised by an erosional unconformity. 5) Upper seismic unit of the basin filling, characterized by parallel seismic reflectors and, locally, by bidirectional onlaps in correspondence to depressions eroding the top of the underlying seismic unit. 6) Hummocky deposits (H1 and H2), characterized by a wedge-shaped external geometry and chaotic facies, probably individuated during two main volcano-tectonic events occurring on the continental shelf off Casamicciola (Ischia north). Hummocky deposits, occur on the continental slope and in the upper part of the basin and grade seawards to marine deposits of unit 5. 7) FST/Forced Regression System Tract, i.e. forced regression prograding wedges of the Late Quaternary depositional sequence, deposited on the continental shelf off Casamicciola.

structures (unit 2 in Fig. 7). The upper seismic unit of the basin filling, off northern Ischia Island (unit 5 in Fig. 7), is characterized by parallel-to-subparallel seismic reflectors and locally, by prograding clinoforms. The unit appears to be strongly downthrown in correspondence to a normal fault and shows facies hetheropy with the lower part of dome-shaped buried volcanic structures (unit 2 in Fig. 7). Dome-shaped volcanic edifices are in lateral contact with the lower seismic unit of the basin filling (unit 3) and, partly, with the second one (unit 4) and are suturated by the erosional truncation located at the top of unit 3 (Fig. 7). An undetermined volcanic unit (unit 1 in Fig. 7), having facies hetheropy with unit 3 (Fig. 7) is eroded at the top by an unconformity, probably subaerial and is interpreted as a volcanic acoustic basement.

Evacuation surfaces due to mass wasting occur on both flanks of the "Banco di Ischia", a wide-terraced volcanic edifice (Figs. 4 and 5), whose emplacement is probably older than 55 ky (Latmiral *et al*., 1971; Bernabini *et al*., 1973; Pescatore *et al*., 1984; Vezzoli, 1988). The slope south of the Banco di Ischia is incised in volcanic deposits covered by a thin sedimentary drape and shows strong hints of erosion. This is suggested by erosional marks located at several water depths, up to the Magnaghi canyon, completely incised in volcanic deposits (Aiello *et al*., 2004a, 2005). Similar morphologies have been observed on the submerged flanks of the Pentapalummo and Nisida volcanic banks based on the interpretation of Subbottom Chirp profiles (see also Fig. 2).

4. Conclusions

Significant submarine instability processes occur on the continental slope offshore the Campania region. As a general rule, they include rock falls on volcanic and/or sedimentary coastal cliffs, debris avalanches on the flanks of volcanic edifices, mass wasting on slopes incised in volcanic deposits, slumping and creeping controlled by high water contents in the sediments and by the occurrence of shallow gas pockets in the subsurface (Correggiari *et al*., 2001; Lee *et al*., 2002; Aiello *et al*., 2004b; Cattaneo *et al*., 2004; Sultan *et al*., 2004; Trincardi *et al*., 2004). In particular, shallow gas in the subsurface has been observed off the Volturno river mouth based on the interpretation of Subbottom Chirp profiles; in this area, the shallow gas controls the occurrence of creeping, involving the first seismic sequences under the sea bottom, made evident by disrupted and chaotic seismic reflectors (Aiello *et al*., 2004b). On the contrary, the interpretation of seismic profiles has not shown shallow gas in the subsurface surrounding Ischia Island, where submarine instabilities appear to be controlled mainly by volcano tectonics.

The Ischia Island case history is presented here in order to show the significant submarine instabilities in a volcanic area. The Ischia offshore is characterized by alkali-potassic volcanic rocks in a continental lithosphere (trachytes, latites, alkali-basalts) and pertains to a volcanic complex emplaced during the last 55 ky.

The main working methodologies and steps include the acquisition and processing of Multibeam bathymetry according IHO standards (IHO, 1998), the generation of a marine DEM, its morpho-structural geological interpretation and integrated interpretation of bathymetry and reflection seismics.

Ischia Island lies on a volcanic ridge, mainly W-E trending. In the Ischia volcanic complex two structural trends exist: a first E-W one and a second ENE-WSW one, occurring in the western offshore part of the island, as highlighted by the distribution of magnetic anomaly fields. At a regional scale, the comparison between the distribution of the magnetic sources and the morpho-structures indicates a low correlation for the E-W anomalies and a high correlation for the ENE-

WSW ones. At a local scale, a systematic correlation between the small submerged volcanic edifices, the linear intrusions (dykes) and the magnetic anomalies exists (Passaro, 2005). This evidence allows us to clarify the geological regional setting of Ischia Island.

The geological interpretation of the marine DEM (Figs. 4 and 6), coupled with Side Scan Sonar imagery and high-resolution, seismic-reflection profiles (Figs. 1, 3 and 7) allowed us to identify important, often multi-phase, submarine instability processes, both catastrophic (debris avalanches) and continuous (accelerated erosion along channels, debris channels and creeping).

Debris avalanches, occurring on the northern, western and southern submerged flanks of the Ischia Island (Figs. 4 and 6) are mainly controlled by the volcano-tectonic uplift of the Mount Epomeo block, involved in calderic resurgence during the last 30 ky (Orsi *et al*., 1991; Acocella and Funiciello, 1999). The most important debris avalanche of Ischia Island is the IDA, having a southern dispersal axis, transporting blocks up to 40-50 km away from the island (Fig. 6). The origin of this event has to be attributed to a land-sea catastrophic collapse, involving the southern flank of the island. This evidence is confirmed by the large scar of in southern Ischia, well evident on the DEM (Figs 4 and 6). The volumetric evaluation of the IDA, based on the DEM analysis (and reported in Fig. 6), furnished values in the order of 1.5 km^3, coherent with the values estimated on the basis of seismic profiles and piston cores (Chiocci and de Alteriis, 2006).

Differently from the IDA, the hummocky facies, occurring on the western flank of the island (Budillon *et al*., 2003) and on the northern flank off the Casamicciola harbour, do not appear related to evident slide scars. The complex topography of the sea bottom on Multibeam bathymetry and Side Scan Sonar imagery highlighs the occurrence of heterometric blocks, that reach extensions of several hundreds of meters, having fallen along the slopes and been inglobated in a sandy-silty matrix. The matrix probably derives both from the volcanoclastics, originally deposited, on the slopes, and from the failure of sediments, previously accumulated in the inner shelf. The debris avalanche deposits are only partly covered by recent marine sediments, put in evidence by the interpretation of Side Scan Sonar photomosaics. Seismic reflection profiles suggest that the deposit occurring off Casamicciola (northern Ischia) may be the result of two distinct, superimposed, catastrophic events (Fig. 7).

REFERENCES

Acocella V. and Funiciello R.; 1999: *The interaction between regional and local tectonics during resurgent doming: the case of the island of Ischia, Italy.* Journal of Volcanology and Geothermal Research, **88**, 109-123.

Aiello G., Budillon F., de Alteriis G., Di Razza O., De Lauro M., Marsella E., Pelosi N., Pepe F., Sacchi M. and Tonielli R.; 1997a: *Seismic exploration of the perityrrhenian basins in the Latium-Campania offshore.* In: Abs. International Congress "ILP Task Force: Origin of Sedimentary Basins", Torre Normanna (Palermo, Italy), June 1997, pp. 5-6.

Aiello G., Budillon F., de Alteriis G., Ferranti L., Marsella E., Pappone G. and Sacchi M.; 1997b: *Late Neogene tectonics and basin evolution of the Southern Italy Tyrrhenian margin.* In: Abs. International Congress "ILP Task Force: Origin of Sedimentary Basins, Torre Normanna (Palermo, Italy), June 1997.

Aiello G., Budillon F., de Alteriis G., Di Razza O., De Lauro M., Marsella E., Pelosi N., Pepe F., Sacchi M. and Tonielli R.; 2001: *Marine geology and morphobathymetry in the Bay of Naples.* In: Faranda F.M., Guglielmo L. and Spezie G. (eds), Structures and processes of the Mediterranean ecosystems, Springer-Verlag, pp. 1-8.

Aiello G., Angelino A., Marsella E., Ruggieri S. and Siniscalchi A.; 2004a: *Carta magnetica di alta risoluzione nel*

Golfo di Napoli (Tirreno meridionale). Boll. Soc. Geol. It., **123**, 333-342.

Aiello G., Iorio M., Marsella E., D'Argenio B. and Fiorentino L.; 2004b: *Submarine instability processes in the Cuma canyon (Campania margin, Southern Tyrrhenian sea, Italy): constraints from high resolution seismic profiling and core petrophysical correlations.* EGS 2004 General Assembly, Abstract.

Aiello G., Angelino A., D'Argenio B., Marsella E., Pelosi N., Ruggieri S. and Siniscalchi A.; 2005: *Buried volcanic structures in the Gulf of Naples (Southern Tyrrhenian sea, Italy) resulting from high resolution magnetic survey and seismic profiling.* Annals of Geophysics, **48**, 1-15.

Bernabini M., Latmiral G., Mirabile L. and Segre A.G.; 1973: *Prospezioni sismiche per riflessione nei Golfi di Napoli e Pozzuoli ed alcuni risultati geologici.* Boll. Soc. Geol. Ital., **90**, 163-172.

Bruno P.P., de Alteriis G. and Florio G.; 2002: *The western undersea section of the Ischia volcanic complex (Italy, Tyrrhenian sea) inferred from marine geophysical data.* Geophysical Research Letters, **29**, 1029-1034.

Budillon F., Violante C. and De Lauro M.; 2003: *I fondali delle isole flegree: geologia e morfologia.* Memorie Accademia Scienze Fisiche e Matematiche in Napoli, **5**, 45-66.

Carracedo J.C.; 1999: *Growth, structure, instability and collapse of Canarian volcanoes and comparison with Hawaiian volcanoes.* Journal of Volcanology Geothermal Research, **94,** 1-19.

Cattaneo A., Correggiari A., Marsset T., Thomas Y., Marsset B. and Trincardi F.; 2004: *Seafloor undulation pattern on the Adriatic shelf and comparison to deep-water sediment waves.* Marine Geology, **213**, 121-148.

Chiocci F.L. and de Alteriis G.; 2006: *The Ischia debris avalanche: first clear submarine evidence in the Mediterranean of a volcanic island prehistorical collapse.* Terra Nova, **18**, 202-209.

Chiocci F.L., Tommasi P., Aiello G., Cristofalo G., De Lauro M., Tonielli R., Baraza J., Ercilla G., Estrada F., Farran M., Gamberi F., Marani M., Milia A., Montella R., Romagnoli C., Senatore M.R., Tommasi P. and Tonielli R.; 1998a: *Submarine debris avalanche off the southern flank of the Ischia volcanic island, Gulf of Naples.* In: Proc. Int. Cong. "Hard soils and soft rocks" , Napoli, Italy, October 1998, pp, 21-23.

Chiocci F.L., Martorelli E., Sposato A., Aiello G., Baraza J., Budillon F., de Alteriis G., Ercilla G., Estrada F., Farran M., Gamberi F., Marani M., Milia A., Montella R., Romagnoli C., Senatore M.R., Tommasi P. and Tonielli R.; 1998b: *Prime immagini TOBI del Tirreno centro-meridionale.* Geologica Romana, **34**, 207-222.

Correggiari A., Trincardi F., Langone L. and Roveri M.; 2001: *Styles of failure in Late Holocene highstand prodelta wedges on the Adriatic shelf.* Journal of Sedimentary Research, **71**, 218-236.

D'Argenio B., Aiello G., de Alteriis G., Milia A., Sacchi M., Tonielli R., Budillon F., Chiocci F.L., Conforti A., De Lauro M., D'Isanto C., Esposito E., Ferraro L., Insinga D., Iorio M., Marsella E., Molisso F., Morra V., Passaro S., Pelosi N., Porfido S., Raspini A., Ruggieri S., Terranova C., Vilardo G. and Violante C.; 2004: *Digital elevation model of the Naples Bay and adjacent areas, Eastern Tyrrhenian sea.* Atlante di Cartografia Geologica scala 1:50.000 (progetto CARG), Servizio Geologico d'Italia (APAT), 32nd International Congress "Firenze 2004", Editore De Agostini, Italy.

de Alteriis G., Tonielli R., Passaro S. and De Lauro M.; 2004: *Batimetria dei fondali marini della Campania. Isole Flegree (Ischia e Procida).* Scala 1:30.000. Liguori Editori, Napoli.

IHO; 1998: *Standards for Hydrographic Surveys.* Special Publ. N° 44, 4th Edition International Hydrographic Bureau, Monaco.

Kokelaar P. and Romagnoli C.; 1995: *Sector collapse, sedimentation and clast population evolution at an active island-arc volcano: Stromboli, Italy.* Bulletin of Volcanology, **57**, 240-262.

Latmiral G., Segre A.G., Bernabini M. and Mirabile L.; 1971: *Prospezioni sismiche per riflessione nei Golfi di Napoli e Pozzuoli.* Boll. Soc. Geol. Ital., **90**, 163-172.

Lee H.J., Syvitsky J.P.M., Parker G., Orange D., Locat J., Hutton J.H.W. and Imran J.; 2002: *Distinguishing sediment waves from slope failure deposits: field examples, including the "Humboldt Slide" and modelling results.* Marine Geology, **192**, 79-104.

Maramai A., Graziani L. and Tinti S.; 2005: *Tsunamis in the Aeolian islands (southern Italy): a review.* Marine Geology, **215**, 11-21.

Marani M. and Gamberi F.; 2004: *Distribution and nature of submarine volcanic landforms in the Tyrrhenian sea: the arc vs. the back-arc.* Mem. Descr. della Carta Geologica d'Italia, **64**, 97-108.

Marsella E., Budillon F., de Alteriis G., De Lauro M., Ferraro L., Molisso F., Monti L., Pelosi N., Toccaceli R., Tonielli R. and Violante C.; 2001: *Indagini geologiche, geofisiche e sedimentologiche dei fondali della Baia dei Maronti (Isola d'Ischia).* Libreria L'Ateneo Due di Salvatore Pironti. Consiglio Nazionale delle Ricerche, Istituto di Ricerca

"Geomare Sud", Napoli, 77 pp.

Mele R. and Del Prete S.; 1998: *Fenomeni di instabilità dei versanti in Tufo Verde del Monte Epomeo (Isola d'Ischia, Campania).* Boll. Soc. Geol. Ital., **117** (1), 93-112.

Milia A., Molisso F., Raspini A., Sacchi M. and Torrente M.M.; 2008: *Syneruptive features and sedimentary processes associated with pyroclastic currents entering the sea: the AD 79 eruption of Vesuvius, Bay of Naples, Italy*. Journal of the Geological Society, **165**, 839-848.

Orsi G., Gallo G. and Zanchi A.; 1991: *Simple shearing block-resurgence in caldera depressions. A model from Pantelleria and Ischia.* Journal Volcanol. Geothermal Research, **47**, 1-11.

Passaro S.; 2005: *Integrazione di dati magnetici e morfobatimetrici in aree vulcaniche e non vulcaniche.* Tesi di Dottorato di Ricerca in Scienze ed Ingegneria del Mare, XVII ciclo, Università degli Studi di Napoli "Federico II".

Pescatore T., Diplomatico G., Senatore M.R., Tramutoli M. and Mirabile L.; 1984: *Contributi allo studio del Golfo di Pozzuoli: aspetti stratigrafici e strutturali.* Mem. Soc. Geol. Ital., **27**, 133-149.

Ruggieri S., Aiello G. and Marsella E.; 2007: *Integrated marine geophysical data interpretation of the Naples Bay continental slope (southern Tyrrhenian sea, Italy).* Boll. Geof. Teor. Appl., **48**, 1-24.

Saxov S. and Niewenhuis J.K.; 1982: *Marine slides and other mass movements.* Plenum Press., New York, 280 pp.

Secomandi M., Paoletti V., Aiello G., Fedi M., Marsella E., Ruggieri S., D'Argenio B. and Rapolla A.; 2003: *Analysis of the magnetic anomaly field of the volcanic district of the Bay of Naples, Italy.* Marine Geophysical Researches, **24**, 207-221.

Sultan N., Cochonat P., Canals M., Cattaneo A., Dennielou B., Haflidason H., Laberg J.S., Long D., Mienert J., Trincardi F., Urgeles R., Vorren T. and Wilson C.; 2004: *Triggering Mechanisms of Slope Instability Processes and Sediment Failures on Continental Margins: A Geotechnical Approach*. Marine Geology, **213**, 291-321.

Trincardi F., Cattaneo A., Correggiari A. and Ridente D.; 2004: *Evidence of soft-sediment deformation, fluid-escape, sediment failure and regional weak layers within the Late Quaternary mud deposits of the Adriatic sea.* Marine Geology, **213**, 91-119.

Vezzoli L.; 1988: *Island of Ischia.* Quaderni De La Ricerca Scientifica, Progetto Finalizzato "Geodinamica", Monografie Finali, **10**, 134 pp.

Ward S.N., 2000: *Lanslide tsunami.* Journal of Geophysical Research, **106**, 11201-11215.

Watts A.B. and Masson D.G.; 1995: *A giant-landslide on the north flank of Tenerife, Canary Islands*. Journal of Geophysical Research, **100**, 24487-24498.

Corresponding author: Gemma Aiello
Istituto per l'Ambiente Marino Costiero
Consiglio Nazionale delle Ricerche
Calata Porta di Massa, Porto di Napoli, 80133 Napoli (Italy)
phone: +39 081 5423820; fax: +39 081 5423888; e-mail: gemma.aiello@iamc.cnr.it