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Gravity instabilities in the Dohrn Canyon (Bay of Naples, Southern Tyrrhenian Sea): potential wave and run-up (tsunami) reconstruction from a fossil submarine landslide

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Abstract: We discuss a mathematical model for wave and run-up generated submarine landslides in the canyons of the Bay of Naples (Magnaghi-Dohrn canyon system). The morpho-bathymetry and submarine gravity instabilities of such incisions have been investigated through the interpretation of a high resolution DEM. The canyons are located in a sector of the bay where there is a variable interaction of volcanic activity (Phlegrean Fields and Ischia and Procida Islands) with sedimentary processes due to the Sarno-Sebeto rivers. At present the Naples canyon-system is inactive, as is shown by the Holocene sedimentary drapes deposited during the present sea-level highstand, but gravity instabilities occurred in the recent past at the canyons' heads. In particular the Dohrn Canyon is characterized by a double regressive head, while the Magnaghi Canyon shows a trilobate head, formed by the junction of three main tributary channels and coincident with the retreat of the shelf break around the 140 m isobath. The results of a simulation of failures in the above source areas show that the amplitude of wave run-up, expressed in terms of the sea floor depth percentage, may range up to 2.5 % of the water depth at the sea bottom.

Key words: Bay of Naples, tsunamigenic potential, run-up landslide, numerical modelling.

Introduction

The aim of this paper is to study potential wave and run-up events caused by submarine landslides located in the canyons of the Bay of Naples.

Tsunami waves, often caused by gravitative failures, may be generated by earthquakes and less frequently by volcanic eruptions. In the Bay of Naples all the above trigger factors are present. As a consequence, the continental slope off the bay represents an appropriate natural laboratory to study geological events potentially leading to submarine slides with their tsunamigenic potential.

The geological setting of the bay has been studied in detail in the framework of research programmes for submarine geological cartography (Aiello et al. 2001; Bruno et al. 2003; D'Argenio et al. 2004). In this gulf the continental slope and the outer shelf are deeply incised by two submarine canyons of kilometric extent, namely the Dohrn and Magnaghi Canyons, representing the drainage system of this active volcanic area during the Late Quaternary. Detailed mapping of the outer shelf and slope morphology contributed to the understanding of erosional and depositional processes related to continental slope settings and allowed their geological interpretation to be proposed (Aiello et al. 2001; D'Argenio et al. 2004).

Several studies about tsunamis have recently been carried out in the Bay of Naples. Landslide-generated tsunamis in the offshore of Ischia Island have been featured by Zaniboni et al. (2007) in the framework of a project on the volcanic hazard and risk assessment of the island of Ischia, by the National Institute for Geophysics and Volcanology and the Italian Department for Civil Protection. The above authors focussed on the study of tsunamis generated by landslides from Ischia's slopes. The catastrophic collapse that formed the large scar in the southern flank of Ischia (the Ischia Debris Avalanche of Chiocci & de Alteriis 2006) may be considered as the upper limit for tsunamigenic failures in the slopes of Ischia, even though the duplication of such an event does not appear probable at the moment. In this study we selected an area of the Dohrn Canyon showing evidence of paleo-landslides and we applied a model to evaluate the wave run-up generated by an estimated flow, using a recent theoretical model (Lynett & Liu 2002; Di Fiore et al. 2008).

General setting of the area

The eastern margin of the Tyrrhenian Sea is characterized by a number of basins formed during the latest Neogene-Quaternary across the structural boundary between the Apennine fold and thrust belt and the Tyrrhenian back-arc extensional area (Fig. 1). These basins, including the Bay of Naples and the Bay of Salerno (Fig. 1) evolved as a consequence of the large-scale orogen-parallel extension and related transtensional tectonics that accompanied the anti-clockwise rotation of the Apennine belt and lithospheric stretching in the central Tyrrhenian Basin (Sacchi et al. 1994; Ferranti et al. 1996; D'Argenio et al. 2004).

As a consequence, the Campania segment of the peri-Tyrrhenian structural belt displays the characteristics of a passive continental margin, where Quaternary orogen-parallel extension caused the formation of half-graben systems (Gulf of Gaeta, Bay of Naples, Bay of Salerno and intervening

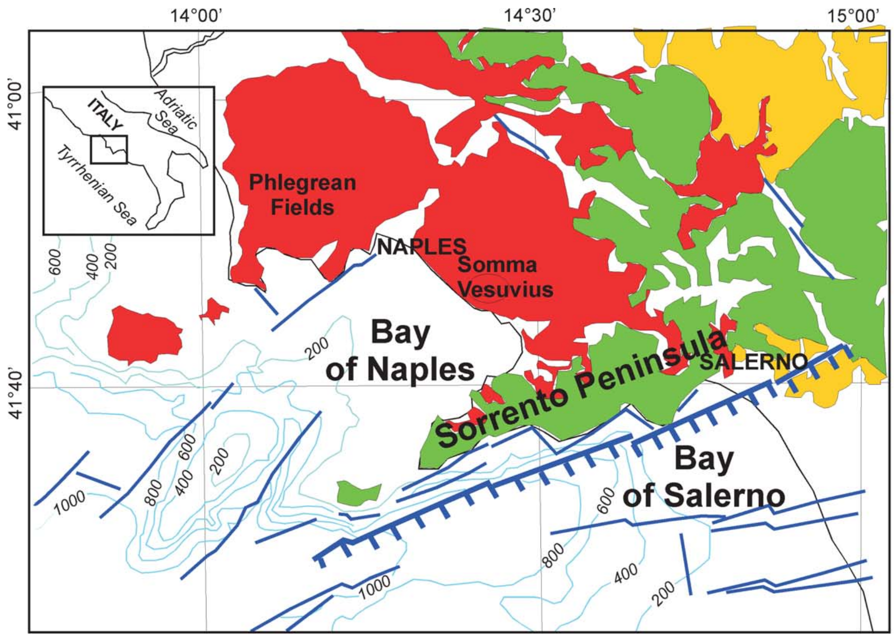


Fig. 1. Tectonic sketch map of western Campania Apennines (modified after D'Argenio et al. 2004). **1** — Shallow-water carbonate and deep basinal units (Mesozoic); **2** — Piggy-back siliciclastic units (Tertiary); **3** — Pyroclastic deposits and lavas (Quaternary); **4** — Continental and marine deposits (Quaternary); **5** — Normal fault; **6** — Detachment faults (barbs indicate downthrown side).

structural highs (e.g. Sorrento Peninsula, Mt Massico), trending perpendicularly to the main axis of the Apennine thrust belt (Mariani & Prato 1988; Sacchi et al. 1994; Milia & Torrente 1999; Aiello et al. 2000).

Off the Campania coasts the peri-Tyrrhenian basins often form the seaward extension of the coastal plains, whose formation was controlled by extensional tectonics during the Plio-Quaternary (Mariani & Prato 1988; Brancaccio et al. 1991). Their tectono-sedimentary evolution is connected with the Neogene evolution of the Apenninic chain (Royden et al. 1987; Patacca & Scandone 1989). In particular, the deformational history of the peri-Tyrrhenian basins is characterized by alternating compressional and extensional tectonic phases during Plio-Quaternary times (Bartole 1984; Argnani & Trincardi 1990; Agate et al. 1993; Sacchi et al. 1994).

The Neogene evolution of the south-eastern peri-Tyrrhenian basins was controlled by large-scale extensional tectonics, responsible for the thinning of the western sectors of the southern Apenninic chain and dating back to the Late Miocene. Thinning due to extension was not homogeneously distributed along the overthrust belt, but rather localized in discrete hyper-extension domains (Ferranti et al. 1996), where the thrust pile was locally reduced to about one half of its original thickness.

Modes of extension along the peri-Tyrrhenian basins are often characterized by listric normal faults and associated antithetic faults, which generated SW-NE trending half-graben systems along the Tyrrhenian Basin-southern Apennines system. Most of them extend landward to the E-NE. This causes a typical coastal landscape made of alternating transversal mountain ridges and intervening coastal plains.

In the Campania Region Quaternary basin fillings overlie submerged "internal" (western) tectonic structures of the Apenninic chain, resulting from the seawards extension of the tectonic units cropping out in the coastal belt of the southern Apennines (D'Argenio et al. 1973: fig. 1). These units form the acoustic basement of the coastal basins and are composed either of terrigenous-shaly basinal sequences or of thick platform and basinal Mesozoic-Cenozoic carbonates (Fig. 1). Extensional tectonics accompanying the uplift of the southern Apennines begin in the Early Pliocene and continue up to the Middle–Late Pleistocene, playing a major role in controlling the present-day physiography of the Campania Region. Indeed, Quaternary marine and continental sediments of the Campania coastal plains reach a thickness of up to 3000 m in the Volturno Plain and of 1500 m in the Sele Plain (Ortolani & Torre 1981).

NW-SE, NE-SW and E trending post-orogenic structures (mainly extensional faults) have been previously recognized under the sea near the Campania Region (Bartole et al. 1983). While the Apenninic (NW-SE) trending structures characterize the continental slope areas between the Pontine Islands and the Cilento Promontory, the Anti-Apenninic (NE-SW) ones often occur under the sea near the Bay of Salerno and the structural high of the Sorrento Peninsula.

In turn, the Quaternary extension along the Campania segment of the Southern Apennine–Eastern Tyrrhenian hinge zone caused the onset of intense volcanism. It was responsible for the creation of both single large volcanoes (Roccamonfina and Somma-Vesuvius — Principe et al. 1987: fig. 1) and volcanic complexes (Ischia, Procida and Phlegrean Fields — Rosi & Sbrana 1987: fig. 1). In the Phlegrean area a thermometamorphic basement about 1500 m deep has been inferred (Rosi & Sbrana 1987), whereas in the Volturno Plain the "Villa-Literno" 1 and "Parete" 1 wells drilled into thick basaltic and andesitic lavas (Ortolani & Aprile 1978).

Morpho-bathymetry and sea bottom instability of the Naples bay canyons

An extensive, high resolution bathymetric survey of the continental shelf/slope system of Campania, Southern Italy has recently been carried out. The relative bathymetric data were acquired during the years 1997 and 2002, using Multibeam systems with an average vertical resolution of ≤0.25 % water depth and a position accuracy of ≤10 m. The survey data were successively merged with a Digital Terrain Model (DTM) created from topographic maps of the Bay of Naples onshore coastal area and islands, to produce a Digital Elevation Model (DEM) based on a homogeneous grid with cell-spacing of 20 m (D'Argenio et al. 2004: fig. 2).

The shaded relief map has provided new, detailed information on the morphology of the Campania coasts. This segment of the Italian continental margin displays evidence of the latest Neogene-Quaternary interplay between tectonics and volcanism, as well as of the depositional processes largely developing as a consequence of frequent and large volcano-sedimentary supply. The major morphological features revealed by the 3D digital maps are: i) the system of marine canyons (Dohrn and Magnaghi) that cut the continental slope at a depth between 250 m and 1100 m; ii) the continental slope system of the Ischia volcanic structure (Chiocci & de Alteriis 2006; Aiello et al. 2009a); iii) the onshore and offshore volcanoes of the Campi Flegrei; iv) the rugged seafloor area of the outer shelf of the city of Naples (Banco della Montagna — Sacchi et al. 2000; D'Argenio et al. 2004); v) the debris flow/avalanche deposits on the inner continental shelf off Mt Vesuvius (Milia et al. 1998, 2008), laterally grading into the "Torre del Greco" volcanic structure (Aiello et al. 2010).

The DEM of the Bay of Naples, representing the base of the geological and morpho-bathymetric interpretation, has a 20×20 m cell and has been based on the integration of different grids. This cell has resulted adequate in detecting the most prominent topographic and bathymetric features of the coastal zone larger than a few tens of meters.

Despite the great number of geological and volcanological studies on the Gulf of Naples, among which Latmiral et al. (1971), Finetti & Morelli (1973), Cinque et al. (1997), Pescatore et al. (1984), Fusi et al. (1991), Milia (1996), Milia et al. (1998, 2008), Aiello et al. (2001, 2004, 2005, 2009a,b, 2010), Bruno et al. (2003), the morpho-bathymetry and the submarine gravity instabilities of the Dohrn and Magnaghi Canyons have not been investigated in detail, nor have the areas of incipient submarine sliding in the surrounding of the canyons even been accurately defined.

The Dohrn Canyon formation was triggered off by the tectonic uplift of both the outer shelf and the fluvial valley mouths, during periods of eustatic fall of sea level (Milia 2000). During the late Quaternary the Bay of Naples continental slope was characterized by slumping and canyon formation and therefore it may be considered to represent an erosional slope-system (Ross et al. 1994; Galloway 1998). The geological conditions for the formation of the Dohrn Canyon appear to be incompatible with models based on oversteepening, high sediment supply, sea-level rise and retrogressive slumping. The Dohrn Canyon developed along a central slope showing low gradients and the landward rotation of the platform block resulted in a substantial decrease of the slope. Moreover, the canyon wall cuts the main body of the slumps, whereas the most prominent scars show no correlation with the canyon walls. So the Dohrn Canyon formation was controlled by a sea-level eustatic fall, inducing a seaward migration of the river systems of the Late Pleistocene and the formation of the valleys, coupled with a fault block rotation, responsible for the outer shelf uplift (Milia 2000).

Based on the interpretation of Multibeam bathymetry we have outlined a schematic geomorphological map of the Dohrn Canyon and of the surrounding continental slope, which shows, in particular, the slide scars and the submarine gravity instability areas (Fig. 2).

The main morpho-structures of the canyon system consist of volcanic structural highs, relic morphologies of the Middle-Late Pleistocene continental shelf, turbiditic slope fans and Mesozoic carbonate structural highs. Some morphological lineaments, such as the canyon's walls, the shelf break, the slope of the "Ammontatura" paleo-canyon, the slide scars and the canyon's axis have also been represented (Fig. 2).

The Dohrn Canyon's width ranges from a few hundred meters to more than 1 km, its depth from 250 m at the shelf edge to some 1300 m at the merging with the bathyal plain; the dip of its walls attains some 35° in the steepest sectors. This canyon starts with two major curved branches. The western branch merges into the shelf through a 1.5 km wide and 20–40 m deep channel ("Ammontatura" channel), characterized by a flat bottom and asymmetrical levees, located along the −200 m isobath and by a sinuous shape in plan view. The Dohrn eastern branch shows a meandering trend and starts from the shelf break of the Sorrento Peninsula, located along the −120 m isobath. The Dohrn western branch is broader than the eastern one and more deeply incised; the two branches form a typical Y-structure.

The abrupt termination of the "Ammontatura" shallow channel against the Nisida volcanic bank, whose growth was older or contemporaneous with the eruption of the volcanic deposits of the NYT (Neapolitan Yellow Tuff — Scarpati et al. 1993) suggests that the Dohrn canyon system is older than the volcanic deposits of the NYT, which forms the main basis of the city of Naples. This implies that most part of the canyon system activity was probably older than 11–12 ka B.P., age of the NYT deposits in the city of Naples (Di Girolamo et al. 1984; Rosi & Sbrana 1987).

The Magnaghi Canyon shows a triple incised head and is pervasively affected by small-scale slope instabilities. It runs parallel to the southern flanks of the Procida and Ischia Islands and then is buried below the Ischia Debris Avalanche (Chiocci & de Alteriis 2006; Aiello et al. 2009a). Three main tributary channels join basinwards into the main axis. Erosion and transport of volcanoclastics in the western sector of the gulf, near the Ischia and Procida Islands, developed along the Magnaghi Canyon axis and it appears unrelated to the present fluvial drainage system on land.

As already noted, the Bay of Naples canyons start from the shelf break near the Phlegrean Fields volcanic district, located along the −140 m isobath. Their trends are controlled by the main morpho-structures of the bay: the "Banco di Fuori" structural high, bounding southwards the whole canyon system and the Capri Island structural high, bounding eastwards the Dohrn Canyon, near its confluence with the bathyal plain. Both the Magnaghi Canyon and the Dohrn western branch show morphological evidence of retreat of the canyon's head.

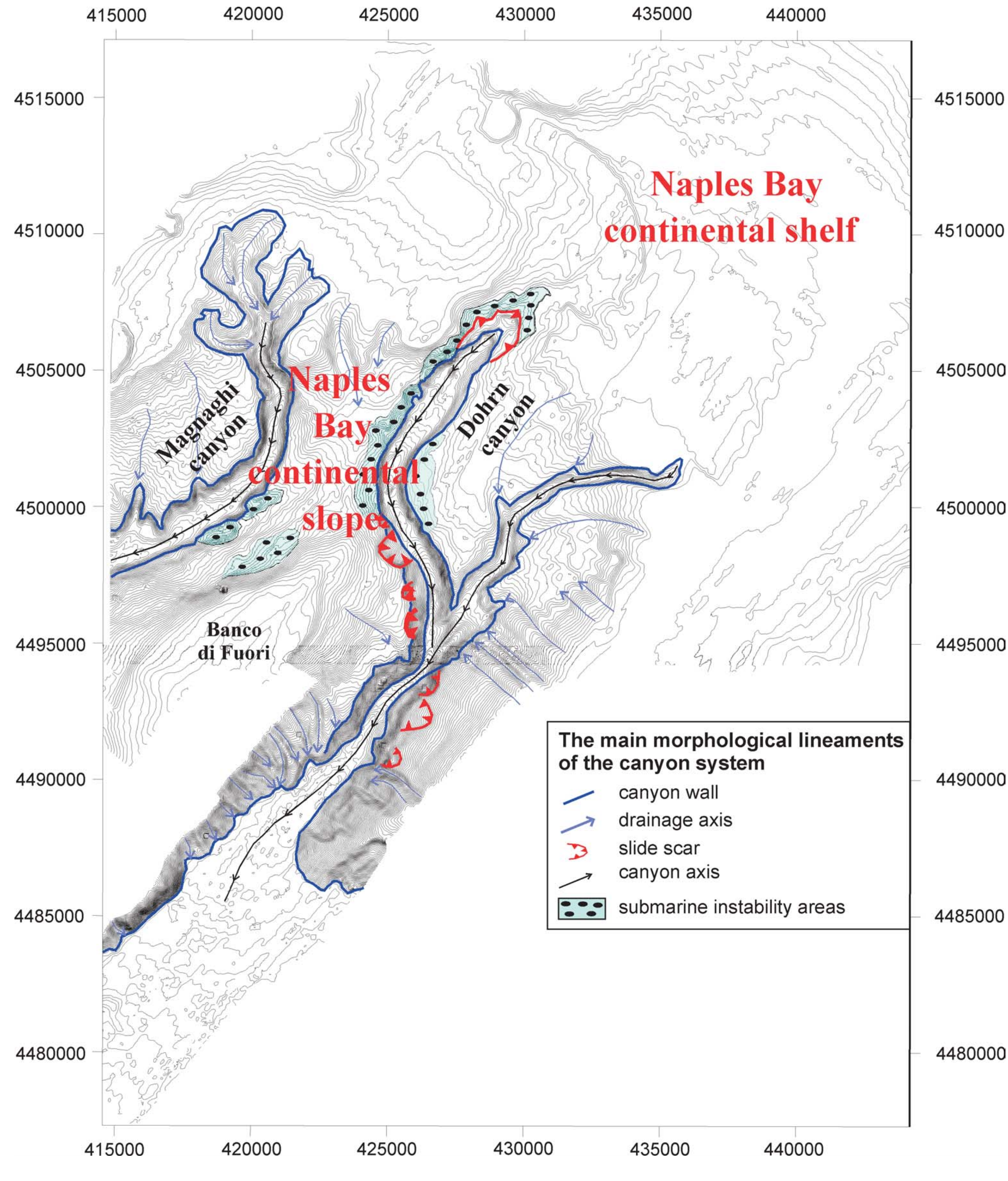


Fig. 2. Morpho-bathymetry of the Bay of Naples canyons and gravity instability map. Note that chief submarine instability areas are located at the Dohrn Canyon's head, on the slope surrounding the western Dohrn branch, on the slope southwards of the Magnaghi Canyon and on the north-eastern slope of the Banco di Fuori structural high. Figures on the side refer to kilometric coordinates.

Based on the interpretation of the Multibeam bathymetry the main features that we interpret as slide scars are located (Fig. 2):

a) on the head of the Dohrn western branch, showing a double retrogressive head, controlled by extensive submarine erosion;

b) on the western slope of the Dohrn western branch (Fig. 3), at its boundary with the eastern flank of the Banco di Fuori morpho-structural high (here a set of coalescent, large slide-scars, not related to the canyon's thalweg, may be observed);

c) on the continental slope, north of the Capri structural high, where large scars are suggested by the trending of the isobaths next to the Dohrn Canyon thalweg.

Here the canyon system is characterized by several terraces and three rectilinear gullies converge into the canyon from the northern slope of the Capri Island. An acoustic basement, probably composed of Mesozoic-Cenozoic carbonate rocks almost reach the sea bottom, under a thin drape of Holocene sediments.

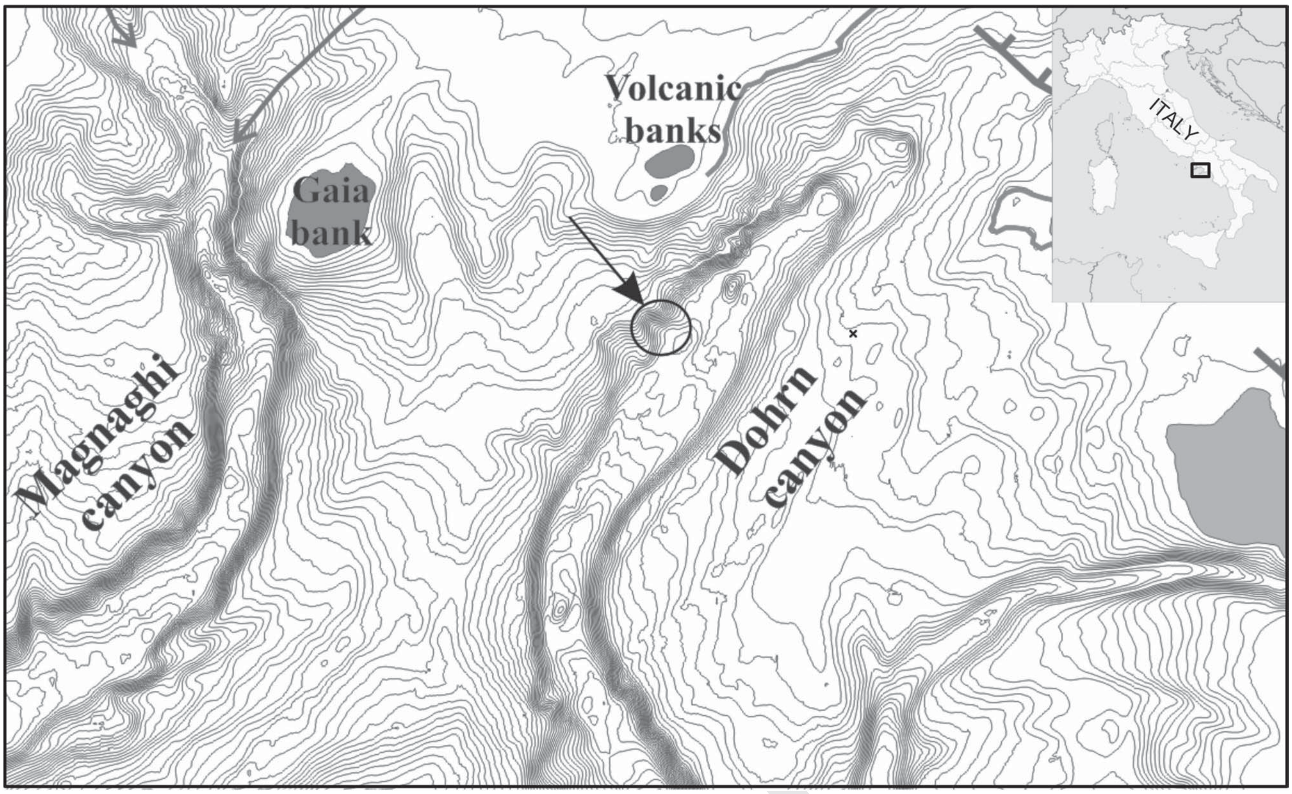


Fig. 3. Detailed bathymetric map of the canyons showing the location of modelled submarine landslide (arrow).

The geomorphological interpretation and the analysis of the canyon morphometric parameters suggest that the submarine instabilities of the canyon system are located (Fig. 2):

a) around the Dohrn western branch, from the canyon's head to the middle of the branch, north of the "Banco di Fuori" morpho-structural high;

b) on the continental slope, southwards of the Magnaghi Canyon, where two large areas of instability, not connected with the canyon's thalweg, may be observed;

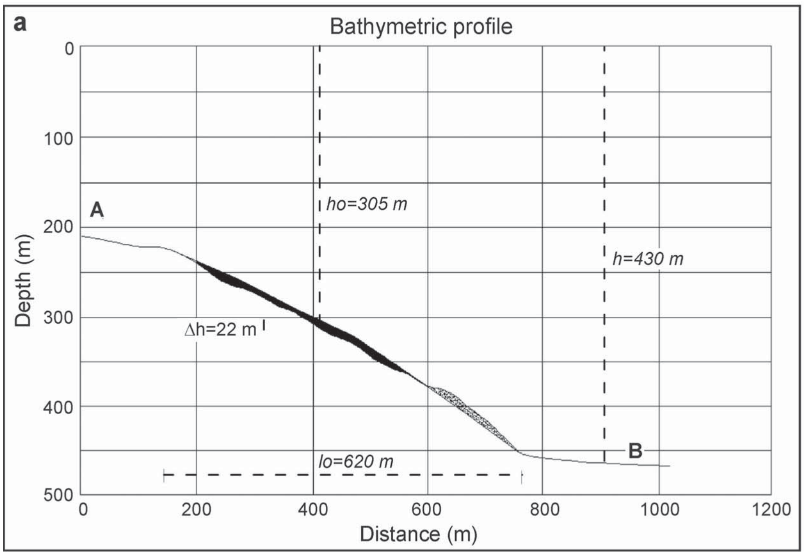
c) on the north-western slope of the "Banco di Fuori" morpho-structural high, where the concave trending of the isobaths suggests the occurrence of an incipient and/or fossil slide scar.

No slumped masses are preserved in the main thalweg, suggesting a probable activity of low-density turbidity currents during the Late Quaternary evolution of the canyon. Large isolated remnants, showing average dimensions of 300×400 m across are present on the canyon floor which, in its upper part, is scoured by a minor meandering channel. These rounded morphologies are interpreted as relic structures, probably due to a selective erosion acting along the canyon's valley. Moreover, terrace rims, located respectively at −340 m and −300 m of water depth, suggest at least two phases in the activity and retreat of the canyon head.

A relative abundance of the V-shaped erosional profiles has been observed in both the branches of the Dohrn Canyon. The flat-bottomed valley depositional morphologies, suggesting recent phases of canyon filling, occur mainly in the wider, southernmost part of the Dohrn western branch and at the confluence of the Dohrn northern and southern branches.

The drainage system of the canyons is composed of a dense network of tributary channels, controlling the overflow of sediments in the surrounding areas of the continental slope. Two main tributary channels originate from the shelf break off the Phlegrean submarine volcanic banks, located along the 140 m isobath and run along the continental slope between the Dohrn and the Magnaghi Canyons, giving rise to channel-lobe systems (Fig. 2). A complex system of tributary channels, located at water depths ranging from −200 m and −500 meters, fed the Dohrn southern branch, starting from the shelf break off the Sorrento Peninsula and it appears partly fault-controlled. This interpretation is suggested by the rectilinear shape in plan view of the southernmost four channels. A system of lobes, genetically linked with some of these channels, has been recognized on a morphological terrace located at water depths of 340 m. Moreover fossil tributary channels hung over the main branches testify stages of rapid re-incision, switching off the feeding from lateral sources and forming suspended valleys.

In conclusion, several submarine slides and scars are evident on the canyon's walls, especially along the western flank of the Dohrn northern branch and on the continental slope as well. The north-western branch of the Dohrn Canyon is affected by instability, with an incipient slump causing a broad depression, 200–300 m across and away from the canyon's edge, and a semi-circular scar on the canyon walls, showing lateral coalescence and defining a large area



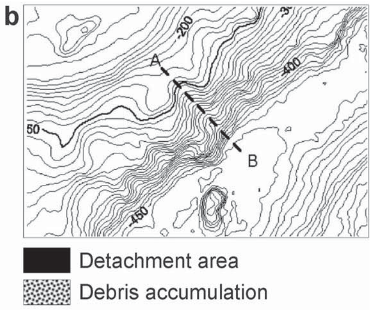


Fig. 4. (**a**) Model scheme referred to the parameters utilized in this paper and evolution of submarine slope surface shape during landslide movement. The detachment area relative to the slide and the debris accumulation area, covering a total distance of 620 m, have also been represented. (**b**) Detailed bathymetric map of the area and slice location (A–B) of the ancient marine landslide.

of instability, located westward of the north-western slope of the "Banco di Fuori" morpho-structural high (Fig. 2).

A bathymetric profile has been constructed in correspondence to the scars involving the Dohrn western branch in order to give quantitative constraints to the numerical modelling. A detachment area, about 415 m across occurs at water depths ranging between −250 m and −370 m. Also debris accumulation develops in water depths ranging from −380 m and −450 m, while the junction with the foot of the thalweg occurs, at water depths of about −430 m (Fig. 4).

Methods of analysis and modelling

In this paragraph we discuss the problems of the possible tsunami generation and characteristics, as we may infer from the above analytical description of the Bay of Naples canyon system. We apply here a mathematical model already proposed by Lynett et al. (2002) in which the generation and propagation of tsunamis is reconstructed from ancient submarine landslides. In such a model we assume that there is a weak frequency dispersion, which means that the ratio of water depth to wavelength is small or <<1. In general, for dispersive properties the depth-integrated equations are valid only for wavelengths greater than two times the water depth, whereas the depth-averaged model is valid for lengths greater than five times the water depth (e.g. Nwogu 1993). In Lynett et al. (2002) the full nonlinear effect is included, namely the ratio of wave amplitude and water depth is order one, and therefore, this model is more general as compared to other models (Liu & Earickson 1983) where the Boussinesq approximation was used.

The motion can be described by Euler's equations:

$$\mu^2 \nabla \cdot \vec{u} + w_z = 0; \qquad (4.1)$$

$$\vec{u}_t + \varepsilon \vec{u} \cdot \nabla \vec{u} + \frac{\varepsilon}{\mu^2} w \vec{u}_z = -\nabla p; \qquad (4.2)$$

$$\varepsilon w_t + \varepsilon^2 \vec{u} \cdot \nabla w + \frac{\varepsilon^2}{\mu^2} w w_z = -\varepsilon p_z - 1; \qquad (4.3)$$

Where (see also nomenclature below):

μ is the frequency-dispersion parameter (h_0/l_0), i.e. when the ratio of water depth to wavelength is small. In general the guideline for dispersive properties is that the depth-integrated equations are valid for wavelengths greater than two water depths;

$\vec{u} = (u, v)$ is the horizontal velocity vector;

$\nabla = \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}\right)$ is the horizontal gradient vector;

p is the depth-dependent pressure;

ε is the nonlinearity parameter (a/h_0), i.e. when $a \ll h_0$, the nonlinearity is not important (the initial wave amplitude is relativity small compared to the wavelength and the water depth).

Fig. 5 shows the parameters used in the algorithm implementation.

In many cases, the seafloor displacement is small with respect to the local water depth. Since the free-surface displacement is directly proportional to the seafloor displacement, namely

$D(\varepsilon\zeta)=D(\delta h)$.

The boundary conditions applied are:

On the free surface $z=\varepsilon\zeta(x, y, t)$, the usual kinematic and dynamic boundary conditions, considering the depth integration interval between z=[−h, εζ], we set:

$$w = \mu^2(\varsigma_t + \varepsilon \vec{u} \cdot \nabla \varsigma) \quad \text{on} \quad z = \varepsilon\varsigma, \qquad (4.4)$$

$p=0$.

Where p is water pressure.

Along the seafloor where $z=-h$, the kinematic boundary condition requires

$$w + \mu^2 \vec{u} \cdot \nabla h + \frac{\mu^2}{\varepsilon} h_t = 0 \quad \text{on} \quad z=-h \qquad (4.5)$$

Integrating from $z=-h$, to $z=\varepsilon\zeta$, the depth-integrated continuity equation, we obtained:

$$\nabla \cdot \left[\int_{-h}^{\varepsilon\varsigma} \vec{u} \cdot dz\right] + \frac{1}{\varepsilon} H_t = 0; \qquad (4.6)$$

Where $H = \varepsilon\varsigma + h$

After integral resolution of the two-dimensional governing equation, we applied the finite difference algorithm to solve the general model equation (Lynett et al. 2002). In their paper Lynett et al. (2002) developed an algorithm for the general two-horizontal-dimension problem analogously to Wei & Kirby (1995) and to Wei et al. (1995). The difference between the two models is that in Wei et al. (1995) terms due to a time-dependent water depth and some nonlinear-dispersive terms have been added, while in this study we use an impulsive bottom movement in a constant water depth.

The previous governing equation was approximated onto a two-dimensional horizontal plane. Some assumptions are listed below to resolve the approximate two-dimensional governing equation (Lynett et al. 2002):

1. only one-horizontal-dimension is examined;
2. nonlinearity is assumed so ε is small;
3. frequency dispersion is weak so μ^2 is small;
4. all spatial derivatives are differenced to fourth-order in numerical analysis.

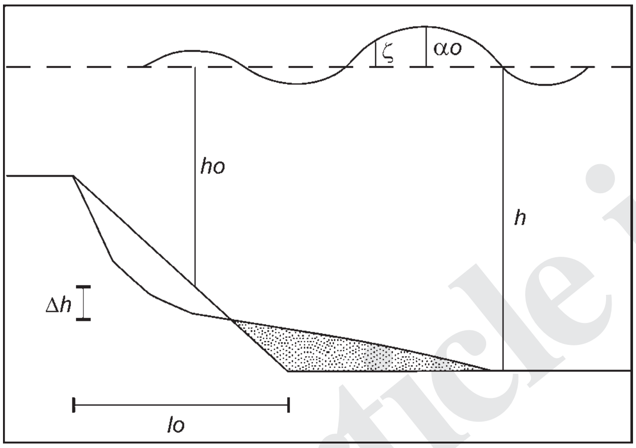


Fig. 5. Schematic representation of the geometrical parameters used in wave-run up computation. $\mathbf{h_0}$ — characteristic water depth and vertical length scale; $\mathbf{l_0}$ — characteristic length of the submarine slide region and horizontal length scale; $\mathbf{l_0/(g\ h_0)^{1/2}}$ — time scale; $\mathbf{a_0}$ — characteristic wave amplitude and scale of the wave motion.

Finally, the numerical analysis was applied resolving two-dimensional equation so obtaining the relative run-up.

The bottom movement, consisting of a length l_0=620 m (Fig. 5), pushed the water masses vertically upwards. The change in depth for this experiment is about 0.1 ($\Delta h/h_0$), and therefore nonlinear effects should play a small role near the source region, and 20 times the water depth from the edge of the source region. The landslide is located near the Dohrn Canyon head (Fig. 3) and we assume that the landslide may move rapidly.

To analyse this model we have introduced the characteristic water depth h_0, as the vertical length-scale, the characteristic length of the submarine slide region l_0, as the horizontal length-scale, $l_0/(gh_0)^{1/2}$ as the time-scale, and the characteristic wave amplitude a_0 as the scale of wave motion.

Fig. 6 shows the results of the analysis in terms of amplitude vs. time-series at x/h=0. It is possible to notice that the amplitude wave run-up expressed in terms of depth of seafloor percentage, ranges from 0 to 2.5 %. In absolute terms the wave height amplitude corresponds to 5–6 m.

Discussion and conclusion

Submarine landslides play a fundamental role in originating tsunamis, especially near the coast. Our experiment in the Bay of Naples could be used as example in the areas where there is a high probability for these events to occur (Tinti et al. 2003). The idea is to produce an offshore hazard map delimiting both the potential tsunamis areas (located near the instability zone) and the influence zone of the water wave.

The morphometric analysis of the Dohrn Canyon slope provides insight into tsunami hazard, including the locations of mass movements, the size of mass failures, their relative importance for the structure of a given margin, and the potential for landslide-generated tsunami hazard. We do not have enough evidence to consider all these detachment areas located on the Dohrn Canyon edges as generated by landslides with impulsive character, or if there has been an evolution over time controlled by small detachments, not significant if compared to the potential needed to generate anomalous waves. The nature of the materials that character-

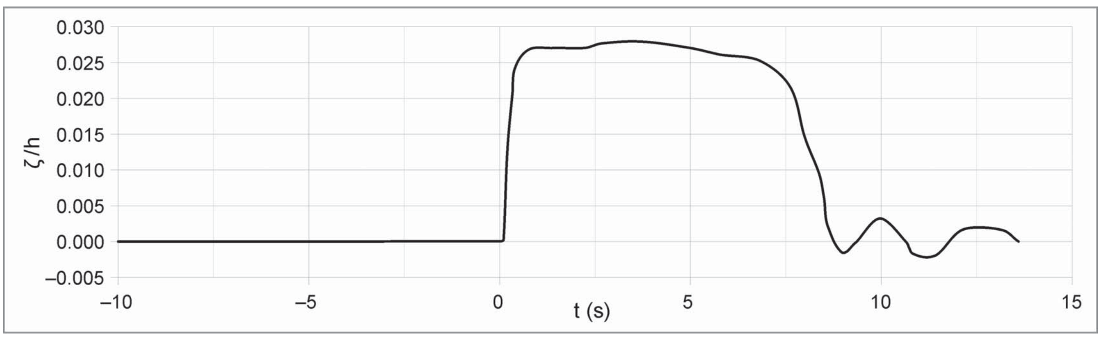


Fig. 6. Water wave amplitude vs. time-series located in x/h=0 (horizontal coordinates of the midpoint of the seafloor movement). The rapid decadence of the amplitude after 8 s is evident. Note that the amplitude wave run-up expressed in terms of depth of sea floor percentage ranges from 0 to 2.5 %. In absolute terms the wave height amplitude corresponds to 5–6 m.

ize the area is both volcanic (Campanian Ignimbrite) and sedimentary. Therefore we deal with a non-coherent material that, together with the presence of the active volcanoes (Somma-Vesuvius and Phlegrean Fields), need to be analysed with regard to its ability to trigger landslides.

The tsunami predictions according to Booth et al. (1993) have to be related not so much to the slope gradient alone, but instead to sedimentation, erosion, local geology, fluid overpressure and regional seismicity as complex causative triggers. This whole complex is critical in determining landslide location and ultimately size of the derived tsunami, considering that the continental shelf of the Gulf of Naples is dipping in average 6° and has a width of 20–22 km, extending for 560 km^2, while the continental slope dips up to 45°. Our study suggests that the tsunami hazard is higher on the canyon margin: in fact, Fig. 2 shows several slide scars and large submarine instability areas near to canyon borders.

In conclusion we observe that the morphological evolution of the analysed area depends on complex systems where volcanism, sedimentation and tectonics affect the coast and the marine bottoms, that show the potential to develop slope instability, even though high urbanization has impacted significantly on the sedimentation, reducing the accumulation rate of materials potentially prone to slide.

Due to the lack of more detailed morpho-bathymetric studies as well as of innovative methods for hazard evaluation in coastal areas, the balance of these opposite trends is difficult to assess. However we stress the importance of the analysis of submarine gravity instability, mainly for its implications in terms of geo-hazard related to landslides as the cause of tsunamis. Much remains to be done to reach an accurate understanding of these problems.

Nomenclature

a	wave amplitude
D	displacement function
g	gravity
h_0	characteristic water depth or baseline water depth, function of space
h	water depth profile, function of space and time
H	total water depth ($\varepsilon\zeta+h$)
l_0	characteristic horizontal length-scale of the submarine slide
p	depth-dependent pressure
t	time
u, v, w	depth-dependent components of velocity in (x, y, z)
$\vec{u}$	horizontal velocity vector, (u, v)
x, y, z	Cartesian coordinates
Δh	characteristic, or maximum, charge in water depth due to seafloor motion
ε	nonlinearity parameter (a/ho)
μ	frequency-dispersion parameter (ho/lo)
ζ	free surface displacement

References

Agate M., Catalano R., Infuso S., Lucido M., Mirabile L. & Sulli A. 1993: Structural evolution of the Northern Sicily continental margin during the Plio-Pleistocene. In: Geological Development of the Sicilian-Tunisian platform. *Unesco Reports in Marine Sciences*, Urbino, Italy 58, 25–30.

Aiello G., Marsella E. & Sacchi M. 2000: Quaternary structural evolution of Terracina and Gaeta basins (Eastern Tyrrhenian margin, Italy). *Rend. Fis. Acc. Lincei* 9, 11, 41–58.

Aiello G., Budillon F., Cristofalo G., D'Argenio B., de Alteriis G., De Lauro M., Ferraro L., Marsella E., Pelosi N., Sacchi M. & Tonielli R. 2001: Marine geology and morpho-bathymetry in the Bay of Naples. In: Faranda F.M., Guglielmo L. & Spezie G. (Eds.): Structures and processes of the Mediterranean Ecosystems. *Springer-Verlag*, 1–8.

Aiello G., Angelino A., Marsella E., Ruggieri S. & Siniscalchi A. 2004: Carta magnetica di alta risoluzione del Golfo di Napoli. *Boll. Soc. Geol. Ital.* 123, 333–342.

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

Aiello G., Marsella E. & Passaro S. 2009a: Submarine instability processes on the continental slopes off the Campania region (Southern Tyrrhenian sea, Italy): the case history of Ischia island (Naples Bay). *Boll. Geof. Teor. Appl.* 50, 2, 193–207.

Aiello G., Marsella E., Di Fiore V. & D'Isanto C. 2009b: Stratigraphic and structural styles of half-graben offshore basins in Southern Italy: multichannel seismic and Multibeam morpho-bathymetric evidences on the Salerno Valley (Southern Campania continental margin, Italy). *Quaderni di Geofisica* 77, 1–34.

Aiello G., Marsella E. & Ruggieri S. 2010: Three-dimensional magneto-seismic reconstruction of the "Torre del Greco" submerged volcanic structure (Naples Bay, Southern Tyrrhenian sea, Italy): Implications for Vesuvius's marine geophysics and volcanology. *Near Surface Geophysics* 8, 1, 17–31.

Argnani A. & Trincardi F. 1990: Paola slope basins: evidence of regional contraction on the Eastern Tyrrhenian margin. *Mem. Soc. Geol. Ital.* 44, 93–105.

Bartole R. 1984: Tectonic structure of the Latian-Campanian shelf. *Boll. Oceanol. Teor. Appl.* 2, 3, 197–230.

Bartole R., Savelli C., Tramontana M. & Wezel F.C. 1983: Structural and sedimentary features in the Tyrrhenian margin off Campania, southern Italy. *Mar. Geol.* 55, 163–180.

Booth J.S., O'Leary D.W. & Popenoe P.D. 1993: U.S. Atlantic continental slope landslides; their distribution, general attributes, and implications. In: Schwab W., Lee H. & Twichell D. (Eds.): Selected studies in the U.S. Exclusive Economic Zone. *U.S.G.S. Bull.* 2002, 14–22.

Brancaccio L., Cinque A., Romano P., Rosskopf C., Russo F., Santangelo N. & Santo A. 1991: Geomorphology and neotectonic evolution of a sector of the Tyrrhenian flank of the Southern Apennines. *Z. Geomorphol.* 82, 47–58.

Bruno P.P.G., Rapolla A. & Di Fiore V. 2003: Structural setting of the Bay of Naples (Italy). *Tectonophysics* 372, 193–213.

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

Cinque A., Aucelli P.P.C., Brancaccio L., Mele R., Milia A., Robustelli G., Romano P., Russo F., Russo M., Santangelo N. & Sgambati D. 1997: Volcanism, tectonics and recent geomorphological change in the Bay of Napoli. *Suppl. Geogr. Fis. Dinam. Quat.* 3, 123–141.

D'Argenio B., Pescatore T.S. & Scandone P. 1973: Schema geologico dell'Appennino meridionale (Campania e Lucania). In: Moderne vedute sulla geologia dell'Appennino. Convegno (Roma, 16–18 Febbraio 1972). *Accademia Nazionale dei Lincei*, Problemi Attuali di Scienza e Cultura, Quaderni, 183, 49–72.

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. & 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). 32° *International Congress "Firenze 2004", Editore De Agostini*, Italy.

Di Girolamo P., Ghiara M.R., Lirer L., Munno R., Rolandi G. & Stanzione D. 1984: Vulcanologia e petrologia dei Campi Flegrei. *Boll. Soc. Geol. Ital.* 103, 349–413.

Di Fiore V., Aiello G. & Angelino A. 2008: Wave and run-up (tsunami) reconstruction from ancient submarine-landslide in the Gulf of Naples, Italy. *Extended Abstract GNGTS 2008*, Trieste, 232–236.

Ferranti L., Oldow J.S. & Sacchi M. 1996: Pre-Quaternary orogen-parallel extension in the Southern Apennine belt, Italy. *Tectonophysics* 260, 325–347.

Finetti I. & Morelli C. 1973: Esplorazione sismica per riflessione nei Golfi di Napoli e Pozzuoli. *Boll. Geof. Teor. Appl.* 16, 175–222.

Fusi N., Mirabile L., Camerlenghi A. & Ranieri G. 1991: Marine geophysical survey of the Gulf of Naples (Italy): relationships between submarine volcanic activity and sedimentation. *Mem. Soc. Geol. Ital.* 47, 95–114.

Galloway W.E. 1998: Siliciclastic slope and base-of-slope depositional systems: component facies: stratigraphic architecture and classification. *AAPG Bull.* 82, 569–595.

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

Liu P.J. & Earickson J. 1983: A numerical model for tsunami generation and propagation. In: Lida J. & Iwasaki T. (Eds.): Tsunamis: their science and engineering *Harpenden. Terra Science*, 227–240.

Lynett P.J. & Liu P. 2002: A numerical study of submarine-landslide-generated waves and run-up. *Proc. R. Soc. London* A(2002) 458, 2885–2910.

Lynett P.J., Tso-Rea W. & Liu P. 2002: Modeling wave run-up with depth-integrated equations. *Coastal Engineering* 46, 89–107.

Mariani M. & Prato R. 1988: I bacini neogenici costieri del margine tirrenico: approccio sismico-stratigrafico. *Mem. Soc. Geol. Ital.* 41, 519–531.

Milia A. 1996: Evoluzione tettono-stratigrafica di un bacino peritirrenico: il Golfo di Napoli. *PhD Thesis*, University of Naples "Federico II".

Milia A. 2000: The Dohrn canyon: a response to the eustatic fall and tectonic uplift of the outer shelf along the eastern Tyrrhenian sea margin, Italy. *Geomarine Lett.* 20, 101–108.

Milia A., Mirabile L., Torrente M.M. & Dvorak J.J. 1998: Volcanism offshore of Vesuvius volcano (Italy): Implications for hazard evaluation. *Bull. Volcanol.* 59, 404–413.

Milia A. & Torrente M.M. 1999: Tectonics and stratigraphic architecture of a peri-Tyrrhenian half-graben (Bay of Naples, Italy). *Tectonophysics* 315, 297–314.

Milia A., Molisso F., Raspini A., Sacchi M. & 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. *J. Geol. Soc.* 165, 839–848.

Nwogu O. 1993: Alternative form of Boussinesq equations for near-shore wave propagation. *J. Wtrwy Port Coastal Ocean Engineering* 119, 618–638.

Ortolani F. & Torre M. 1981: Guida all'escursione nell'area interessata dal terremoto del 23-11-80. *Rend. Soc. Geol. Ital.* 4, 173–214.

Ortolani F. & Aprile F. 1978: Nuovi dati sulla struttura profonda della Piana Campana a sud-est del fiume Volturno. *Boll. Soc. Geol. Ital*. 97, 591–608.

Patacca E. & Scandone P. 1989: Post-Tortonian mountain building in the Apennines. The role of passive sinking of a relic lithospheric slab. In: Boriani P. et al. (Eds.): The lithosphere in Italy. *Advances in Earth Science Research*, *Atti dei Convegni Lincei* 80, 157–176.

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

Principe C., Rosi M., Santacroce R. & Sbrana A. 1987: Explanatory notes in the geological map. In: Santacroce R. (Ed.): Somma-Vesuvius. *Quaderni De La Ricerca Scientifica* 114, 8, 1–47.

Rosi M. & Sbrana A. 1987: Phlegrean Fields. *Quaderni De La Ricerca Scientifica*, Roma 114, 1–175.

Ross W.C., Halliwell B.A., May J.A., Watts D.E. & Syvitski J.P.M. 1994: Slope readjustment: a new model for the development of submarine fans and aprons. *Geology* 22, 511–514.

Royden L., Patacca E. & Scandone P. 1987: Segmentation and configuration of subducted lithosphere in Italy: an important control on thrust-belt and foredeep-basin evolution. *Geology* 15, 714–717.

Sacchi M., Infuso S. & Marsella E. 1994: Late Pliocene–Early Pleistocene compressional tectonics in offshore Campania (Eastern Tyrrhenian sea). *Boll. Geof. Teor. Appl.* 36, 141–144.

Sacchi M., D'Argenio B., Morra V., Petrazzuoli S., Aiello G., Budillon F., Sarnacchiaro G. & Tonielli R. 2000: Pyroclastic lumps; rapidly deforming sedimentary structures beneath the sea floor off the Naples Bay, Italy. *EUG General Assembly*, *Abstr.*, Nice.

Scarpati C., Cole P.D. & Perrotta A. 1993: The Neapolitain yellow tuff — A large volume multiphase eruption from Campi Flegrei, southern Italy. *Bull. Volcanol.* 55, 343–356.

Tinti S., Pagnoni G. & Piatanesi A. 2003: Simulation of tsunamis induced by volcanic activity in the Gulf of Naples (Italy). *Natural Hazards and Earth System Sciences* 3, 311–320.

Wei G. & Kirby J.T. 1995: A time-dependent numerical code for extended Boussinesq equations. *J. Wtrwy Port Coastal Ocean Engineering* 120, 251–261.

Wei G., Kirby J.T., Grilli S.T. & Subramanya R. 1995: A fully nonlinear Boussinesq model for surface waves. Part 1. Highly nonlinear unsteady waves. *J. Fluid Mech.* 294, 71–92.

Zaniboni F., Tinti S., Pagnoni G., Gallazzi S., Della Seta M., Fredi P., Marotta E., Orsi G., De Vita S. & Sansivero F. 2007: Landslides-generated tsunamis in the Ischia island (Italy). *Geophys. Res. Abstr.*, Vol. 9, 06246, 2007.