Integrated marine geophysical data interpretation of the Naples Bay continental slope (southern Tyrrhenian Sea, Italy)

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ABSTRACT The Bay of Naples continental slope provides valuable information about relationships between the buried volcanic structures emplaced during Late Quaternary activity of the Campania district, related magnetic anomalies and morphological expression of the structures at the sea bottom. Integrated geological interpretation of high-resolution Multibeam bathymetric, magnetic and seismic data collected by the CNR-IAMC Institute onboard the R/V Urania has been carried out. Well-developed magnetic anomaly fields are related to volcanic banks located near the shelf break and the Dohrn and Magnaghi canyons. High-resolution bathymetric, magnetic and seismic data interpretation supported the relationships between morpho-structural lineaments and magnetic data fields.

1. Introduction

The Gulf of Naples continental slope and outer shelf are deeply incised by two submarine canyons of kilometric extension, namely the Dohrn and the Magnaghi canyons, representing the drainage system of this active volcanic area during the Late Quaternary. The study area is located in the southern Tyrrhenian Sea, a young extensional domain with restricted areas of oceanic-type crust, which encloses a number of basins in its margins, as the Gulf of Naples ["peri-Tyrrhenian"; Fabbri *et al.* (1981), Malinverno and Ryan (1986), Trincardi and Zitellini (1987), Oldow *et al.* (1990)], that show marked differences in size, thickness and internal architecture of the filling sequence.

Notwithstanding the great number of geological and volcanological works about the Gulf of Naples (Latmiral *et al.*, 1971; Finetti and Morelli, 1974; Pescatore *et al.*, 1984; Fusi *et al.*, 1991; Milia, 1996; Aiello *et al.*, 1997a, 1997b, 2001; Cinque *et al.*, 1997), the relationships between bathymetric features and related seismic and magnetic structures have not even been investigated in detail. One aim of this research is to give a contribution to the knowledge of erosional and depositional processes related to slope settings through a detailed mapping of morphological features in the outer shelf and slope. Another aim of this paper is to relate main morphological features on the Bay of Naples continental slope to related seismic and magnetic structures by using a high-resolution survey, allowing us to identify submarine features of the slope with a detail never achieved before (Fig. 1).

Submarine canyons provide valuable information on the history of erosional and depositional processes on continental slopes (Brown and Fisher, 1977; Bouma, 1982; Kenyon, 1987; Bugge e*t al.*, 1988; Soh *et al.*, 1990; Ergin *et al.*, 1991; Ediger *et al.*, 1993; Hagen *et al*., 1994, 1996; Pratson and Coakley, 1996; Talling, 1998; De Pippo *et al.*, 1999). Submarine canyons may represent sources of eroded sediments and/or ways of mass sediment transport, as well as sites of distinctive deposits (Shepard and Dill, 1966; Middleton and Hampton, 1976; Sanford *et al.*, 1990; Satterfield and Behrens, 1990). Tectonism and volcanism are important check factors on the morphology and evolution of submarine canyons, especially in geologically-active continental margins (Soh *et al.*, 1990; Kokelaar and Romagnoli, 1995; Lucchi and Kidd, 1998; Kidd *et al.*, 1998; Chiocci *et al.*, 1998a, 1998b).

Shallow geological structures based on the techniques of seismic stratigraphy (Vail *et al.*, 1977) have been investigated; the volcanic nature of some of these structures has been inferred by the qualitative correlation with the magnetic anomalies. The magnetic anomalies have been singled out by the processing and the interpretation of magnetic lines recorded along the same navigation lines of seismics. Detailed magnetic data-processing allowed the constructing in of a high resolution magnetic anomaly map of the Bay of Naples (Siniscalchi *et al.*, 2002; Aiello *et al.*, 2004; Ruggieri, 2005). A qualitative geological interpretation of the map already showed complex magnetic anomaly fields, associated to shallow volcanic structures, as evidenced by the interpretation of seismic reflection profiles combined with high-resolution Multibeam bathymetry of the Bay (Figs. 2 and 3).

A further interpretation was given by Secomandi *et al*. (2003), who re-processed the magnetic data collected during the GMS00-05 cruise to produce reduced maps of the pole, analytic signal and horizontal derivative data and correlated them to the bathymetry and the gravimetric data of the area. The latter were obtained by digitising the gravimetric map by Berrino *et al.* (1998) and filtering the data through a method based on discrete wavelet transform (Fedi and Quarta, 1998). The interpretation of geophysical data of Secomandi *et al*. (2003) is in agreement with the interpretations of magnetic anomaly fields in the Bay of Naples given by Siniscalchi *et al.* (2002) and Aiello *et al.* (2004).

Finally, a geological interpretation of buried volcanic structures in the Bay of Naples based on high-resolution magnetic and seismic lines has been recently carried out by Aiello *et al.* (2005). Selected seismic profiles were plotted together with magnetic lines recorded on the same navigation tracks of seismics in order to give an integrated interpretation of buried structures. An evaluation of the volcanic nature of buried mounds recognised by seismic interpretation through their correlation with magnetic anomalies has been attempted.

The aeromagnetic anomaly map of Italy produced by the AGIP oil company (1981) was, until now, the best reference point for many magnetic interpretations, also in this area. The shaded magnetic relief anomaly map of Italy (Chiappini *et al.*, 2000) outlines the lack of detailed magnetic measurements in the Bay of Naples. The map is based on onshore measurements collected in the frame of the CNR-Progetto Finalizzato Geodinamica (1977-1981), while offshore magnetic measurements were recorded by the Osservatorio Geofisico Sperimentale (OGS; Trieste, Italy; 1965-1972). Main magnetic signatures recognised on the shaded magnetic anomaly relief map of Italy have been related to tectonic structures at a regional geological scale. As a general rule, a good regional correlation between the geology of shallow structures and magnetic anomalies exists. Integrated high-resolution magnetic and seismic data interpretation can be inferred by Multibeam bathymetric maps, whose geological interpretation can represent a useful tool to assess the relationships between sea-bottom topography, geological structures and magnetic anomaly fields. This kind of integrated

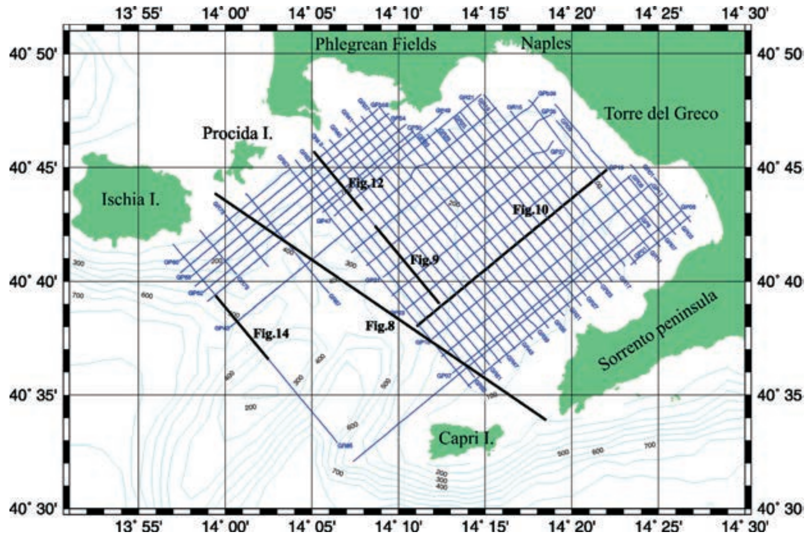

Fig. 1 - Navigation lines of high-resolution seismic and magnetic profiles recorded by the CNR-IAMC Institute during the GMS00-05 cruise (R/V Urania, National Research Council, Italy). Bold lines indicate seismic profiles shown in the text.

interpretation was attempted in our paper, in which high resolution magnetic, seismic and bathymetric data collected in the Bay of Naples have been interpreted and correlated to furnish some new geological evidence on continental slope settings.

A shaded bathymetric relief map of the Bay of Naples has been constructed based on high-resolution Multibeam bathymetric data collected by the CNR-IAMC Institute through several oceanographic cruises (Fig. 3; Ruggieri, 2005); a contour map of magnetic anomalies has been superimposed on Multibeam bathymetry and represented in yellow in Fig. 3. In this map, it is possible to infer the magnetic nature of some banks, being structures hat evidently have a positive relief on shaded-relief Multibeam bathymetry, like the Ischia bank (IB in Fig. 3), the Miseno bank (MB in Fig. 3) and the Nisida bank (NB in Fig. 3), the Pentapalummo bank (PPB in Fig. 3) with respect to the Banco di Fuori bank, where the magnetic signature is totally absent.

2. Geological setting

The Gulf of Naples lies in the southern part of a tectonic depression, the Campanian Plain, produced from the back-arc extension that accompanied the NE-verging accretion of the Apenninic thrust belt during the roll-back of the subducting foreland plate. The period of wedge accretion goes from Middle-Late Miocene to the end of the Early Pleistocene. In the Campanian Plain, the first stage of lowering and submersion (Early Pleistocene in age) was probably controlled by a NW-SE extension like the following one (Middle Pleistocene). Normal faults, inherited from both these stages were then reactivated during Late Pleistocene and Holocene phases of subsidence and uplift, especially in the zones affected by volcano-tectonics (Cinque *et al*., 1997).

The Phlegrean Fields are a volcanic district surrounding the western part of Gulf of Naples, where volcanism has been active for at least 50 ky (Rosi and Sbrana, 1987). The present morphology of this volcanic district refers to events which occurred after the emplacement of the Campanian Ignimbrite, a huge pyroclastic flow erupted 35 ky ago, when the area experienced a first phase of calderization. The first regressive peak of the last glacial period [isotopic stage 4 of Martinson *et al*. (1987) and Chappell and Shackleton (1986)] brougth about an advance of the coastline 30 km south-westwards, bringing it, in fact, close to the present location of the shelf break in the Gulf of Naples, near the –140 m isobath. The glacio-eustatic controlled emersion was reinforced by the pyroclastic aggradation of the Campanian Plain induced by the eruption of the Campanian Ignimbrite, which carpeted the whole plain with 20 to 60 meters of a welded grey tuff. The volcanic districts of Procida, Vivara and Ischia Islands represent the seaward prolongation of the Phlegrean Fields area, that also includes a number of submerged volcanoes [volcanic banks of Pentapalummo, Nisida and Miseno: Latmiral *et al*. (1971) and Pescatore *et al*. (1984)]. The eruption centres occurring on these islands range between 150 ky and historical times (Rosi and Sbrana, 1987; Vezzoli, 1988). The volcanic activity on these islands also played a major role in the formation and the activity of the Dohrn western branch and of the Magnaghi canyon, since they supplied a great volcanoclastic input to the slope during major eruptive phases.

In the eastern sector of the Bay of Naples volcanoclastic inputs and erosional and depositional processes on the continental shelf and slope during the Late Quaternary have been controlled mainly by the Somma-Vesuvius volcanic activity and the sedimentary processes in the Sarno-Sebeto coastal plain. The coastal plain of the Sebeto River, where the eastern part of the town of Naples lies, is located at the boundary of the Somma-Vesuvius volcanic complex and towards the Tyrrhenian coastline. The individuation of the plain seems to have been controlled by a main NE trending normal fault (the onshore part of the Acerra-Dohrn fault), probably active after the emission of the Campanian Ignimbrite pyroclastic flow (35 ky) and after the eruption of the Neapolitain Yellow Tuff (12 ky). The Sarno-Sebeto River has given rise to the main progradational units in the eastern part of the Gulf of Naples.

3. Data acquisition and processing

Magnetic data were recorded by using the G-811 Proton Magnetometer. The sensor was placed in a towed fish generally at 200 m from the ship and 15 m below sea-level; the depth of the magnetometer was controlled and recorded regularly. The cruising speed did not exceed 6 knots and the data were spatially sampled at 6.25 meters thanks to the information provided by the GPS; in fact, the navigation program calculated the distances and sent them to a trigger box which was able to automatically switch to a temporal sample of 3 seconds, in case of the malfunctioning of the navigation system.

An accurate magnetic data processing was performed in order to preserve data information contents (Ruggieri, 2005). Initially, raw data were edited manually or using a median filter to remove spikes due to non-geological sources. The repositioning of the marine paths was performed taking into account the offset distance between the fish and the GPS positioning system. The elimination of the diurnal component was carefully controlled by adopting the geomagnetic observatory of L'Aquila (42° N; 12° E), kindly provided by the Istituto Nazionale di Geofisica e Vulcanologia (INGV, Rome, Italy) as a base magnetic station. The distance between the surveyed area and the Observatory of

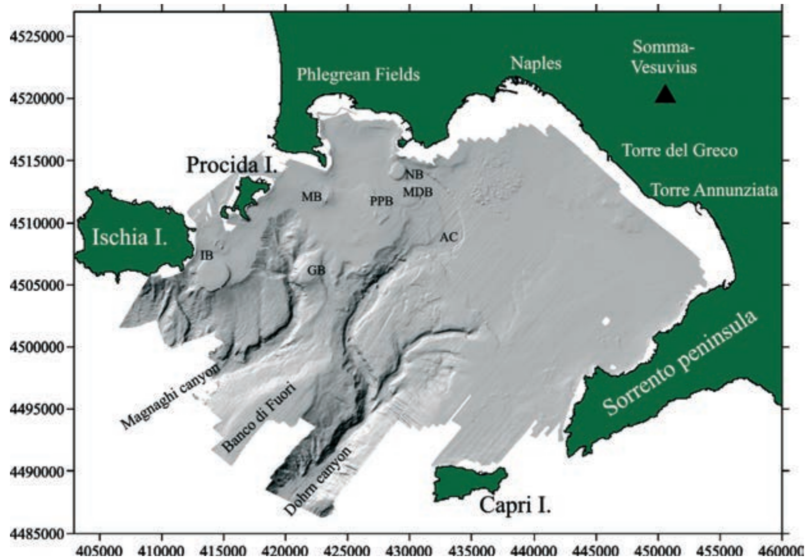

Fig. 2 - Shaded relief map of the Multibeam bathymetry (ELAC, Bottomchart MK2) recorded in the Bay of Naples by the CNR-IAMC Institute [reported from Aiello *et al.* (2001) and D'Argenio *et al.* (2004)].

L'Aquila is about 200 kilometers. Such a distance does not necessarily ensure a good removal of the diurnal component. The measuring periods are characterized by quiet magnetic activity; we checked the goodness of such corrections by controlling absolute mis-tie distribution before and after its application. A significant statistical improvement of mis-ties after this correction was observed; in particular, the average absolute mis-tie was reduced from 19.4 nT to 12.8 nT and the mis-tie distribution improved all its normal statistical values. To recover the total-field anomaly, the values of the main magnetic fields must be subtracted from the measurement values corrected as above. We adopt the Italian Geomagnetic Reference Field (ItGRF) model with values calculated for the reduction epoch, year 2000.

Several factors contribute to level shifts in the magnetic field between adjacent survey lines. These include elevation differences between navigation lines and inadequate removal of mentioned time, varying (diurnal) magnetic field variations. A zero-order network adjustment was therefore performed bringing the lines into approximately level positions. This levelling procedure reduces mis-ties without distortion of the original data and the average absolute mis-tie has been reduced to 7.2 nT. Each line was resampled at the original spacing of 6.25 m to fill the gap introduced by the magnetic spikes and the DGPS-GPS shift in navigation. This sampling was necessary in order to avoid aliasing problems caused by the fact that the minimal distance between the sensor and the sea bottom (possibly sub-emerging magnetic source) is of the order of 30 m.

High-resolution seismic profiles (950 km of lines) have been recorded on the same navigation lines as magnetics (Fig. 1). Seismic acquisition was performed at a constant distance interval of 6.25 m (or 3 s). The minimum source-receiver offset was 130.00 m and therefore the fold was 1200 %.

Data acquired by the hydrophones were recorded with the *Stratavisor* NX (Geometrics Inc.). *Stratavisor* recorded 24-channels with a group interval of 6.25 m. Anti-alias analog filters of 500 Hz

48 DB/octava were applied to the seismic signals before sampling. Seismic data were stored in tape drives during acquisition using a SEG-Y format. Preliminary processing of Watergun profiles limited to the production of single-channel, near-trace seismic profiles was carried out onboard. Firstly, the extraction of the first channel from the shot gathers was executed. Then, an AGC (Automatic Gain Control) operator length was applied to the seismic signal in order to define the length of the AGC windows used for gain computation. The AGC program moves the window down the trace sample-by-sample and calculates a factor scale at each location. The scale factor is equal to the inverse of the RMS amplitude in the window. Then, a spectrum analysis of the traces was performed to examine the frequency energy content in the seismic signal. Finally, a time-variant band-pass filter was applied. The type of filter applied was a Butterworth band-pass with 18 dB/octave low roll-off and 36 dB/octave high roll-off.

Despite their obvious limitations, near-trace profiles turned out to be extremely useful in providing a first, fairly accurate description of the traversed structures. The availability of this information a few hours after the termination of each line was essential to redesign the cruise along the geologically most interesting lines. These profiles also offered the chance of discussing related geological problems. Particularly interesting segments of the near-trace profiles were further refined to provide the best available resolution.

On seismic sections, near-surface multiples occur in correspondence to the sea bottom and short-path multiples are present in the stratigraphic record, as a single and/or double repetition of seismic horizons. Seismic interpretation was carried out taking into account the occurrence of multiples and noises and carefully eliminating them from the geological interpretation.

An ELAC Nautik Bottom Chart MK2 Multibeam system was adopted to record Multibeam bathymetry of the Bay of Naples (Aiello *et al*., 2001; D'Argenio *et al*., 2004) by using a bathymetric range of –50/-3000 m (Figs. 2 and 3). The ELAC system was equipped with a transducer with 256 beams, arranged to generate a 15° to 150° fanwidth; the vertical accuracy was about 0.25% of water depth, whereas the spatial resolution (the size of the "footprint") ranged from 1 to 5 m. The maximum horizontal coverage was 7.5 times the water depth. During the acquisition, CTD profiles were collected every 6 hours. The line spacing was set to obtain a variable overlap (from 30%, up to 100%) between swaths. During the acquisition, about 1500 km of Subbottom Chirp profiles were recorded on the same navigation lines of Multibeam bathymetry for the recognition and calibration of the acoustic facies.

4. Morphobathymetry and seismic stratigraphy of the Bay of Naples continental slope

A morphological sketch map of the Bay of Naples continental slope has been constructed through the geological interpretation of Multibeam bathymetry in order to explain the geological setting of the area (Fig. 4). Moreover, several bathymetric profiles have been constructed and interpreted in order to provide detailed constraints on the geological evolution of the Dohrn and Magnaghi canyons (Figs. 6 and 7). Detailed bathymetric contour maps of Dohrn and Magnaghi canyons reporting the location of bathymetric profiles are respectively shown in Figs. 5 and 7.

The Dohrn canyon's width ranges from a few hundred meters to more than 1 km, its depth goes from 250 m at the shelf edge to some 1300 m in the bathyal plain, the dip of its walls attains some 35° in the steepest sectors (Figs. 2, 3 and 5). The western branch merges into the shelf through a 1.5

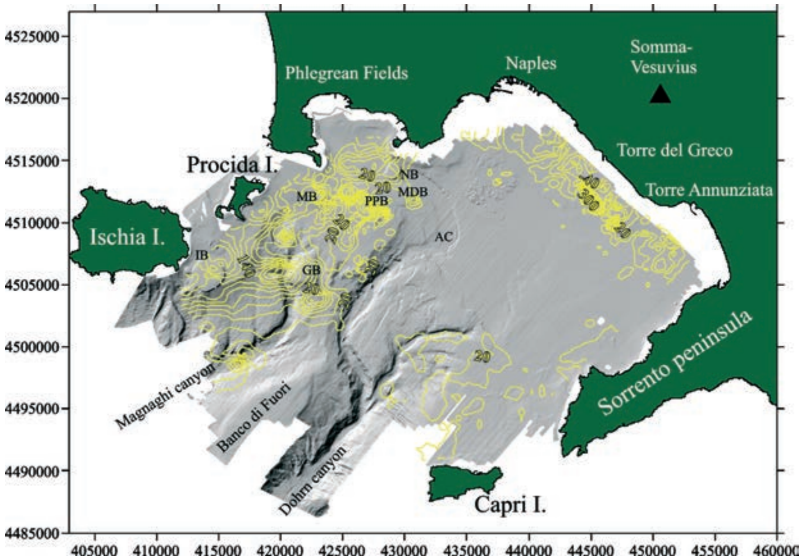

Fig. 3 - Shaded relief map of the Multibeam bathymetry of the Bay of Naples, superimposed by a contour map of the magnetic anomalies (yellow lines in the figure). Main morphological features and corresponding magnetic signatures have been singled out by labels (AC: Ammontatura Channel; MDB: Monte Dolce Bank; NB: Nisida Bank; PPB: Pentapalummo Bank; MB: Miseno Bank; GB: Gaia Bank; IB: Ischia Bank). The correlation between magnetic signatures and morphological lineaments in the Bay of Naples is evident here.

km wide and 20-40 m deep channel (“Ammontatura” channel; Figs. 2, 3 and 4) located along the –200 m isobath and characterized by a flat bottom and asymmetrical levees and by a curved shape in the plan view. The origin of the “Ammontatura” shallow channel can be tentatively correlated to the hydrodynamic regime driven by the western axis of the Dohrn canyon. Its emplacement seems to postdate the latest stages of erosion and transportation in the canyon and to predate the formation of the most recent volcanic edifices in the Gulf of Pozzuoli, as suggested by its abrupt termination towards the Nisida submarine volcanic edifice (Figs. 2, 3 and 4).

The Dohrn eastern branch shows a meandering trending and starts from the shelf break of the Sorrento Peninsula, located along the - 120 m isobath (Figs. 2, 3, 4 and 5). The Dohrn western branch is broader than the eastern one, and more incised; the two branches are not joined and form a typical Y-structure, as appears well evident from bathymetric maps and profiles (Figs. 5 and 6).

The erosion and the transportation of the volcanoclastic input in the western sector of the Bay (offshore the islands of Ischia and Procida) has acted along the axis of the Magnaghi canyon. Its head is typically trilobate with three main tributary channels joining basinwards into the main axis (Figs. 2, 3 and 7). Shaded-relief Multibeam bathymetry shows the occurrence of erosional phases presently acting on the continental slope located south-east of Procida Island and of debris “outrunner” blocks (Prior *et al*., 1984), a few kilometers SW of the “Banco di Ischia” volcanic edifice (Fig. 3).

Both the Dohrn and Magnaghi canyons start from the shelf break of the Bay of Naples, offshore the Phlegrean Fields volcanic complex, located along the –140 m isobath (Figs. 2, 3 and 4). The trending of the canyons is conditioned by the occurrence of main morpho-structural lineaments, as the Banco di Fuori structural high (Figs. 2, 3 and 4), bounding the whole canyon system and the

Island of Capri structural high southwards and the Dohrn canyon, near its confluence with the bathyal plain eastwards. The Magnaghi canyon and the Dohrn western branch show morphological evidence of the canyon heads retreating (Figs. 4, 5, 6 and 7).

Bathymetric profiles located along the Dohrn western branch (Fig. 6) confirmed the occurrence of several slide scars, already evidenced by Multibeam bathymetry in plan view (Figs. 3 and 4). Rounded morphologies, located in the canyon's thalweg are interpreted as relic structures, probably due to a selective erosion acting along the canyon's valley (bathymetric profiles D5-D7; Fig. 6). The section D3 (Fig. 6), carried out in the retreating Dohrn canyon's head, shows terrace rims respectively located at a –340 m and –300 m water depth. This morphological evidence suggests at least two phases in the activity and retreat of the canyon's head. Well-developed terrace rims (at least five rims) have been recognized also on the bathymetric profile D6 (Fig. 6), respectively located at water depths of – 520 m, - 400 m, - 380 m, - 350 m and –320 m. They suggest the occurrence of several phases of erosion and deposition in the evolution of the canyon.

The interpretation of bathymetric profiles allowed us also to study the distribution of the V-shaped erosional profiles with respect to the U-shaped depositional profiles in the whole Dohrn canyon system (Fig. 6). A relative abundance of V-shaped erosional profiles has been observed in both the branches of the canyon (profiles D3, D4, D7, D9, D11; Fig 6). The U-shaped 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 two branches (Fig. 6).

A dense network of tributary channels, controlling the overflowing of sediments in the surrounding areas of the continental slope, laterally fed the Dohrn eastern branch. Two main tributary channels start from the shelf break of the Phlegrean submarine volcanic banks (located along the –140 m isobath) and run along the continental slope between the Dohrn and Magnaghi canyons, giving rise to channel-lobe systems (Figs. 2, 3 and 4). A complex system of tributary channels, located at water depths ranging from -200 and – 500 meters, fed the Dohrn eastern branch starting from the shelf break of the Sorrento Peninsula; it seems partly fault-controlled, as suggested by the rectilinear shape in plan view of the southernmost four channels in Multibeam bathymetry (Figs. 3 and 4). The hypothesis that these channels are fault-controlled was already proposed by Chiocci *et al*. (1998a) after a deep-towed TOBI Side Scan Sonar survey of the sea bottom in the Bay of Naples. 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. Fossil tributary channels suspended over the main branches testify phases of rapid re-incision, switching off the feeding from lateral sources and forming suspended valleys (Fig. 4).

Several submarine slides and scars are still evident on the canyon's walls, and on the continental slope as well (Figs. 3 and 4). Submarine slides are controlled by loading and underconsolidation of sediments due to rapid sedimentation, oversteepening of slopes consequent to phases of deep linear erosion, earthquakes and sea-level changes (Saxov and Nieuwenhuis, 1982; O'Leary and Dobson, 1992). Most parts of the slide scars involving the Dohrn canyon appear to be concentrated along the western slope of its western branch; the other branch does not appear to be involved by mass wasting. Slide scars have been identified by geological interpretation also on bathymetric profiles (profiles D4 and D5; Fig. 6).

Seismic interpretation of multichannel profiles recorded by the CNR-IAMC in the Bay of Naples by using a Airgun seismic source (Fig. 8) already showed the stratigraphic architecture of seismic

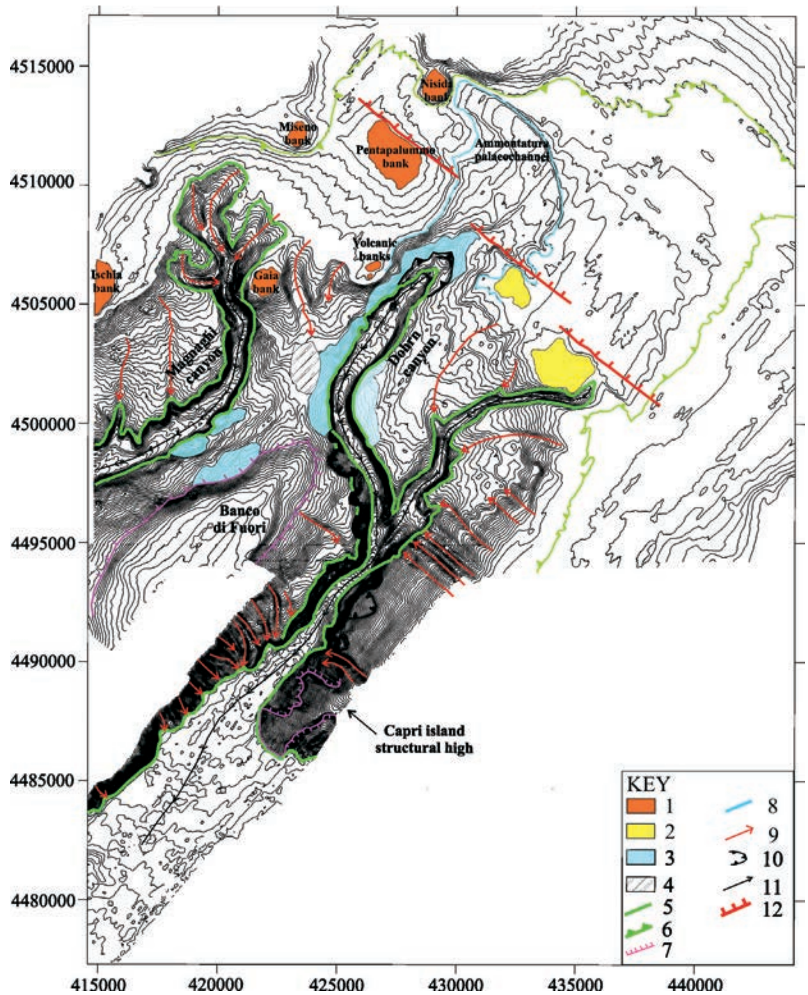

Fig. 4 - Sketch morphological map of the Bay of Naples continental slope based on the geological interpretation of Multibeam bathymetry. Key: 1: volcanic morphostructural high; 2: relic morphology of the Middle-Late Pleistocene continental shelf; 3: areas involved by significant submarine slope instability; 4: turbidite slope fan; 5: canyon's wall; 6: shelf break; 7: carbonatic morpho-structural high; 8: slope of palaeocanyon; 9: drainage axis; 10: slide scar; 11: canyon's axis; 12: normal fault.

units and related unconformities (Aiello *et al.*, 1997a, 1997b, 2001; D'Argenio *et al.*, 2004), resumed in Table 1. The age of seismic units reported in Table 1 is qualitative and based on the geological correlation between the units and onshore volcanic sequences established by Rosi and Sbrana (1987) in the Phlegrean Fields, Santacroce (1988) in the Somma Vesuvius and Vezzoli (1988) on the Island of Ischia. The basin-filling of the Bay of Naples is formed by the seismic units from 6 to 2, while unit 1 represents the acoustic basement (see Table 1). Holocene highstand drape (unit 7 in Table 1) overlies the sea bottom in the whole bay.

Further evidence is given by the interpretation of the regional seismic profile NAM3 (Fig. 8), showing the seismo-stratigraphic setting of the area. Several seismic sequences separated by

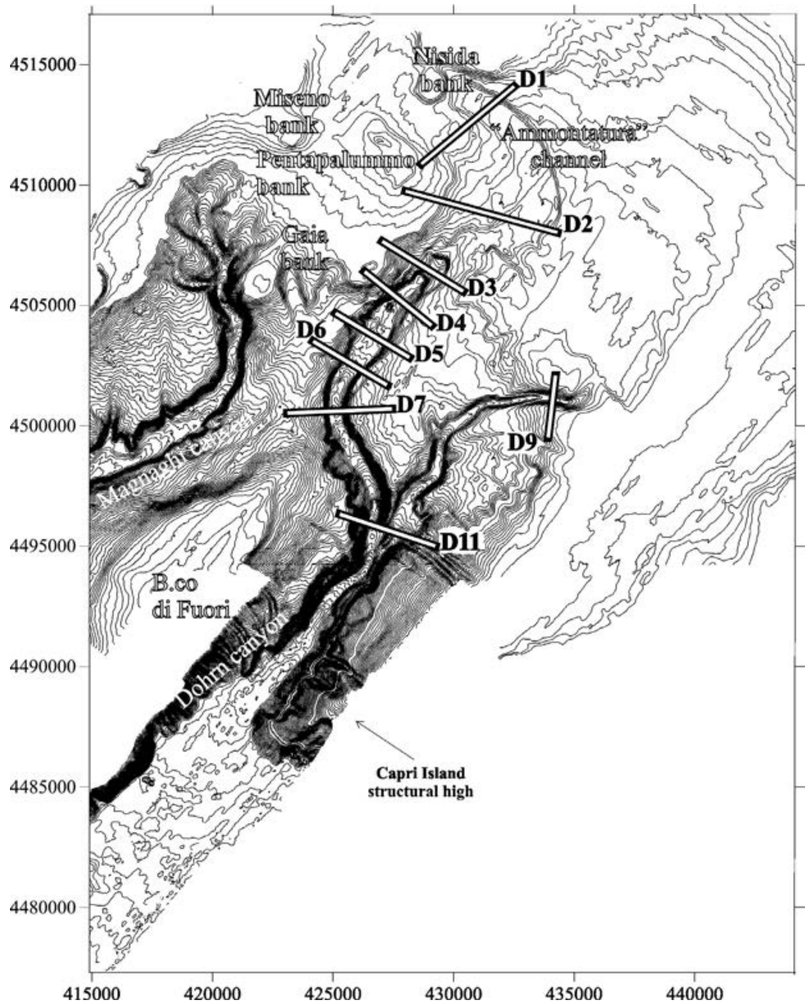

Fig. 5 - Mutibeam bathymetric contour map of the Dohrn canyon. The location of the bathymetric profiles shown in Fig. 6 has been reported.

unconformities have been distinguished. The acoustic basement is represented by Meso-Cenozoic platform carbonates (unit 1 in Table 1 and in Fig. 8), cropping out onshore on the Sorrento Peninsula and on the Island of Capri and organised as a monoclinalic structure dipping north-westwards. The measured inclinations of reflectors in the carbonate sequence are of about 6°-7°; such values are similar to those shown in outcrops of Meso-Cenozoic carbonates in the Sorrento Peninsula (Perrone, 1988).

The basin filling consists mainly of two prograding wedges (units 2 and 4 in Table 1 and in Fig. 8), each characterised by distinctive acoustic patterns and seismic facies. The oldest one (unit 2) is interpreted as a wide relic prograding wedge, north-westwards dipping, formed by siliciclastic deposits, probably Pleistocene in age and occurring offshore the Sorrento Peninsula and the Island of Capri. Both the Meso-Cenozoic carbonates and unit 2 have been probably involved in a tectonic

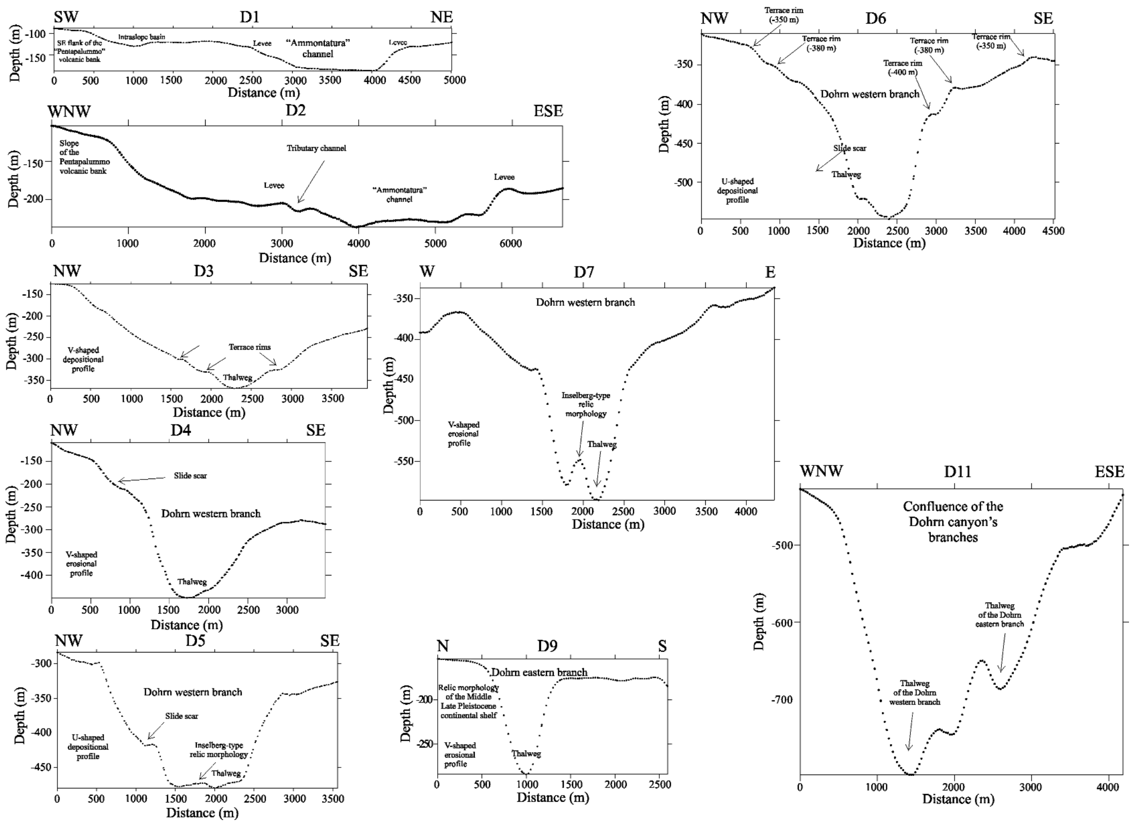

Fig. 6 - Bathymetric profiles crossing the two branches of the Dohrn canyon. Schematic geological interpretation is also reported (see the text for further details).

tilting during Pleistocene extensional phases of the Sorrento Peninsula, slightly increasing the steepness of the seismic reflectors. On the continental shelf the seismic reflectors are involved by a main subaerial unconformity (unconformity B in Fig. 8), whose areal extension varies from 2-3 kilometres to some hundreds of meters proceeding towards the emerged areas. The unconformity B probably indicates a main, relative sea-level fall and a strong, basinwards shifting of coastal and marine facies, accompanied by sedimentary bypass and strong erosion on the shelf and slope.

Above the unconformity B, the clinoforms of unit 3 (Fig. 8) progressively onlap the slope and basin areas up to the continental shelf. Unit 3 represents a wedge-shaped, transgressive unit, mainly developed in slope and basin settings and probably composed of siliciclastic deposits.

Above unit 3 a wide prograding wedge (unit 4 in Fig. 8 and in Table 1) develops: it shows well-preserved offlap breaks and thickens from the shelf towards the slope. This wedge is of notable importance in the study of the stratigraphic architecture of the bay; it grades laterally, or alternatively, is overlain by the volcanic units 5a, 5b and 5c (see Table 1) and is deeply incised by the Dohrn canyon axes. Moreover, it is worth noting that this unit gives origin to morphological relic highs (Fig. 4), located in the central sector of the bay, next to the present-day shelf break and northwards of the Dohrn eastern branch. Unit 4 has been probably supplied by the Sarno River mouth during the

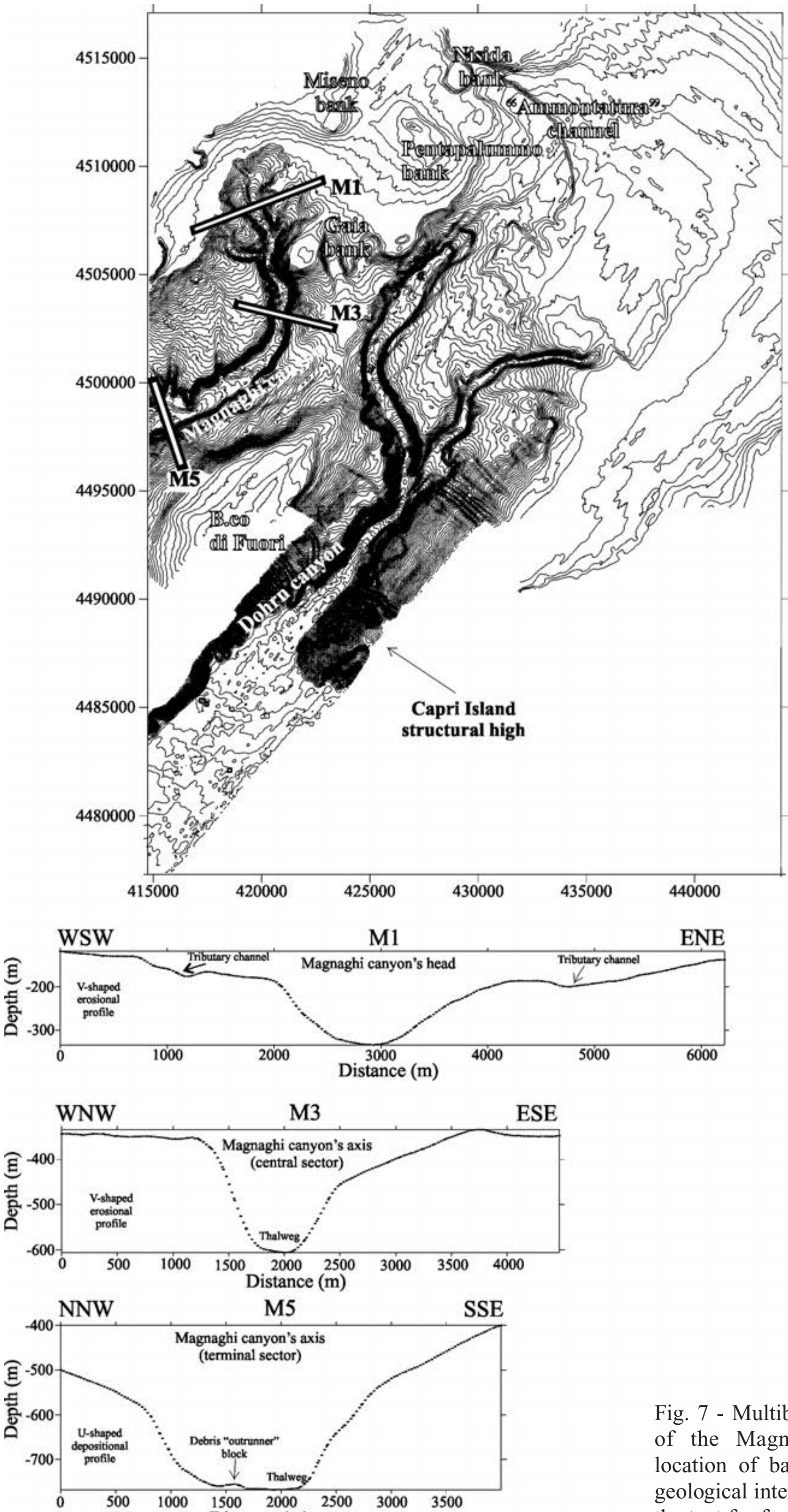

Fig. 7 - Multibeam bathymetric contour map of the Magnaghi canyon, reporting the location of bathymetric profiles. Schematic geological interpretation is also reported (see the text for further details).

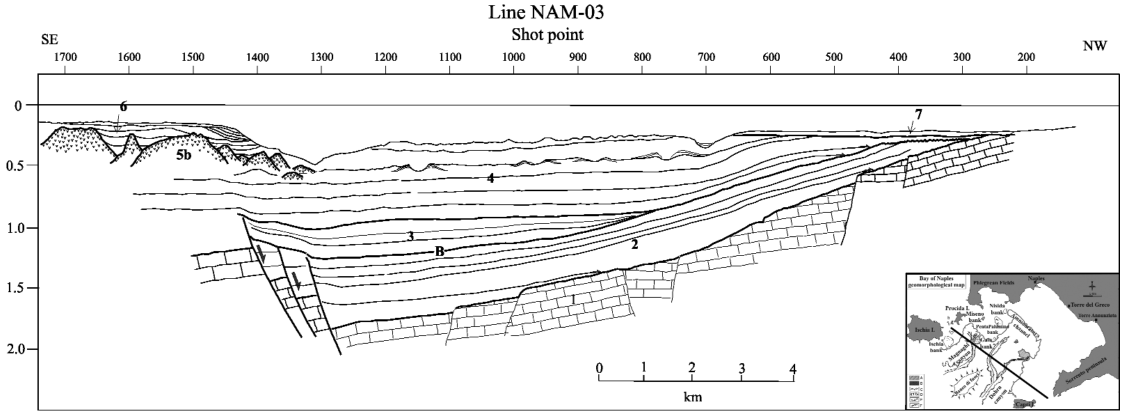

Fig. 8 - Line drawing of the multichannel seismic profile NAM3, recorded by the CNR-IAMC in the Bay of Naples by Airgun seismic source. The profile shows the stratigraphic architecture of the Bay of Naples along a NW-SE transect, from offshore Ischia and Procida towards the Sorrento Peninsula. The acoustic basement, represented by Meso-Cenozoic carbonates, is strongly downthrown by normal faulting towards the centre of the bay. The basin filling is composed of several seismic sequences; two of them (units 2 and 4) are represented by wide relic prograding wedges and appear to be the most relevant in the tectono-sedimentary evolution of the area.

Middle-Late Pleistocene. Other feeding sources of the wedge may be represented by siliciclastic deposits produced during erosional phases accompanying the tectonic uplift of the Sorrento Peninsula during Middle-Late Pleistocene.

Above unit 4 and/or in facies hetheropy with the latter, a wedge-shaped seismic unit, acoustically transparent and volcanic in origin has been recognised (unit 5a). This unit mainly occurs in the eastern sector of the bay; in particular, it has been well-identified offshore the Sorrento Peninsula, where it unconformably overlies the Meso-Cenozoic carbonates and/or seismic unit 2. The same unit has been also identified offshore the Somma-Vesuvius volcanic complex. The top of this unit is often deformed by dome-shaped structures, reaching also a kilometric extension (Aiello *et al*., 2004, 2005). These structures, often corresponding to strong magnetic anomalies are interpreted as buried parasitic vents, genetically related to the Somma-Vesuvius volcanic complex.

The Dohrn canyon exposes hundreds of meters of a Middle-Late Pleistocene prograding wedge along its walls (unit 4 in Fig. 8 and in Table 1), constituted of siliciclastic sediments and genetically related to the Sarno fluvial system (Fig. 9). The seismic profile GP19 (Fig. 10) runs along the progradation axis of the wedge, which underlies a wedge-shaped, acoustically-transparent seismic unit, interpreted as the Campanian Ignimbrite pyroclastic flow deposits (unit 5a in Table 1).

The location of the Dohrn eastern branch and several seismo-stratigraphic pieces of evidence suggest a genetic link between the activity of the Dohrn canyon and the Sarno palaeo-drainage system during sea level lowstands. This hypothesis was already suggested by Aiello *et al*. (2001) and by D'Argenio *et al*. (2004) in their papers on the Bay of Naples morphobathymetry. During sea-level lowstand phases of the Middle-Late Pleistocene and contemporaneously to a subaerial shelf exposure in the Bay of Naples, the Sarno delta has fed slope settings directly, giving origin to a thick prograding wedge (unit 4), over which the Dohrn canyon then developed; in particular, the Dohrn eastern branch could have been directly linked to the Sarno River mouth during sea level lowstands.

A seismic sequence, 30-40 m thick, overlying older undisturbed reflectors and including overbank deposits with channel-levee complexes, crops out at the sea bottom in the surroundings of the canyon (Fig. 9). These deposits do not seem related to the main branches, which result deeply incised, but in the presence of tributary channels, controlling the overflowing of sediment fluxes in the surrounding areas.

Such a hypothesis is supported by the occurrence of two sedimentary bathymetric highs located near to the heads of the Dohrn canyon (Figs. 3 and 4). Seismic stratigraphy reveals that they consist of deltaic sediments arranged in clinoform patterns and related to the distal part of the prograding wedge fed by the paleo-Sarno River mouth (Aiello *et al*., 2001). These highs, having an elevation with respect to the surrounding average depth in the order of 20-30 m, are relic morphologies of the Middle-Late Pleistocene continental shelf (Fig. 10). Line GP19 crosses one of these highs, located next to a channel feeding the Dohrn eastern branch (Fig.10). Relic morphologies of the Middle/Late Pleistocene continental shelf at the center of the Bay of Naples have been recognised also based on the interpretation of Multibeam bathymetry and mapped in the geomorphological map of Fig. 4. Their occurrence can be accounted for by differential erosion during the shelf subaerial exposure related to an eustatic lowstand. Seismic evidence allows us to infer a pre-Campanian Ignimbrite (35 ky) of this erosional phase (Aiello *et al*., 2001). As suggested by the interpretation of line GP19 (Fig. 10) the erosional phase dates back to 35 ky (age dating reported in the literature for the Campanian Ignimbrite; see also Barberi *et al*., 1978) and is coeval with the emplacement of the Campanian Ignimbrite deposits.

A major morphostructural high (Banco di Bocca Grande or Banco di Fuori) separates the Dohrn from the Magnaghi canyon and is presumably formed by a Mesozoic carbonate block that resulted from the regional uplift and tilting of the acoustic basement, cropping out in the Sorrento Peninsula-Capri Island structural high (Fusi *et al*., 1991). The Banco di Fuori structure is well evident on the Multibeam bathymetry of the Bay (Fig. 3) and has been surveyed by seismic profiles (Aiello *et al*., 2005). The sedimentary nature of the Banco di Fuori high is suggested by its location along the structural alignment Capri Island-Sorrento Peninsula and confirmed by the lack of significant magnetic anomalies (Aiello *et al*., 2004, 2005).

5. Magnetic anomaly fields and related morphostructural features

Volcanic bodies occurring in the subsurface of the Gulf of Naples are significantly linked to eruptive phases of Somma-Vesuvius, Phlegrean Fields and Ischia and Procida Island volcanic complexes. The role of the Dohrn canyon as a main morphological and structural lineament in the investigated area has also been confirmed by our data analysis. The Dohrn canyon western branch sharply separates a south-eastern sector of the Gulf of Naples, characterized by the occurrence of sedimentary units by a north-western one, where main volcanic bodies and units are localized.

Significant magnetic anomalies are located in correspondance to a belt of submarine volcanic banks located in the external part of the Gulf of Pozzuoli, offshore the Phlegrean Fields volcanic complex (Figs. 3 and 11). They are named Pentapalummo, Miseno and Nisida banks and represent relic volcanic morphologies cropping out at the sea bottom in the outer shelf off the Gulf of Pozzuoli and have been already interpreted as the submerged border of the Phlegrean caldera based both on volcanological evidence (Barberi *et al*., 1978, 1991; Orsi *et al*., 2003, 2004) and on a high resolution

Table 1 - Seismic units in the Bay of Naples.

Key	Seismic facies	Description	Attribution
7	Highly-continuous parallel and sub-parallel reflectors	Wedge-shaped or drape-shaped unit cropping out at the sea bottom in the whole Bay of Naples	Holocene highstand drape
6	Highly-continuous sigmoidal to obliquous clinoforms; subparallel reflectors	Prograding wedges deposited on the continental shelf and/or on the flanks of volcanic edifices; Drapes filling basinal depressions	Late Quaternary marine and coastal deposits
5c	Acoustically-transparent seismic facies	Wedge-shaped unit occurring offshore the city Naples	Volcanic and volcanoclastic deposits of the Neapolitan Yellow Tuff , erupted from the Phlegrean Fields about 18 ky
5b	Acoustically-transparent seismic facies	Irregular units occurring in the western sector of the Bay offshore the Phlegrean Fields and the Ischia and Procida islands	Volcanic and volcanoclastic deposits erupted from the Ischia and Procida volcanic complexes, ranging from 55 to 18 ky Volcanic deposits of the Pentapalummo, Nisida and Miseno banks
5°	Acoustically-transparent seismic facies	Wedge-shaped unit occurring in the eastern sector the Bay of thinning seawards and overlying an inclined paleomorphology	Campanian Ignimbrite pyroclastic flow deposits erupted about 35 ky ago
4	Highly-continuous sigmoidal clinoforms	Progradational unit with well preserved offlap breaks thickening seawards; laterally grading to volcanic units 5a, 5b and 5c; deeply incised in correspondance to the Dohrn canyon; giving origin to relic morphologies at the center of the Bay	Middle-Late Pleistocene prograding wedge supplied by the Sarno River mouth and by the Sorrento Peninsula tectonic uplift
3	Highly-continuous sigmoidal to obliquous clinoforms onlapping the B unconformity	Wedge-shaped, transgressive unit developed in outer shelf and slope settings Occurrence of interstratified volcanic domes and necks	Pleistocene s.l. siliciclastic marine deposits occurring in the central part of the basin
2	Alternating intervals of highly continuous obliquous to parallel reflectors and acoustically-transparent intervals	NW-dipping progradational unit with eroded topsets and preserved clinoforms; probably occurrence of alternating sands and shales forming depositional cycles	Early/Middle Pleistocene prograding wedge localised offshore the Sorrento Peninsula and the Island of Capri, tectonically tilted and uplifted together with the underlying Meso-Cenozoic carbonates
1	Chaotic seismic facies	Acoustic basement underlying the basin filling; NW dipping monoclinalic structure	Meso-Cenozoic carbonates

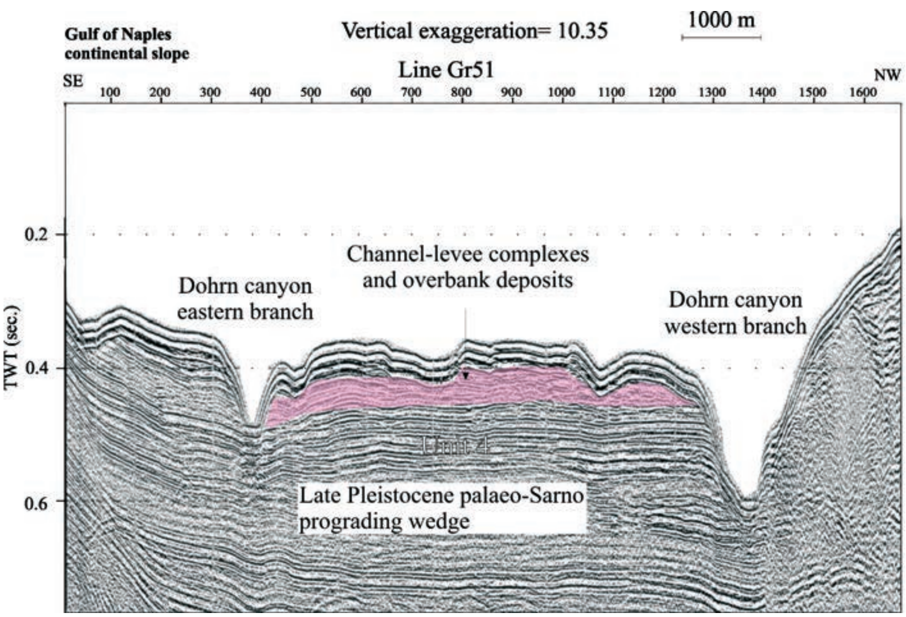

Fig. 9 - High resolution seismic reflection profiles showing the two branches of the Dohrn canyon. Vertical exaggeration 10:1. Note the occurrence of a distinctive seismic facie between the two branches interpreted as channel-levee complexes cropping out at the sea bottom.

magnetic anomaly map of the Bay (Siniscalchi *et al*., 2002; Aiello *et al*., 2004). This interpretation was supported by the maps of pole reduced, analytic signals and horizontal derivatives constructed by Secomandi *et al*. (2003), confirming the presence of the southern rim of the Phlegrean caldera in this area. Two of these banks (Pentapalummo and Miseno banks) are crossed by the GR51 seismic profile, represented in Fig. 11, also that shows detailed magnetic anomaly maps of the same area.

Two magnetic anomaly fields have been identified off the Gulf of Pozzuoli area (Fig. 12). The first anomaly, E-W oriented and located in the northernmost part of the area (1 in the inset D of Fig. 12) shows a minimum of –150 nT, associated to a maximum of + 185 nT (these values are referred to the zero-level calculated during the last part of the magnetic processing). The second anomaly, NW-SE oriented, located in the easternmost part of the area (2 in the inset D of Fig. 12) shows a maximum-minimum couple with a relative intensity similar to that of the previously discussed field. Besides these two magnetic anomaly fields, corresponding to magnetic bodies and/or volcanic edifices, other anomalies of lower intensity, ranging between 40 and 135 nT are due to the occurrence of small volcanic edifices (Fig. 12). A precise correlation between the submarine morphology of the Pentapalummo bank and the shape of related magnetic anomalies is not evident, since it is related to a complex magnetic anomaly field (PPB in the inset D of Fig. 12). On the other side, the magnetic anomaly field related to the Miseno Bank (MB in the magnetic map of Fig. 12) shows a NW-SE trending composed of a maximum of + 175 nT and a minimum of about – 50 nT. Secomandi *et al*. (2003) also pointed out that the Pentapalummo bank is related to a complex series of magnetic signatures along a WNW-ESE trending.

No magnetic anomaly field is related to the submarine volcanic bank Gaia (GB in Fig. 3), located

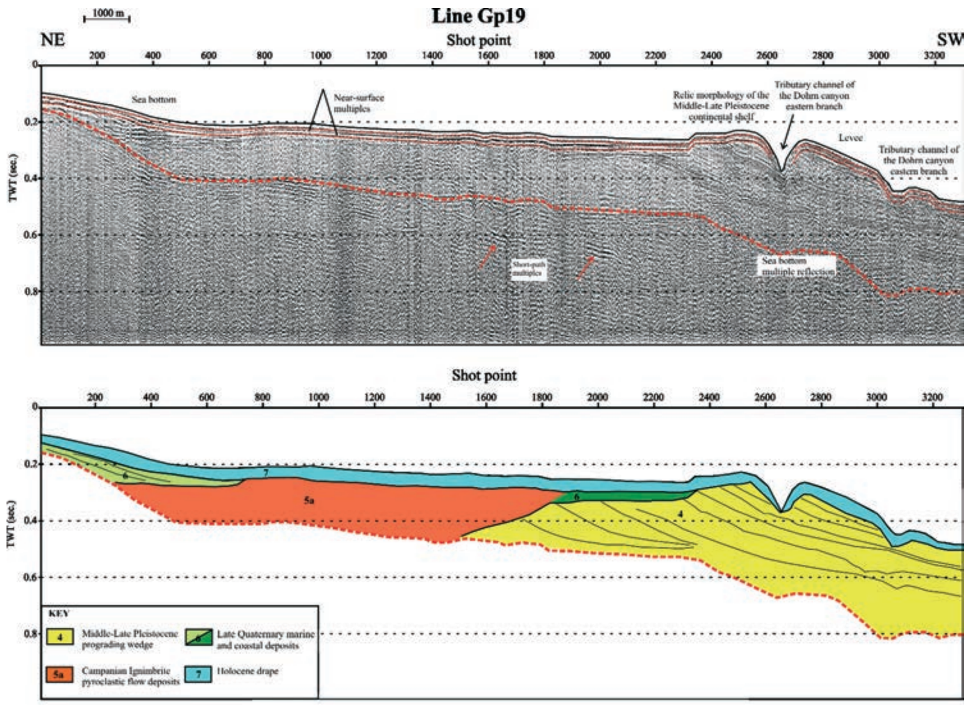

Fig. 10 - High-resolution seismic reflection profile from offshore Somma-Vesuvius volcanic complex towards the centre of the bay. Note the occurrence of a seismic unit, widely occurring in the eastern submerged part of the Bay of Naples, interpreted as the Campanian Ignimbrite pyroclastic flow deposits (unit 5a in Table 1), underlying a Middle-Late Pleistocene prograding wedge (unit 4 in Table 1).

next to the shelf break between the two canyons (Fig. 13; see also Fig. 3). Another main magnetic anomaly field is related to three small volcanic banks located near to the – 140 m isobath and to the east of the Gaia bank (GB in Fig. 3). Seismic evidence shows a well defined body which, thanks to the correlation with magnetic data, can be interpreted as magnetic (Fig. 13); it is related to a magnetic maximum of +145 nT and so it can be recognised as a buried volcanic edifice, located at the centre of the slope between the two canyons (Siniscalchi *et al*., 2002; Secomandi *et al*., 2003; Aiello *et al*., 2004).

Significant magnetic anomaly fields are also related to the Magnaghi canyon's head and axis, confirming that it incised a sector of the slope composed only of highly magnetized volcanic deposits (Fig. 14). A magnetic maximum of about 200 nT is observed next to the canyon's head with an E-W enlarged shape while, along the axis, a cleary NNE-SSW trend dipolar shape is visible with values variable between -60 and +210 nT (Fig. 14); in this case, the relationships between the morphology of the canyon, detected through bathymetry (Fig. 3) and the shape of the magnetic anomaly field are not of immediate comprehension. The Magnaghi canyon was already singled out by Secomandi *et al*. (2003) as a site where a series of magnetic structures occur; in particular, two anomalies occur between the branches of Magnaghi trilobate head, another anomaly corresponds to a depression and a latter one to a small relief, located on the canyon's axis. The authors also performed an inversion of two of these anomalies in order to construct a three-dimensional magnetization model of the

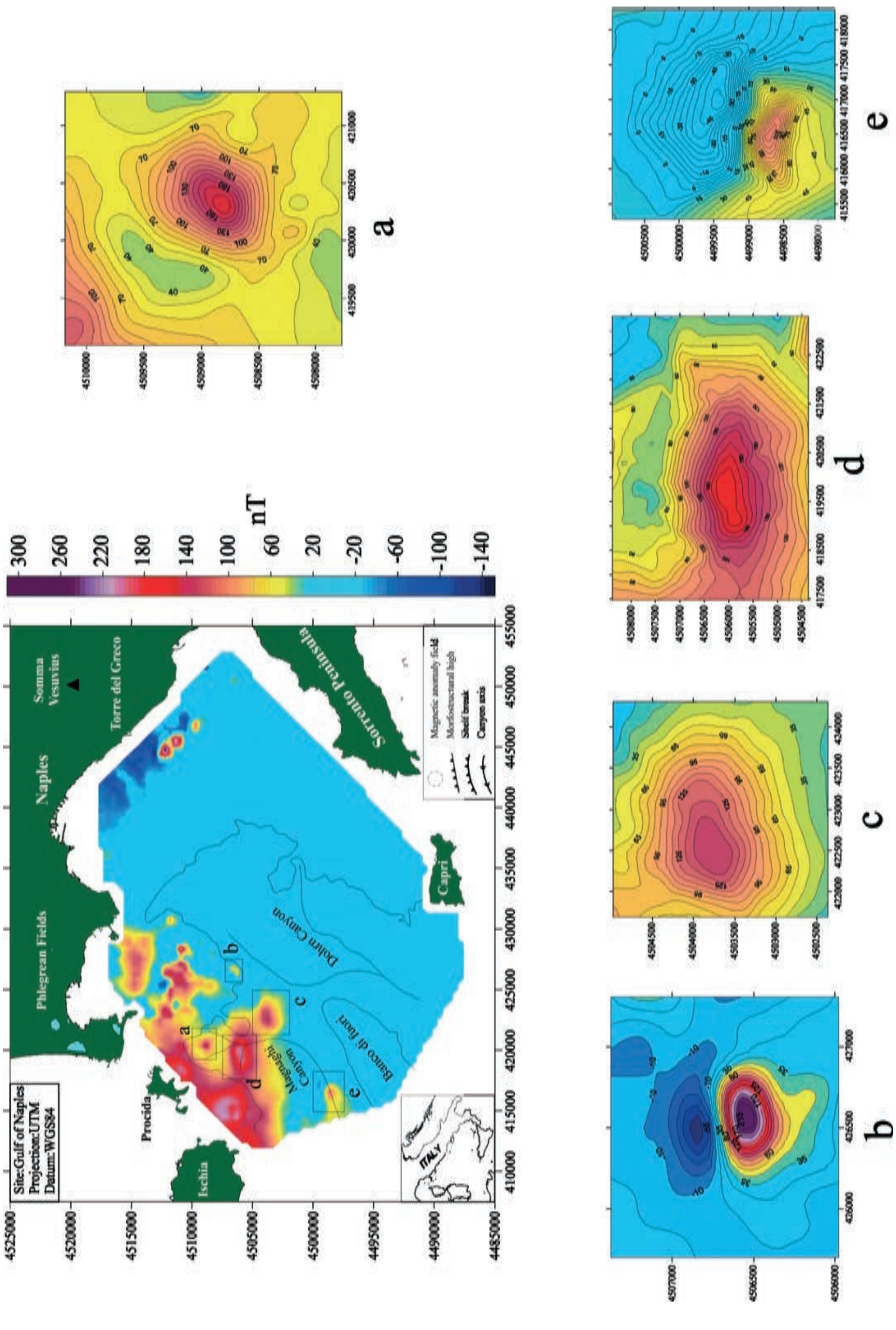

Fig. 11 - Magnetic anomaly fields in the Bay of Naples [reported from Siniscalchi *et al.* (2002) and Aiello *et al.* (2004)]; detailed magnetic maps of main morphological lineaments of the Bay of Naples continental slope are also shown. Key: a: magnetic anomaly field related to the Magnaghi canyon's head (contour interval: 10 nT); b: magnetic anomaly field related to three small volcanic banks located near the shelf break (contour interval: 10 nT); c: magnetic anomaly field related to a volcanic edifice located between the Dohrn and the Magnaghi canyons (contour interval: 10 nT); d: magnetic anomaly field related to the Magnaghi canyon's head (contour interval: 10 nT); e: magnetic anomaly field related to the Magnaghi canyon's axis (contour interval: 5 nT).

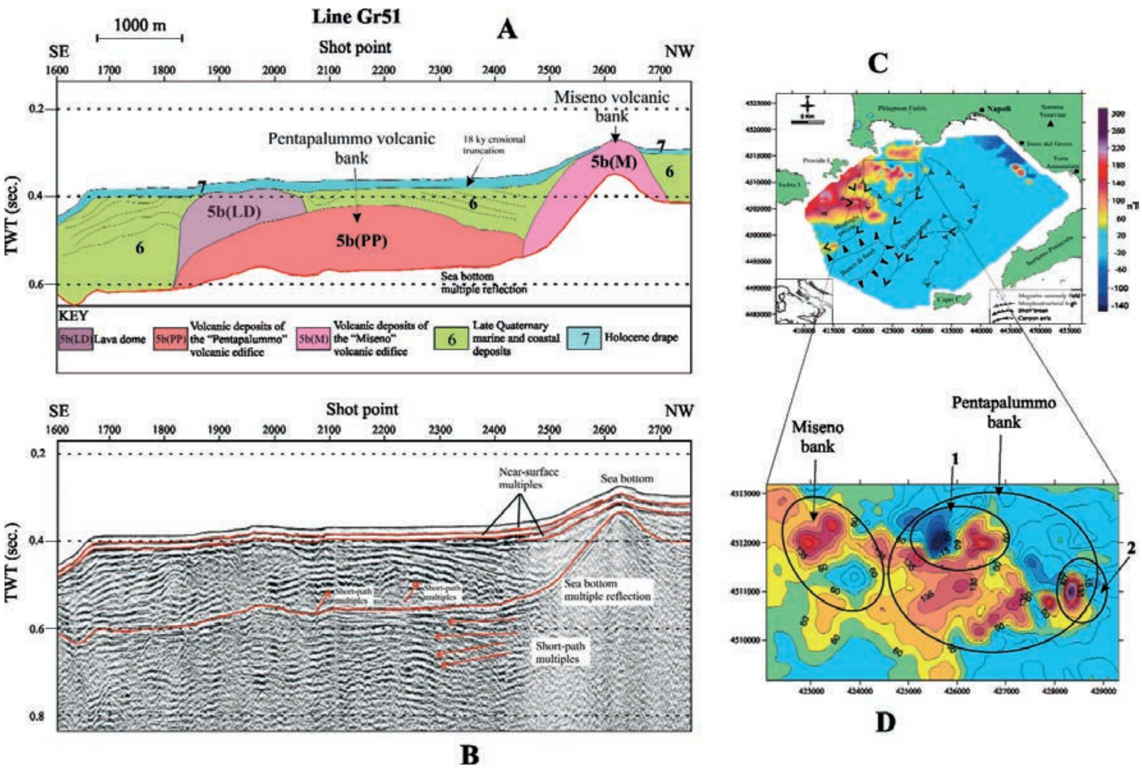

Fig. 12 - High-resolution seismic reflection profile offshore the Phlegrean Fields volcanic complex and crossing the submerged border of the Phlegrean caldera (see Fig. 1 for location). Corresponding geological interpretation and magnetic anomaly field are also reported (see the text for further discussion).

anomalies, giving also indications on the shape and the geometry of the magnetic source body.

6. Conclusions

Integrated high-resolution magnetic and seismic data interpretation can be inferred by Multibeam bathymetric maps, whose geological interpretation can represent a useful tool to assess the relationships between sea bottom topography, geological structures and magnetic anomaly fields. This kind of integrated interpretation was attempted in our paper, in which high resolution magnetic, seismic and bathymetric data collected in the Bay of Naples have been interpreted and correlated to furnish some new geological evidence on continental slope settings.

The Bay of Naples continental slope was involved in extensive erosion and mass wasting processes controlled by Late Quaternary multi-phase eruptive activities of the Phlegrean Fields and the Ischia and Procida Island volcanic complexes that lasted from 55 ky B.P. (Rosi and Sbrana, 1987; Vezzoli, 1988).

Large volcanoclastic supplies coming from adjacent onshore areas controlled the formation of the Dohrn and Magnaghi canyons, that drained large amounts of sediment during the Late Quaternary.

Morpho-bathymetric evidence seems to indicate that, while the Dohrn western branch is

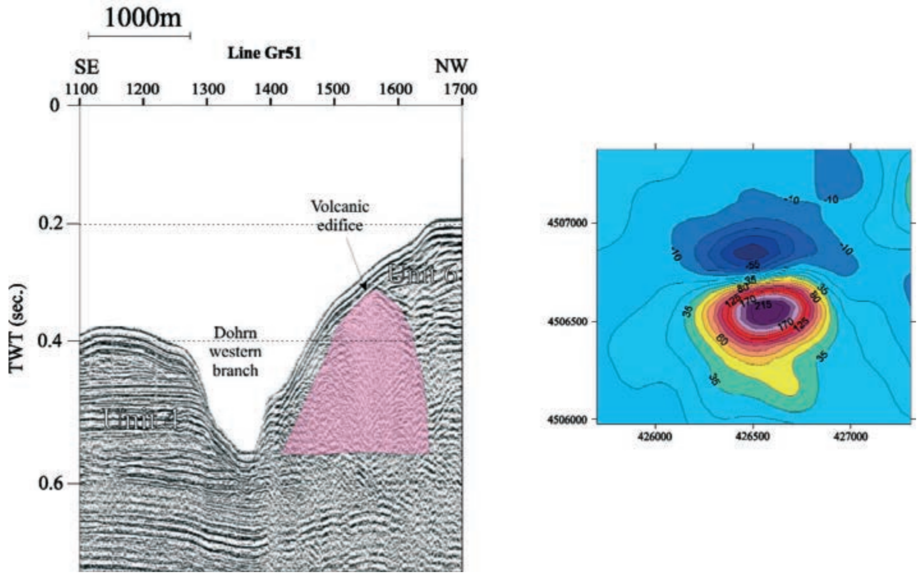

Fig. 13 - Geologic interpretation of the magnetic anomaly field named as B in Fig. 8 (contour interval: 10 nT) and tentative correlation with corresponding seismic reflection profiles (vertical exaggeration 7.3:1). Note that the N-S trending dipolar anomaly field corresponds to outcrops of volcanic acoustic basement located near the shelf break.

genetically linked to the eruptive activity of the Phlegrean Fields volcanic complex, the Dohrn eastern branch drained sedimentary inputs induced from the Sorrento Peninsula tectonic uplift and coming from the Sarno River mouth.

The Dohrn western branch merges into the outer shelf to the Ammontatura channel, a deep and flat incised valley, whose activity is related to the emplacement and activity of the Nisida Bank (Figs. 2, 3 and 4), located near to the submerged border of the Phlegrean caldera (Aiello *et al*., 2004).

The Dohrn eastern branch is laterally fed by several tributary channels draining the inputs coming from the Sorrento Peninsula and Sarno River mouth; some of them seem to be tectonically-controlled based on Side Scan Sonar surveys (Chiocci *et al*., 1998a) and are located in correspondence to a high of Mesozoic carbonatic acoustic basement bounding the canyon west word (Capri structural high; Figs. 4 and 5).

Extensive mass wasting involved the western flank of the Dohrn western branch, as put in evidence by large slide scars; submarine instability processes are also detected in the surroundings of the canyon slopes and retreating heads (Fig. 4) as incipient gravity slides and local mass wasting of the slope areas.

Several phases of alternating erosional and depositional processes are suggested by terrace development mainly in correspondence to the Dohrn western branch, more incised and broader than the eastern one (Figs. 4, 5 and 6). Recent retrogressive failures are associated with the retreating of the Dohrn canyon's head showing a double head characterized by very similar shape in plan view (Figs. 4, 5 and 6); failure of shelf sediments next to the canyon's head initiates coarse-grained turbidity currents, which become an important agent in canyon erosion by downcutting the canyon and creating a sinuous thalweg (Twichell and Roberts, 1982; Farre *et al*., 1983; Pratson and Coakley,

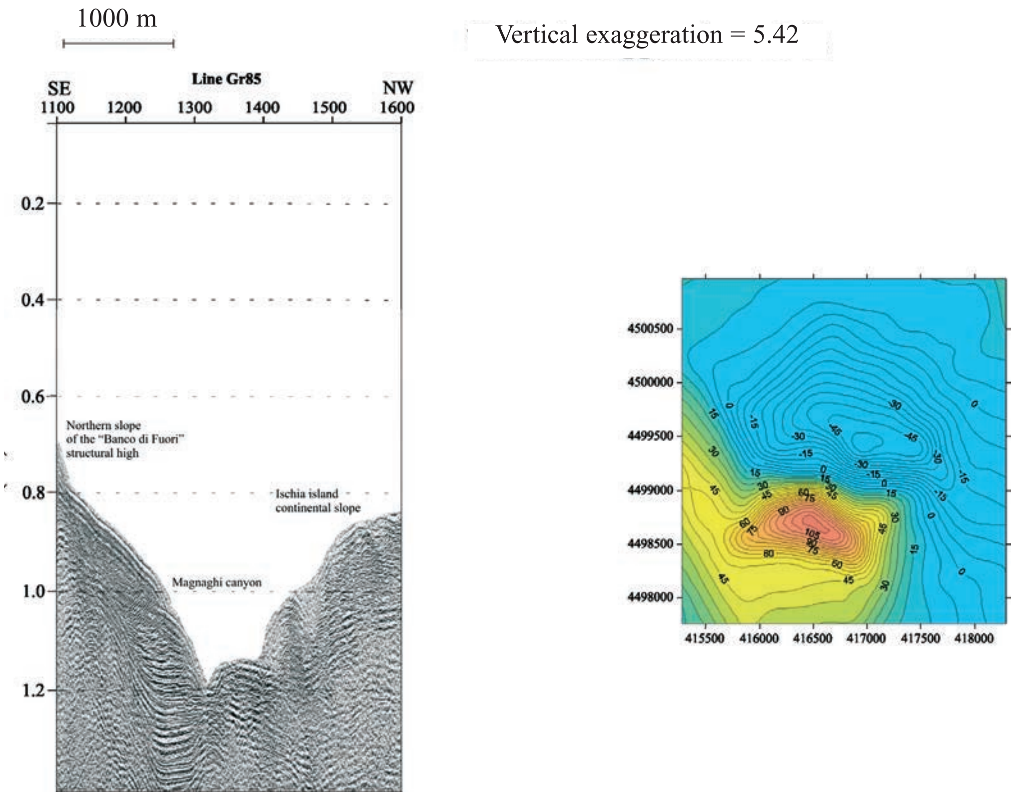

Fig. 14 - Geological interpretation of the magnetic anomaly field in the Magnaghi canyon's axis and tentative correlation with seismic reflection profiles (vertical exaggeration 5.42:1). A NE-SW trending dipolar shaped anomaly occurs in correspondence to the canyon's axis.

1986).

Channel-levee complexes related to the activity of tributary channels are revealed by seismic stratigraphy as cropping out at the sea bottom in the slope at the center between the two canyons, as a result of distal turbidite deposition induced by repeated sediment flows (Fig. 9).

The Magnaghi canyon is characterised by a trilobate head composed of three main tributary channels joining basinwards into a main axis; it incised the slope southwards of Procida Island draining large volcanoclastic inputs coming from Ischia and Procida Islands.

Submerged volcanic edifices and /or banks are revealed in the surroundings of the Dohrn and Magnaghi canyons by Multibeam bathymetry; the volcanic nature of some of these structures is supported by well-developed magnetic anomaly fields; some of them show a strong correspondence between the shape of the magnetic anomaly fields and the morphology of the magnetic anomaly (Fig. 12).

Main magnetic signatures are related both to relic volcanic banks or buried edifices located near the shelf break and the Dohrn and Magnaghi canyons (Fig. 12).

In the case of isolated volcanic banks, a good match between the shape of the magnetic anomalies and the morphology of related lineaments has been observed, based on the integrated geological interpretation of data (Figs. 11, 13 and 14).

The relationships between bathymetry and magnetics appear to be more complex in the case of the Magnaghi canyons, showing strong and well developed fields both in correspondence to the head and the axis; such features suggest the occurrence of highly magnetized, volcanic deposits all along the canyon (Fig. 14).

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