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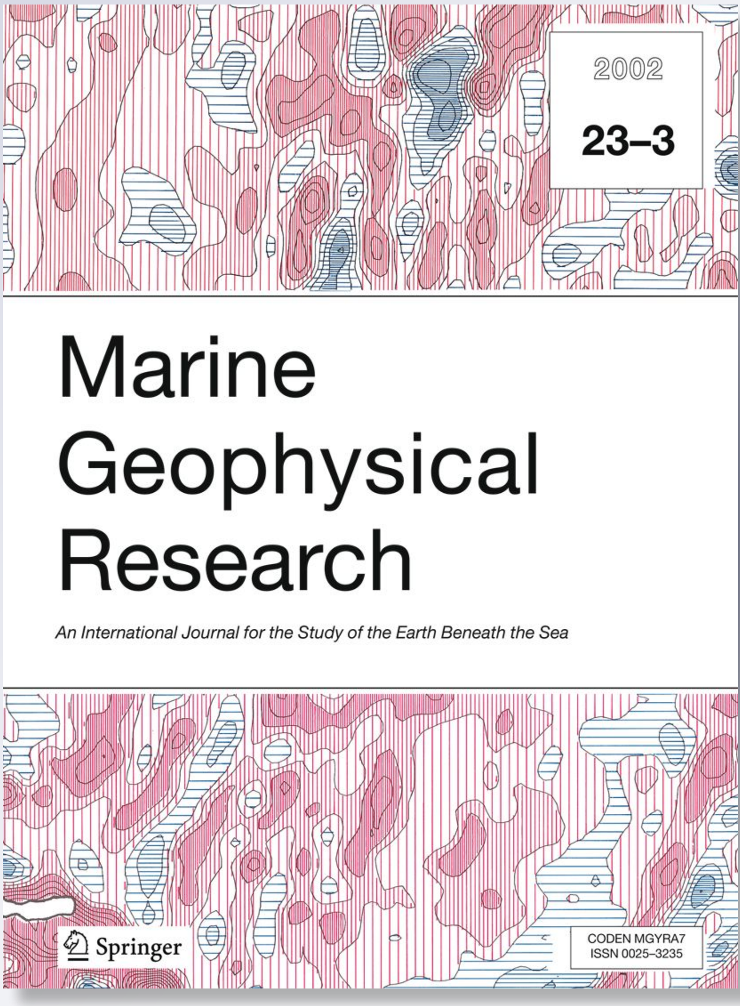

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ORIGINAL RESEARCH PAPER

New seismo-stratigraphic and marine magnetic data of the Gulf of Pozzuoli (Naples Bay, Tyrrhenian Sea, Italy): inferences for the tectonic and magmatic events of the Phlegrean Fields volcanic complex (Campania)

Gemma Aiello · Ennio Marsella · Vincenzo Di Fiore

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Abstract A detailed reconstruction of the stratigraphic and tectonic setting of the Gulf of Pozzuoli (Naples Bay) is provided on the basis of newly acquired single channel seismic profiles coupled with already recorded marine magnetics gathering the volcanic nature of some seismic units. Inferences for the tectonic and magmatic setting of the Phlegrean Fields volcanic complex, a volcanic district surrounding the western part of the Gulf of Naples, where volcanism has been active since at least 50 ka, are also discussed. The Gulf of Pozzuoli represents the submerged border of the Phlegrean caldera, resulting from the volcano-tectonic collapse induced from the pyroclastic flow deposits of the Campanian Ignimbrite (35 ka). Several morpho-depositional units have been identified, i.e., the inner continental shelf, the central basin, the submerged volcanic banks and the outer continental shelf. The stratigraphic relationships between the Quaternary volcanic units related to the offshore caldera border and the overlying deposits of the Late Quaternary depositional sequence in the Gulf of Pozzuoli have been highlighted. Fourteen main seismic units, both volcanic and sedimentary, tectonically controlled due to contemporaneous folding and normal faulting have been revealed by geological interpretation. Volcanic dykes, characterized by acoustically transparent sub-vertical bodies, locally bounded by normal faults, testify to the magma uprising in correspondence with extensional structures. A large field of tuff cones interlayered with marine deposits off the island of Nisida, on the western rim of the gulf, is related to the emplacement of the Neapolitan Yellow Tuff deposits. A thick volcanic unit, exposed over a large area off the Capo Miseno volcanic edifice is connected with the Bacoli-Isola Pennata-Capo Miseno yellow tuffs, cropping out in the northern Phlegrean Fields.

Keywords Gulf of Pozzuoli · Seismic stratigraphy · Marine magnetics · Phlegrean fields · Volcanology

G. Aiello (✉) · E. Marsella · V. D. Fiore
Institute of Marine, Environment and Coastal Area (IAMC), National Research Council (CNR), Calata Porta di Massa, Porto di Napoli, 80133 Naples, Italy
e-mail: gemma.aiello@iamc.cnr.it

Introduction

The aim of this paper is to provide new seismo-stratigraphic evidence from the Gulf of Pozzuoli, Italy, on the basis of the geological interpretation of recently collected Sparker profiles in order to deliver an up-to-date geological setting of the area during the Late Quaternary through seismo-stratigraphic concepts. In this way, the geological knowledge on the active volcanic area of the Phlegrean Fields (Naples Bay) and the adjacent offshore sectors (Gulf of Pozzuoli) will be improved through a new stratigraphic setting. The stratigraphy of the study area is relatively unknown through recent geological and geophysical studies and the volcanological implications of this stratigraphy have not been yet shown in detail. The seismo-stratigraphic setting herein discussed based on recently collected high resolution seismic reflection data will contribute to a better delineation of the offshore stratigraphic units. Furthermore, the tectonic setting of the area will be examined based on geological interpretation of seismic sections through the identification of tectonic styles involving the seismic sequences.

The stratigraphy and geology of active volcanic areas is an intriguing research theme, particularly applied to the case history of the Gulf of Pozzuoli (Naples Bay)

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representing the submerged border of the Phlegrean caldera. The state-of-the-art methodological aspects for mapping volcanic areas, applied also to case histories of Naples Bay, have been recently delineated, highlighting recent studies on the stratigraphy, structure and evolution of active volcanic terranes (Groppelli and Goette 2010).

New stratigraphic and volcanological studies, mainly onshore, dealing with the definition of volcanological units during the field survey and specific volcanological features, petrographic, geochemical and petrological studies and geophysical models have been recently presented (Lucchi et al. 2010; Tibaldi 2010; Bonomo and Ricci 2010; Palladino et al. 2010; Milia 2010; Perrotta et al. 2010; De Vita et al. 2010). These studies allowed us to delineate the problems related to stratigraphy and volcanology of active volcanic districts of southern Italy, referring in particular to Naples Bay.

Another aim of this paper is to produce a qualitative correlation of the seismo-stratigraphic data with marine magnetics already recorded both in the Gulf of Pozzuoli (Galdi et al. 1988) and in the Phlegrean Fields offshore (Secomandi et al. 2003; Aiello et al. 2004) better constraining the volcanic nature of some seismic units recognized through seismic stratigraphy. Significant interest will be focused on the interpretation of high-resolution multichannel seismic profiles coupled to maps of total magnetic field in order to contribute to the understanding of volcanic structures in the Gulf of Pozzuoli and the reconstruction of the Late Quaternary geological setting of the investigated area.

A correlation with the terrestrial geology of the Phlegrean Fields has been attempted in order to highlight tectonic and magmatic implications in the geological evolution of the Phlegrean Fields volcanic complex, intensively studied through field geology (Morhange et al. 2005; Bellucci et al. 2006; De Natale et al. 2007; Bodnar et al. 2007).

The Gulf of Pozzuoli, offshore of the Phlegrean Fields volcanic complex (Naples Bay, southern Tyrrhenian Sea) is an inlet with limited dimensions, bounded seawards by several submerged volcanic banks (Pentapalummo Bank, Nisida Bank, Miseno Bank; Fig. 1).

The morphological sketch map of the Pozzuoli Bay shows several offshore morphological units, including the inner continental shelf, the central basin, the submerged volcanic banks and the outer continental shelf (Fig. 2). The inner shelf is positioned in the northern sector of the gulf, whose shelf break occurs at about 50 m water depth. It grades through a weakly inclined slope to a central basin, developed at about 100 m water depth. The basin is bounded seawards by a belt of submarine volcanic highs. Proceeding seawards, the outer continental shelf has an average gradient of 1 % and reaching at the shelf-slope break a water depth of 140–160 m (Fig. 2).

The Phlegrean Fields is an active volcanic center near Naples, Italy (Fig. 3). Numerous eruptions have occurred here during the Quaternary (Fig. 3) and repeated episodes of slow vertical ground movement (bradyseism) have been documented since Roman times. Vertical ground movements have been observed since the nineteenth century, when the sea-level marks left on the ruins of a Roman

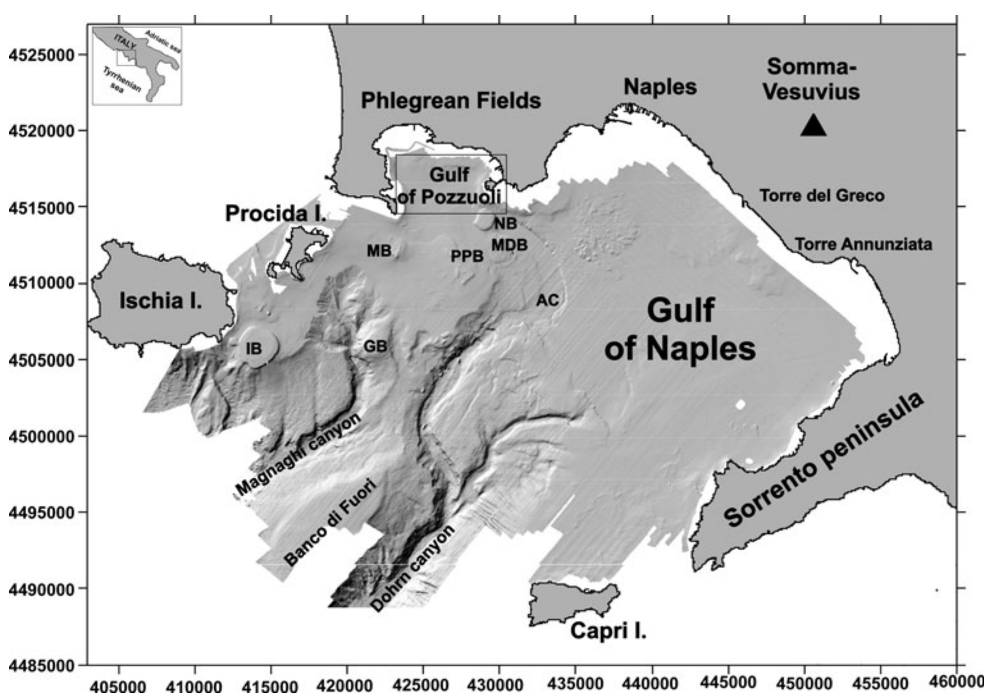

Fig. 1 *Shaded* relief map of the Multibeam bathymetry (ELAC, BottomChart MK2) recorded in the Bay of Naples. *AC* Ammontatura Channel, *MDB* Monte Dolce Bank, *NB* Nisida Bank, *PPB* Pentapalummo Bank, *MB* Miseno Bank, *GB* Gaia Bank, *IB* Ischia Bank

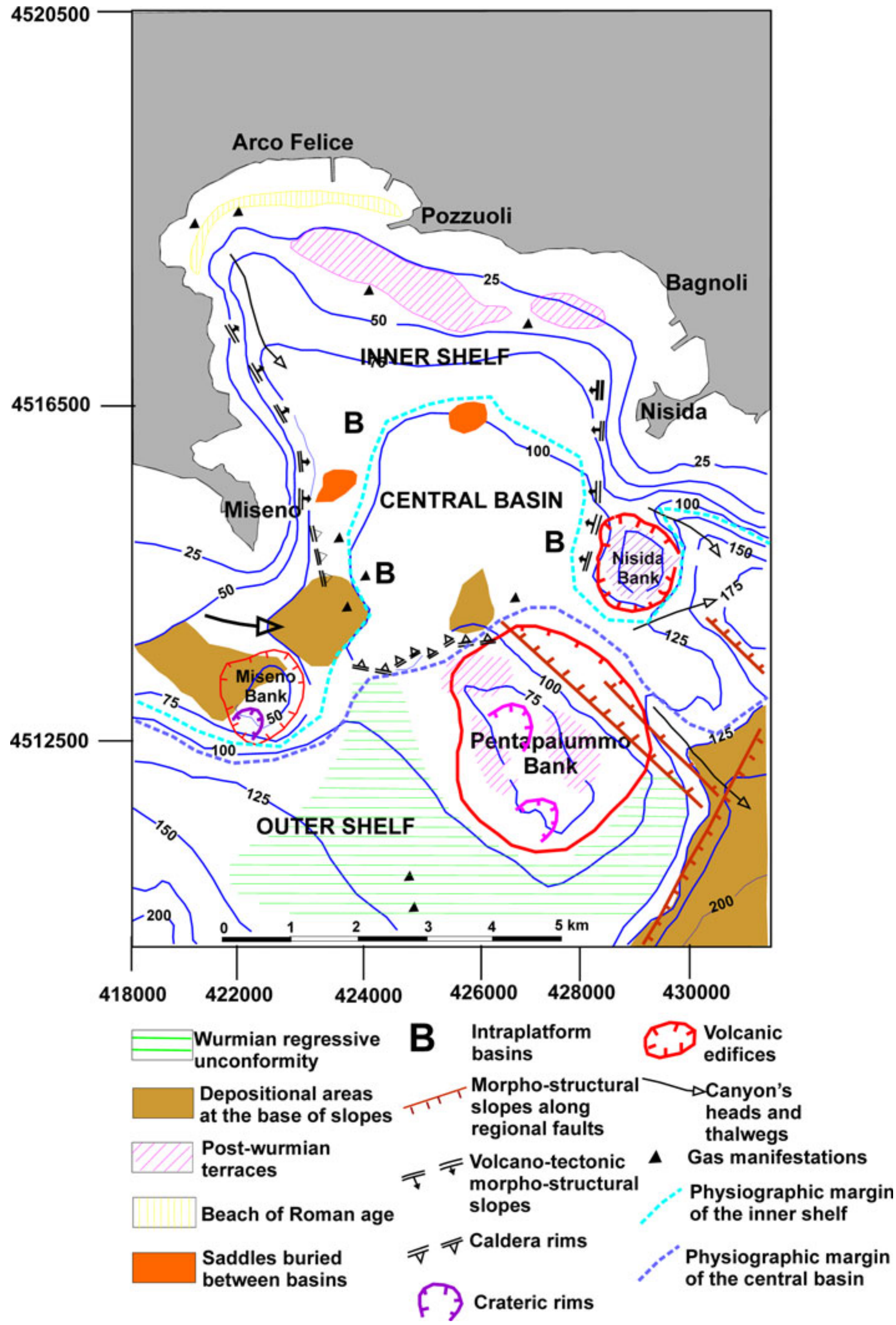

Fig. 2 Sketch morphological map of the Pozzuoli Bay (modified after De Pippo et al. 1984)

market ("Serapeo") in the Pozzuoli town indicate a gradual subsidence of the area (Dvorak and Mastrolorenzo 1991; Morhange et al. 2005).

Detailed ground levelling carried out in the area showed that the maximum subsidence happened in the town of Pozzuoli, regularly decreasing alongshore toward the east and west (Berrino et al. 1984). The downward movement of the ground continued up to 1968, when it started to reverse.

Two main episodes of soil rising (relative to the earth's surface) involving the Pozzuoli area during the periods 1970–1972 and 1982–1984 have accounted for uplift, calculated with respect to the previous levelling, respectively of 170 and 182 cm at the point of maximum deformation (Berrino et al. 1984). The geometrical shape of the uplift resulted opposite with respect to that one of the falling observed since the 1968, with a maximum centered on the town of Pozzuoli and a regular decrease of the deformation

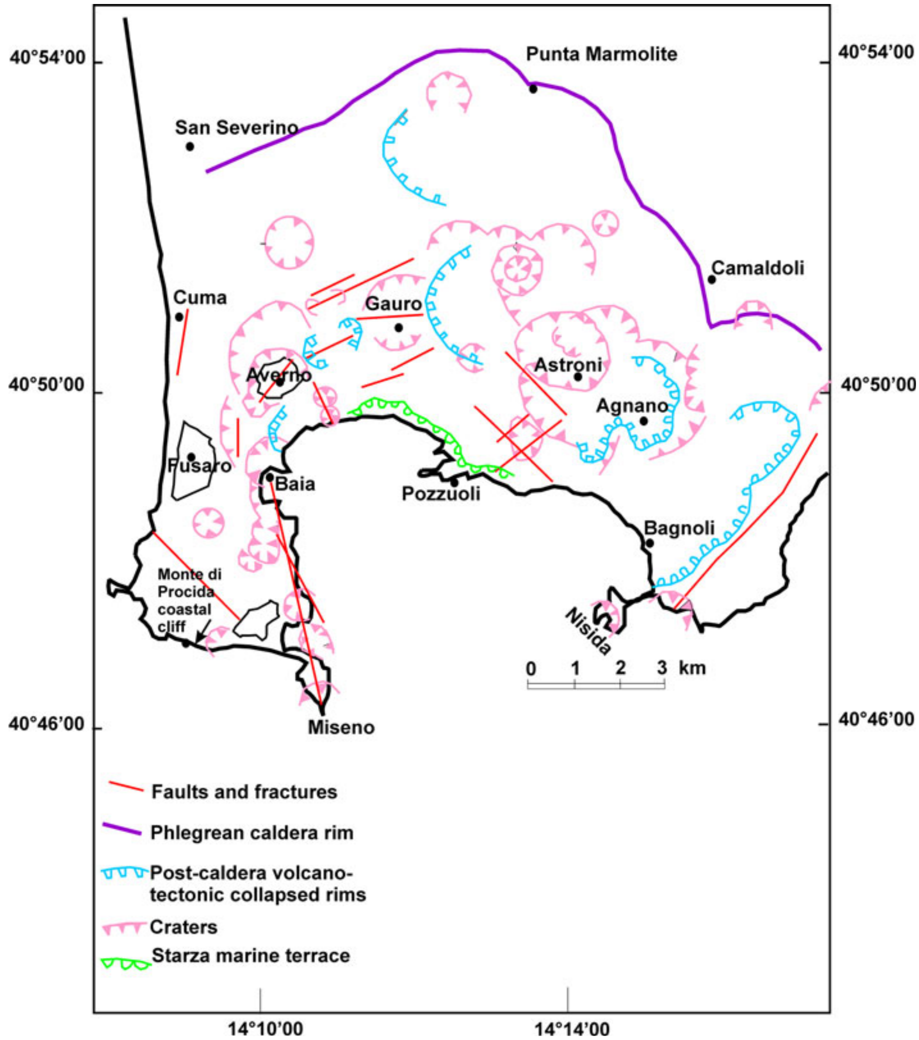

Fig. 3 Volcano-tectonic sketch map of the Phlegrean Fields volcanic complex (modified after Rosi and Sbrana 1987)

toward the caldera rims. The downward movement should be connected with the normal compaction of the pyroclastic products filling the caldera depression (Berrino et al. 1984) or alternatively with the draining of the underlying magma chamber.

Recent vertical crustal movements of the Phlegrean Fields caldera based on ancient coastal ruins have been reconstructed (Dvorak and Mastrolorenzo 1991; Morhange et al. 2005). Geologic history of rapid sea level movements and deformation in the Phlegrean Fields is recorded at the Serapis Roman marketplace, where it is inferred by several documents (Dvorak and Mastrolorenzo 1991; Morhange et al. 2005). Three marble columns at Serapis showed evidence of once being submerged at least 7 m, then uplifted at a similar amount. Based on the elevation of other coastal ruins near Serapis, Dvorak and Mastrolorenzo (1991) estimated that the maximum amount of subsidence at Serapis has been 12–17 m. Two periods of uplift have been reconstructed, the first one a few decades before the 1538 eruption in the Phlegrean Fields and the other one in two distinct episodes, the first one from 1969 to 1972 and the second one from 1982 to 1984. Later, radiocarbon-dated biological indicators on the pillars of the Roman market have shown three 7 m relative sea level highstands, respectively during the fifth century, the early Middle Ages, and before the 1538 eruption of Monte Nuovo (Morhange et al. 2005). These repeated uplift and subsidence cycles, not always followed by volcanic activity, have important implications for the evaluation of the volcanic hazard (Morhange et al. 2005).

During the spring of 1983, several months after the beginning of the phase of uplift, a seismic crisis started (Del Pezzo et al. 1987). The earthquakes happened mostly in the coastal region surrounding Pozzuoli. Some deep earthquakes occurred in Naples Bay, while no event was localized under the Phlegrean Fields. The hypocenters were localized at depths varying from hundred of meters to as deep as 5 km. The maximum recorded magnitude was 4 (Richter scale) and the higher-energy events occurred in correspondence with the normal faults bordering the margins of the Phlegrean caldera (Del Pezzo et al. 1987; Florio et al. 1999; Rapolla et al. 2002).

Different models have been proposed to explain the ground deformation in the Phlegrean Fields volcanic complex. A purely mechanical model has attributed the episodes of uplift to the intrusion of magma at shallow depths (Corrado et al. 1976; Berrino et al. 1984; Bonafede et al. 1986; Bianchi et al. 1987). An alternative model has considered the uplift to be a result of warming and pore expansion of the water (Oliveri Del Castillo and Quagliariello 1969; Casertano et al. 1976). Other models have suggested that the uplift mainly derives from fluid-dynamic processes in a geothermal system located at shallow depths (Bonafede 1990; De Natale et al. 1991). Ground deformation and seismicity are related with the occurrence of a strong hydrothermal activity, concentrated at the Solfatara vent, where the CO_2 and H_2O fluxes are intense, probably representing a magmatic degassing (Chiodini et al. 2001; Caliro et al. 2007).

Alternative models have been proposed (De Vivo and Lima 2006; De Vivo et al. 2007; Bodnar et al. 2007), explaining the bradyseism according to a new hydrothermal model, based on the analogy between the mineralized systems of "porphyry" type (Burnham 1979; Fournier 1999) and the geothermal system of Phlegrean Fields. The fluid inclusions entrapped in the crystals of the Phlegrean rocks show the occurrence of different mineral phases, which cannot be mixed, during the magmatic evolution of the volcanic complex. The fluids derived from a deep magma in mixing underwent a strong lithostatic pressure for a long-lasting geologic time interval. Consequently, they produced an overpressure confined by an impermeable layer, which caused an uplift of the overlying rocks (positive bradyseism). After the maximum uplift, coincident with seismicity, a pressure release apparently occurred, starting the subsidence phase (negative bradyseism).

Data and methods

A grid of Sparker Multitip seismic profiles recorded in the Gulf of Pozzuoli in the frame of research projects of submarine geologic cartography has been interpreted to give new insights on seismic stratigraphy of Pozzuoli, i.e., the submarine elongation of the Phlegrean Fields volcanic complex. It consists of seven seismic sections; four of them have a ESE-WNW trend and cover the whole bay (L71_07, L70_07, L69_07 and L68_07). Two perpendicular sections, N–S trending (L73_07 and L74_07) have provided significant cross-points for seismic interpretation. The navigation map of the interpreted sections in the Gulf of Pozzuoli is shown in Fig. 4.

The survey was conducted using a multielectrode sparker system (SAM96 model). The advantages of the Multitip Sparker include shorter pulse lengths for an equivalent energy discharge, as well as an increase in peak pressure,

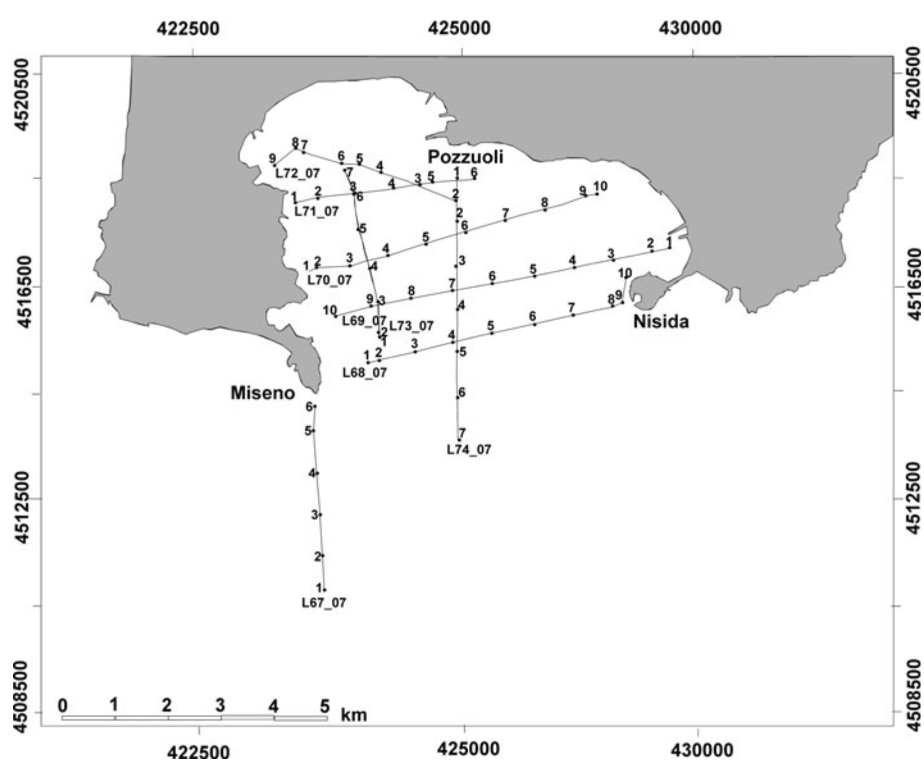

Fig. 4 Navigation map of the Sparker seismic profiles in the Pozzuoli Bay. Note the occurrence of five tie seismic sections (L72_7, L71_7, L70_7, L69_7, L68_7) and of three dip seismic sections (L68_7, L67_7, L74_7)

i.e., the amplitude of the outgoing acoustic wave. The sparker source used in this survey generated 200 J in the 200–2,000 Hz frequency range.

Ship positioning was determined using a GPS system with a positioning accuracy of 1 m. All seismic sections were recorded graphically on continuous paper sheets with a vertical recording scale of 0.25 s. The best vertical resolution was approximately 1 m for the sparker data.

This seismic grid covering Pozzuoli Bay facilitated stratigraphic correlations between seismic sections and revealed detailed structural and stratigraphic variations along the seismic lines.

Sparker seismic sources can generate seismic energy to investigate the continental margins when there are near surface or deep-towed (10–50 m beneath the sea surface). Sparker systems can produce low-frequency acoustic wave (the maximum frequency contained in the spectrum of acoustic signal is approximately 2,000 Hz) that can penetrate several hundred meters of sediment.

In particular, the SAM 96 Sparker source is characterized by a varying number of electrodes that can be disposed as "dual-in line" (SAM96) and "planar array" multi electrode electro- acoustic source (SAM 400/800; Corradi et al. 2009). Recently, by means of Multi-tip SAM 96 (0.1–1 kJ), SAM400 (1–4 kJ) transducer it was possible to record high resolution seismic data in the Bay of Naples both in coastal and deep sea research (Corradi et al. 2009).

Other Multitip Sparker systems have been developed and their potentiality to make high resolution seismic profiling in deep waters has been discussed (Rutgers and de Jong 2003). The characteristics of the Multitip sparker sources have been measured in laboratory using different arrangements of the capacitive energy storage and salinity of water.

The applied stratigraphic subdivision derives from the type of data utilized in marine geology (reflection seismics) and by the methods of seismic interpretation (high resolution sequence stratigraphy). The geological structures recognized through seismic interpretation are acoustically transparent volcanic units, representing the rocky acoustic basement and the systems tracts of the Late Quaternary depositional sequence (Fabbri et al. 2002). The seismo-stratigraphic analysis has allowed us to characterize depositional systems, respectively reflecting sea-level fall (Falling Sea Level System Tract; Helland Hansen and Gjelberg 1994), sea-level lowstand (Lowstand System Tract) and related internal subdivisions (Posamentier et al. 1991), transgressive phase (Transgressive System Tract; Posamentier and Allen 1993; Trincardi et al. 1994) and the highstand phase of sea level (Highstand System Tract; Posamentier and Vail 1988).

Significant correlations between geophysical data come from the comparative analysis of seismic and magnetometric datasets. A magnetometer usually measures the strength or direction of the Earth's magnetic field. This last can vary both temporally and spatially for various reasons, including discontinuities between rocks and interaction among charged particles from the Sun and the magnetosphere. The proton precession magnetometer was largely used to explore magnetic anomalies in the Bay of Naples. Interesting examples of magnetic data acquisition related in the Bays of Pozzuoli and Naples are reported by Galdi et al. (1988) and Aiello et al. (2004). For a detailed analysis of the magnetic anomaly field of the volcanic district of the bay of Naples, see Secomandi et al. (2003).

Magnetic survey of the Gulf of Pozzuoli has been recorded using an acquisition system allowing for the contemporaneous acquisition of magnetic (proton magnetometer) and positioning (differential GPS) data hosted on a little boat (Galdi et al. 1988). During this period 994 positions of Earth Magnetic Field (EMF) have been collected in the Pozzuoli Bay (Fig. 5). The survey has been realized through a proton magnetometer, G-856 model (Geometrics Inc.), having a precision of reading of 0.1 nT and an accuracy of 0.5 nT. The positioning of measurements was ensured by a short range differential system GPS-Motorola III. The measurements have been collected along N–S oriented tracks, having an average distance ranging between 200 and 300 m.

During the days of magnetic acquisition the check of the magnetic data furnished both by the Capri station and by the L'Aquila Geomagnetic Observatory (Masci et al. 2008) has evidenced the absence of significant short-period magnetic perturbations. The data have not been corrected for the diurnal correction of the Earth Magnetic Field intensity, since the measurements have been collected in a few hours, during which the Earth Magnetic Field variations, evidenced by the base station of Capri island, were insignificant.

Magnetic data offshore of the Phlegrean Field volcanic complex have been recorded using a G811 Proton Magnetometer (Aiello et al. 2004, 2005). The sensor was placed in a towed fish generally at 200 m from the ship and 15 m below the sea surface; the depth of the magnetometer was regularly controlled and recorded. The cruising speed did not exceed 6 knots. The data were sampled at 3 s, which corresponds to an average spatial sampling rate of about 6.25 m. Accurate magnetic data processing was performed to preserve data information contents. For further details on the magnetic data processing see Siniscalchi et al. (2002) and Aiello et al. (2004).

Geo-volcanologic setting

The Phlegrean Fields are a volcanic district surrounding the western part of the Gulf of Naples, where volcanism has been active since at least 50 ka. They correspond to a resurgent caldera (Rosi and Sbrana 1987; Di Vito et al. 1999; Nunziata et al. 1999; Orsi et al. 2002, 2009; D'Argenio et al. 2004; Deino et al. 2004; Milia and Torrente 2007; Blockley et al. 2008) with a diameter of 12 km (Phlegrean caldera) resulting from the volcano-tectonic collapse induced from the eruption of pyroclastic flow deposits of the Campanian Ignimbrite (35 ka). Coastal sediments ranging in age from 10 to 5.3 ka crop out 50 m above sea level in the marine terrace of La Starza (Gulf of Pozzuoli), indicating a volcano-tectonic uplift of the caldera center (Dvorak and Mastrolorenzo 1991; Morhange et al. 2005).

Monogenic volcanic edifices representing the offshore rim of the caldera center (Pentapalummo Bank, Miseno Bank, Nisida Bank; Fig. 1) are well known from a geological and volcanological point of view (Aiello et al. 2001, 2005; Milia 2010). These banks represent relict volcanic morphologies characterized by polycyclic erosional surfaces cropping out at the sea floor, eroding volcanic deposits and covered by Holocene sediments, highly varying in thickness (Fig. 6).

The geological setting of the Phlegrean Fields and their stratigraphy have been summarized by Rosi and Sbrana (1987). The Quaternary volcanic area of the Phlegrean Fields is located in a central position within the graben of the Campania Plain (D'Argenio et al. 1973; Bigi et al. 1992). The main structural element is represented by a wide caldera (the Phlegrean caldera—Fig. 3), individuated after the volcano-tectonic collapse following the emplacement of the Campanian Ignimbrite, a large pyroclastic flow, which covered the whole plain about 35 ka (Barberi et al. 1978; Rosi et al. 1996, 1999; Civetta et al. 1997; Pappalardo et al. 1999; Signorelli et al. 2001; Fedele et al. 2002, 2008; Rolandi et al. 2003; Marianelli et al. 2006; Pyle et al. 2006). Within the Phlegrean caldera and along its margins, the volcanic activity continued into historical times.

The pre-calderic volcanic activity developed in correspondence with small and scattered volcanic centers,

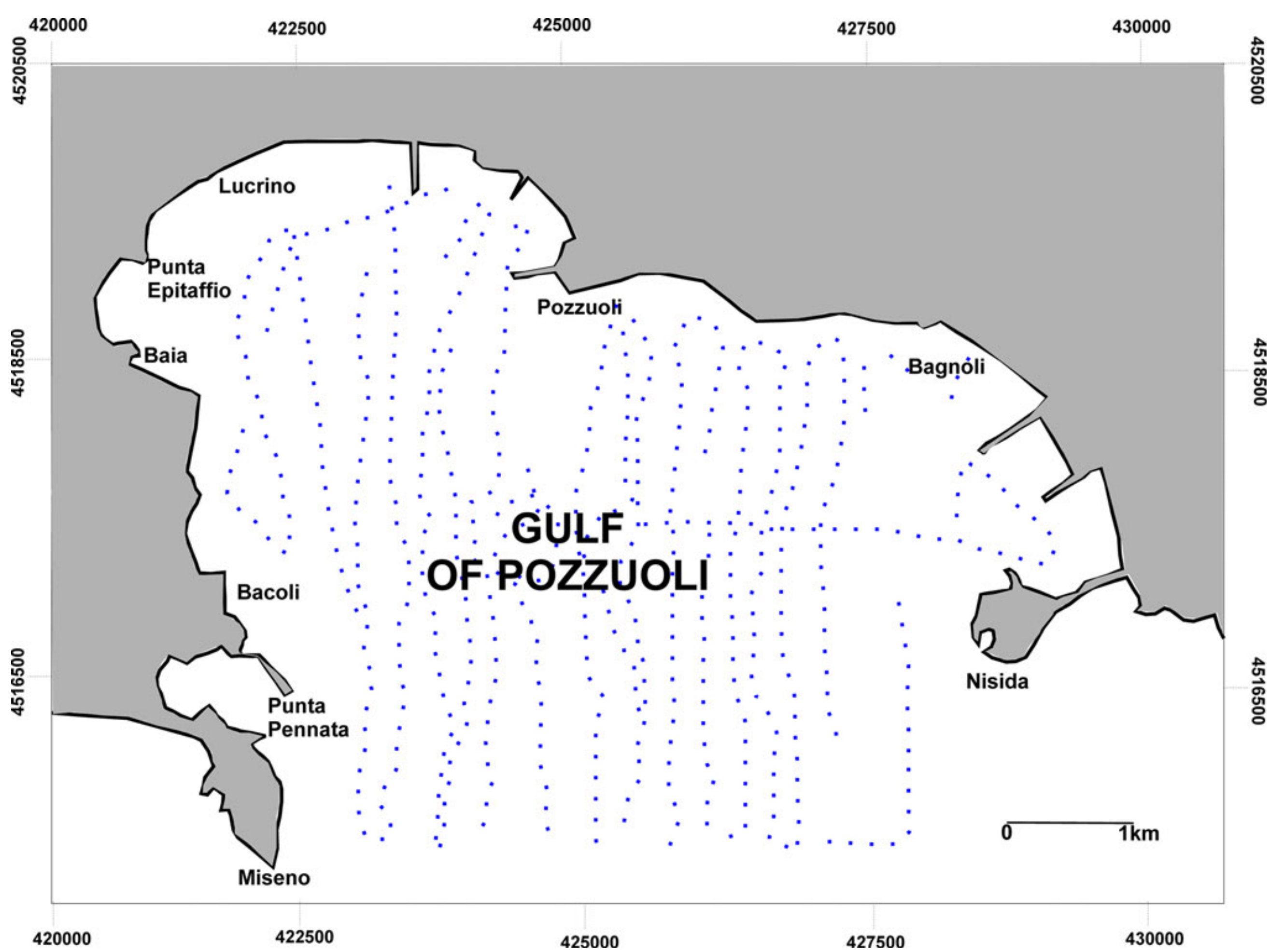

Fig. 5 Location of the acquisition points of the Earth Magnetic Survey intensity in the Pozzuoli Bay (modified after Galdi et al. 1988)

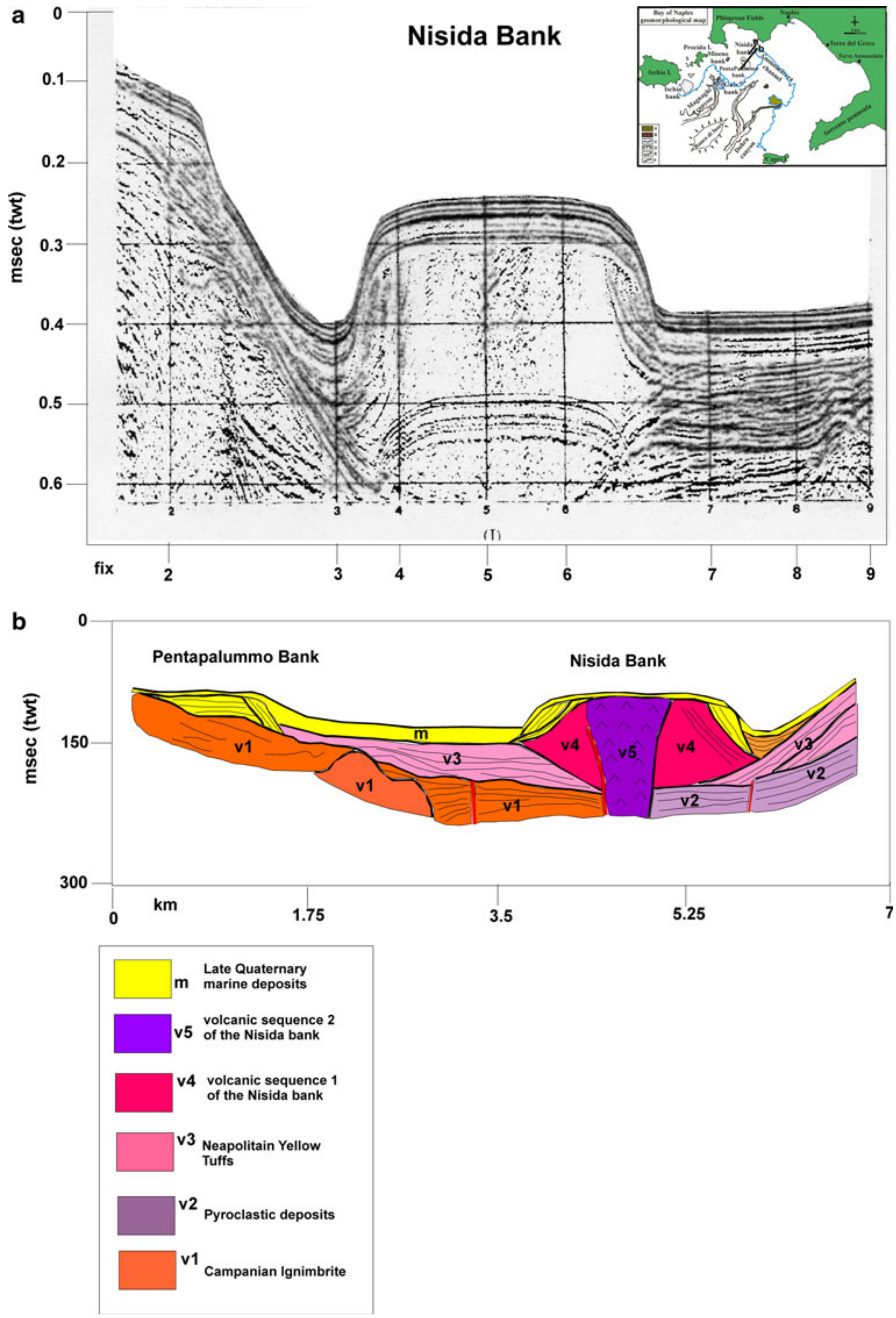

Fig. 6 Sketch qualitative stratigraphic diagrams across the Banco di Pentapalummo and the Banco di Nisida (modified after Latmiral et al. 1971). Note the stratigraphic relationships between volcanic seismic units in correspondence to the Banco di Pentapalummo and Banco di Nisida

erupting trachytic pyroclastics and lavas. The corresponding outcrop located at M.te di Procida coastal cliff (Fig. 3) exhibits a thick subaerial pyroclastic sequence with several interbedded paleosols. It includes four main pumice fall beds, a welded pyroclastic flow deposit, and dark lapilli and ashes erupted by the Fiumicello volcanic center (Procida island).

The post-calderic volcanic activity developed during four main phases, individuated through radiometric age determinations and paleogeographic evolution, in a time interval spanning from 35 ka to historical times. The oldest one (35–11.5 ka) has been established based on deep well stratigraphy in the Phlegrean area (Mofete and San Vito geothermal areas; Figs. 7, 8) and includes thick submarine

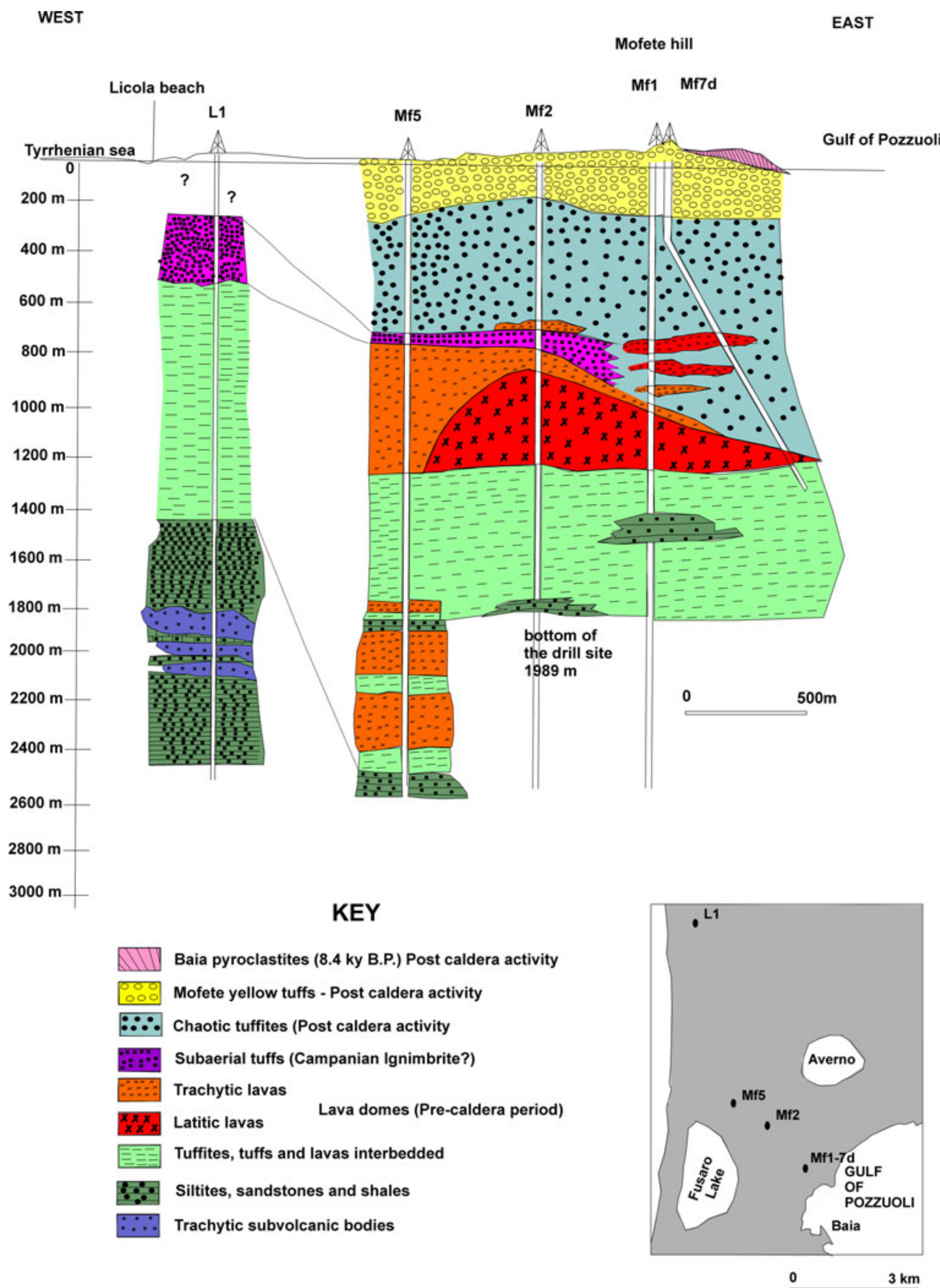

Fig. 7 Sketch stratigraphic section of the Mofete geothermal area in the Phlegrean Fields (Gulf of Pozzuoli; modified after Rosi and Sbrana 1987)

volcaniclastic deposits (tuffites) interlayered with minor lava bodies, covered by large outcrops of yellow tuffs, reaching their maximum thickness in the city of Naples (Neapolitan Yellow Tuff; Scarpati et al. 1993). Stratified yellow tuffs form the proximal facies of typical tuff-cones cropping out in the surroundings of Naples and Pozzuoli towns. The Neapolitan Yellow Tuffs crop out mainly in the peripheral areas of the Phlegrean caldera and have been erupted by several volcanic centers. A number of vents have been identified in field outcrops of the town of Naples. The second, third and fourth eruptive phases spanned from 10.5 ka to A.D.1538 and were mainly subaerial. The corresponding volcanic deposits are separated by well stratified paleosols, emplaced within the caldera and along its outer margins (Deino et al. 2004; Pabst et al. 2008).

Among the main volcano-tectonic structures of the Phlegrean Fields there is La Starza terrace (Rosi and Sbrana 1987; Fig. 3), a marine terrace near the centre of the caldera, characterized by littoral deposits overlain by thin subaerial pyroclastic deposits. It is articulated into two

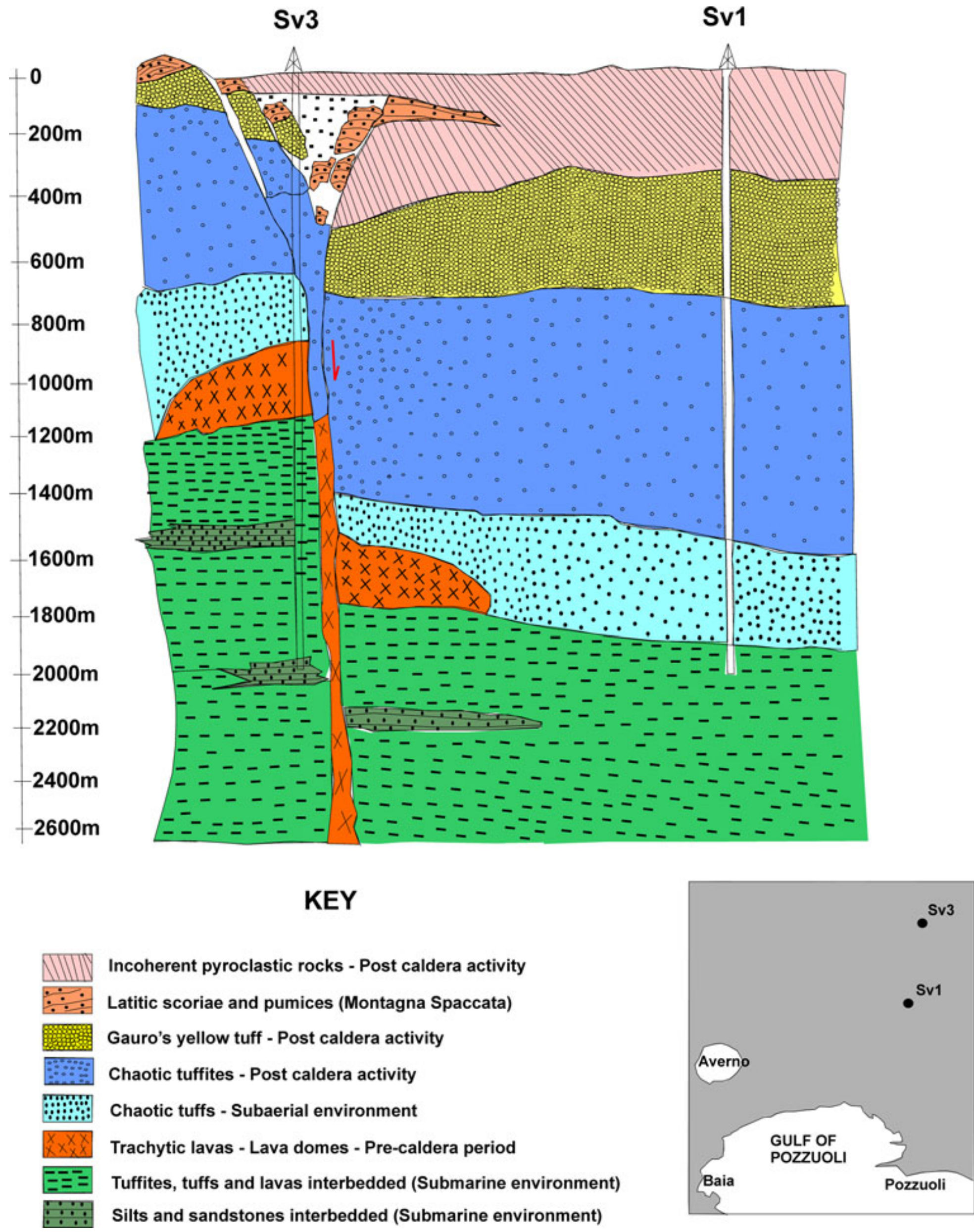

Fig. 8 Sketch stratigraphic section of the San Vito geothermal area (Gulf of Pozzuoli; modified after Rosi and Sbrana 1987)

levels separated by a step; the upper one, on which the town of Pozzuoli is superimposed, reaches a height of 50–54 m, while the lower one developed at 40 m.

A sketch geomorphic map of the Pozzuoli area has also been constructed to improve the geological knowledge of the onshore area (Fig. 9). The main morphological lineaments are the lava domes, the crater rims, the collapse rims, the Late Holocene sea cliff, the Middle Holocene sea cliff, the faults older than marine ingression, the faults affecting the La Starza terrace, the rims of subaerial terraces and the local elevation of terraces. The Holocene marine terrace of La Starza is bounded by an abandoned sea cliff (Cinque et al. 1985, 1997). The succession exposed in this cliff overlies a volcanic substratum of yellow tuffs, including fossiliferous littoral deposits alternating with subaerial pyroclastic deposits and paleosols (Cinque et al. 1985, 1997). The lowest marine interval exposed in the cliff has been radiometrically dated at 10.5 ka (Insinga et al. 2002); an overlying paleosol gave an age of about 8 ka and the uppermost beach deposits an age of 4.6 ka. The continental intervals of the succession were deposited during periods of uplift having rates greater than sea-level rise. The final uplift of the terrace (about 30 m in a few centuries) was probably related to the caldera resurgence, accompanying the onset of a new period of strong volcanic activity of the Phlegrean Fields (Cinque et al. 1997; Insinga et al. 2002).

The stratigraphic study of five deep cores drilled in the Gulf of Pozzuoli along with the radiometric age dating

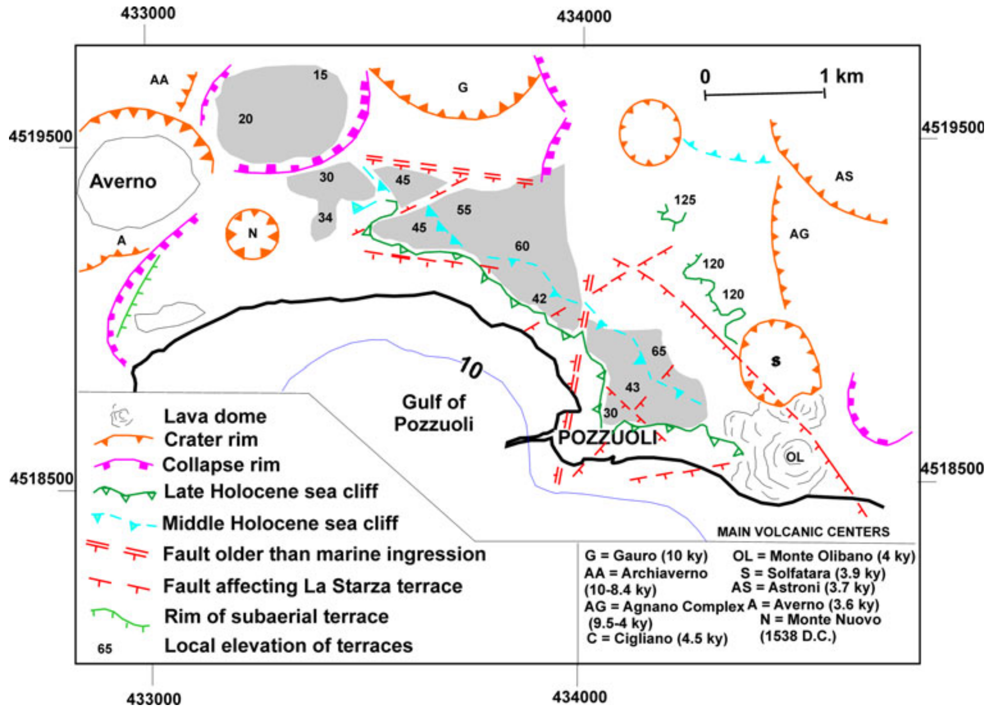

Fig. 9 Sketch geomorphic map of the Pozzuoli area (Phlegrean Fields). Main volcanic centers have also been reported (modified after Cinque et al. 1997)

(^{14}C AMS) of two peat layers and a number of geotechnical tests allowed for the reconstruction of the stratigraphic framework and the determination of physical and mechanical properties of the Holocene succession beneath the sea floor (Insinga et al. 2002).

The Holocene succession is characterized by transgressive volcanic sandy deposits, including a thick pyroclastic unit. Samples collected from the peat layers yelded radiometric ages of 3560 and 7815 cal year B.P. (Insinga et al. 2002). This suggested a correlation between the cored peat layers and two paleosols documented on land that are associated with periods of quiescence during the volcanic activity of the Phlegrean Fields. The Holocene deposits can be correlated with distinct seismo-stratigraphic units identified in the subsurface of the southern and central sectors of Pozzuoli Bay. They can be also correlated with the section cropping out onshore, along the erosional slope of La Starza terrace, where the marine Holocene sequence has been uplifted about 40 m above sea level in the last few thousand years (Insinga et al. 2002).

Results

Seismic stratigraphy of the Gulf of Pozzuoli and Phlegrean Fields volcanic complex offshore

A sketch stratigraphic diagram of the Late Quaternary depositional sequence has been constructed based on Sparker seismic profiles in order to show the stratigraphic relationships between the Quaternary volcanic units, the submerged border of the Phlegrean Fields caldera, and the overlying Late Quaternary marine and coastal deposits in Pozzuoli Bay (Fig. 10).

A volcanic acoustic basement (represented in red; Fig. 10) correlates with the volcanic units of the Pentapalummo Bank, a wide relict volcanic edifice located on the outer shelf of Pozzuoli Bay. These volcanites should be genetically related with the pre-caldera volcanic activity (Rosi et al. 1996, 1999) and deposited before the emplacement of the Neapolitan Yellow Tuff (12 ka; Pabst et al. 2008). A pyroclastic unit (represented in pink; Fig. 10) accumulated in lowered zones on the flanks of the bank and is younger than the establishment of the volcanic bank. The unconformity located at the top of the pyroclastic unit is probably related to the Wurmian regression (18 ka) and marks the base of the Late Quaternary depositional sequence. Thick regressive prograding deposits (Lowstand System Tract; represented in yellow; Fig. 10) have been recognized on the southeastern flank of the bank, where oblique progradational patterns prevailed. The trangressive deposits (represented in green; Fig. 10) have been identified on both flanks of the bank as wedge-shaped seismic units. They are represented by coastal, deltaic, and continental-shelf deposits, characterized by retrogradational patterns of the seismic reflectors.

Bidirectional onlaps of the seismic sequence have been identified on the northwestern flank of the bank. The highstand deposits are composed of prograding sequences on the northwestern flank of the bank with downlap

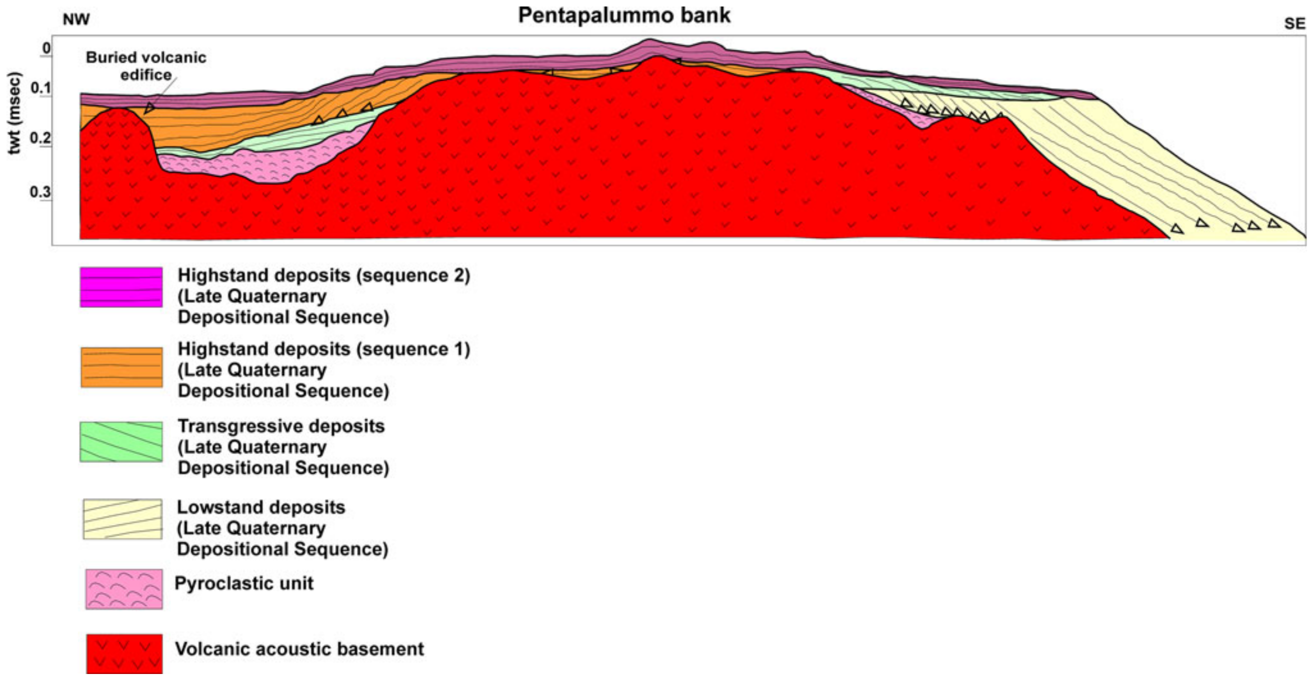

Fig. 10 Sketch stratigraphic diagram of the Late Quaternary depositional sequence in Pozzuoli Bay

terminations grading to parallel reflectors corresponding with the buried volcanic edifice adjacent to the Miseno Cape (Fig. 10).

Lowstand deposits of the Late Quaternary depositional sequence formed between the beginning of the sea level fall, after the highstand phase concluding at 128 ka (isotopic stage 5e) and the lowstand phase of 18 ka (isotopic stage 2; Martinson et al. 1987; Shackleton et al. 2003), during which the shoreline was located at −120/130 m with respect to the present-day shoreline. The beginning of the sea level fall could be located in a time interval ranging between 110 and 80 ka. Transgressive deposits developed after the lowstand of the isotopic stage 2, particularly in the Adriatic Basin (Trincardi et al. 1994). The rising was very rapid and culminated at 6 ka with the maximum marine ingression, while the successive highstand phase is still in course. This eustatic cycle is not symmetrical, since the sea level lowstand lasted more than the 80 % of the overall duration (Hunt and Gawthorpe 2000).

Assuming an average duration of the last eustatic cycle of 100 ka, the phase of sea level fall develops in a time interval of 82 ka (deposition of the Forced Regression System Tract/Lowstand System Tract), while the phase of rapid rising and that one of highstand lasted, respectively 12 ka (deposition of the Transgressive System Tract) and 6 ka (deposition of the Highstand System Tract).

The seismic profile L68_07 (Fig. 11) running from the western continental shelf of Pozzuoli Gulf and Nisida island has been interpreted to show main stratigraphic and structural features of Pozzuoli Gulf, reported in the geological interpretation (in the low inset of Fig. 11).

A sketch stratigraphic table represents the key to the geological section of Fig. 11 and describes the main characteristics and possible chronostratigraphic attribution of the seismic units based on the stratigraphic relationships. Large compressional features have been individuated on the seismic section, i.e., the Punta Pennata anticline, the central syncline of Pozzuoli Gulf and the Nisida anticline (Fig. 11). The structural lineaments involved in deformation of the volcaniclastic unit V3 (Fig. 11) have been produced by compressional events genetically related to tectonic and magmatic events involving the Phlegrean Fields during the Late Quaternary.

The Pozzuoli marine and volcanic sequences have been deformed by kilometer-scale folding during a main compressional event, probably due to tectonic inversions of the basin, already documented on the Tyrrhenian margin (Sartori et al. 2004; Jolivet et al. 2006; Gaullier et al. 2010). Based on seismo-stratigraphic evidence the uplift of the marine terrace of "La Starza", on which the town of Pozzuoli is located (Dvorak and Mastrolorenzo 1991; Morhange et al. 2005), and the formation of an erosional platform on the inner Pozzuoli continental shelf are linked to an anticlinal crest, while the present basin depocenter is located on a syncline (Fig. 11). These folds formed during the deposition of the seismic sequence G3 (Fig. 11), as evidenced by wedging geometries of the seismic unit and overall thinning toward the hinge of the anticline.

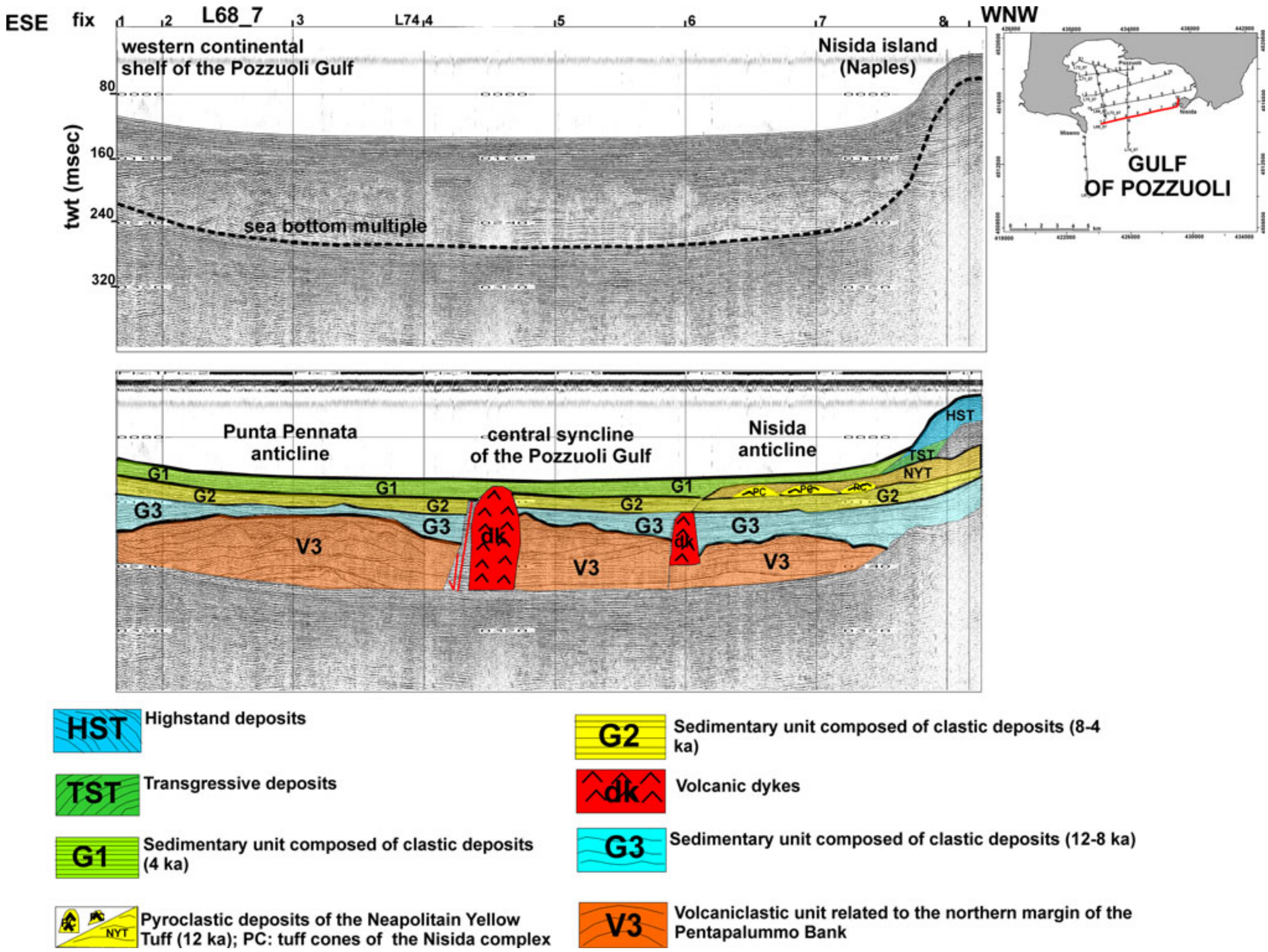

Fig. 11 Seismic profile L68_7 in the Pozzuoli Gulf and corresponding geologic interpretation. Note the occurrence of a wide antiformal structure, composed of the Punta Pennata and Nisida anticlines, distinguishing respectively the western and eastern continental shelves of the Gulf of Pozzuoli and of the central syncline of the Gulf of Pozzuoli. Volcanic dykes, characterized by sub-vertical volcanic bodies, acoustically transparent and locally bounded by normal faults have been identified through seismic interpretation

Eight seismic units have been distinguished through seismo-stratigraphic analysis (Fig. 11). The oldest one (V3 in Fig. 11) is a volcaniclastic unit related to the northern margin of the Pentapalummo Bank, characterized by discontinuous seismic reflectors. It is intensively deformed in correspondence to Punta Pennata and Nisida anticlines, separated by the central syncline of the Pozzuoli Gulf. The overlying unit (G3 in Fig. 11), probably composed of clastic deposits based on its seismic facies, is characterized by discontinuous-parallel reflectors and synsedimentary wedging and growth contemporary with folding. The "dk" unit distinguishes volcanic dykes, categorized by acoustically transparent vertical bodies, locally bounded by normal faults. The G2 unit, probably composed of clastic deposits based on its seismic facies, is characterized by parallel seismic reflectors.

A wedge-shaped seismic unit, genetically related to the Neapolitan Yellow Tuff (12 ka; Scarpati et al. 1993) has been identified from the central Pozzuoli Gulf to Nisida (Fig. 11). It interstratifies with tuff cones located next to Nisida island (Naples town) and is genetically related to the Neapolitan Yellow Tuff (Nisida volcanic complex; Milia and Torrente 2000; Fig. 11). Here transgressive and highstand deposits have also been identified.

Wide compressional lineaments have been identified on the L70 profile, including the Punta Pennata anticline and the central Pozzuoli syncline (Fig. 12), deforming the V3 seismic unit.

Strong wedging and growth of G3 and G2 units suggest their synsedimentary nature (Fig. 12).

Seven seismic units have been distinguished through seismo-stratigraphic analysis (Fig. 12). The oldest one (V3 in Fig. 12) is a volcaniclastic unit related to the northern margin of the Pentapalummo Bank, eroded at its top and deformed in correspondence with the Punta Pennata anticline. The overlying unit (G3 in Fig. 12) is a thick seismic

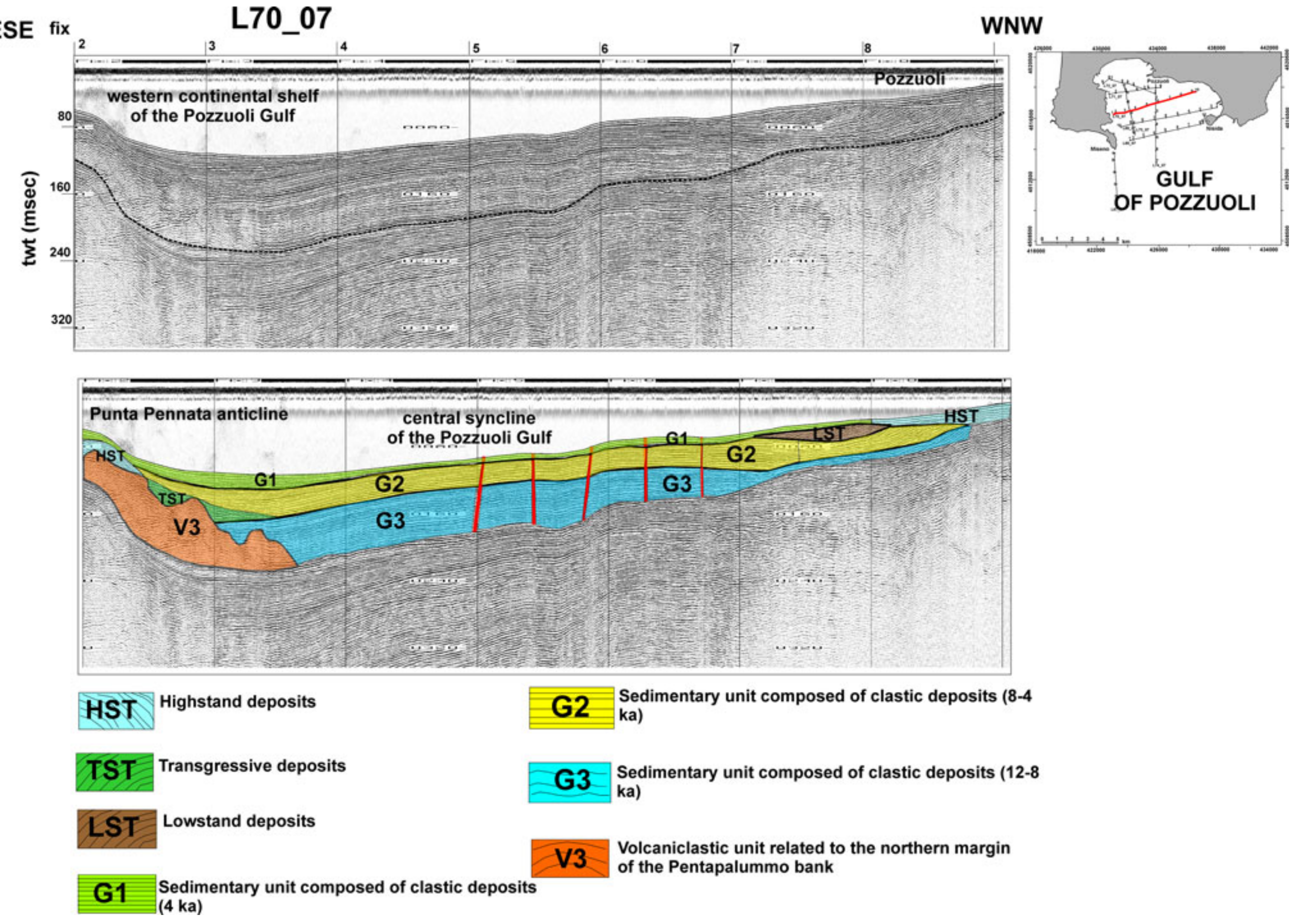

Fig. 12 Seismic profile L70_7 in the Pozzuoli Gulf and corresponding geological interpretation. The profile has crossed part of the Punta Pennata anticline and the central syncline of the Pozzuoli Gulf

sequence characterized by parallel seismic reflectors. Together with the overlying unit G2, having the same seismic characteristics, the unit constitutes the main bulk of the filling in the Gulf of Pozzuoli, being about 0.6 s (twt) thick, corresponding to 510 m (v = 1,700 m/s). Lowstand deposits have been identified on the inner shelf, characterized by prograding reflectors, erosionally truncated at their top (Fig. 12). Transgressive and highstand deposits also occur (Fig. 12).

The interpretation of the seismic profile L69_07, running from Nisida island (Naples) toward the western Pozzuoli shelf has allowed us to distinguish eight seismo-stratigraphic units (Fig. 13). The deepest one is the previously described V3 volcaniclastic unit (Fig. 13), deformed in correspondence with the Nisida and Pozzuoli anticlines. It is overlain by the already described G3 unit. A wide palaeo-landslide (lsl1 on Fig. 13) overlies the two units towards Naples. The G2 unit is overlain by another fossil landslide (lsl2 on Fig. 13). The G1 unit shows lateral variation with the highstand deposits toward Pozzuoli, while toward Naples it grades into the lowstand and transgressive deposits (Fig. 13).

The seismic profile L71_07 (Fig. 14) has crossed the east–west trending continental shelf of Pozzuoli Gulf. The shallow water depths allowed for a very superficial seafloor multiple reflection. Here only the marine seismo-stratigraphic units have been identified, but not the underlying volcanic substratum (Fig. 14). The G3 unit appears to be folded in correspondence with the central syncline of the Gulf of Pozzuoli (Fig. 14). On the continental shelf the unit is deformed by normal faults having little vertical throw (Fig. 14). The occurrence of normal faults is not inconsistent with the folding observed in this region based on seismic interpretation, since it represents an area of active transtensional tectonics and volcanism (Milia and Torrente 2000).

The seismic profile L72_7 crosses the western inner continental shelf of the Gulf of Pozzuoli toward the eastern sector in correspondence with the town of Baia (Figs. 5, 15). An isolated outcrop of the V3 volcaniclastic unit has been identified off Baia (Figs. 5, 15). It is probably

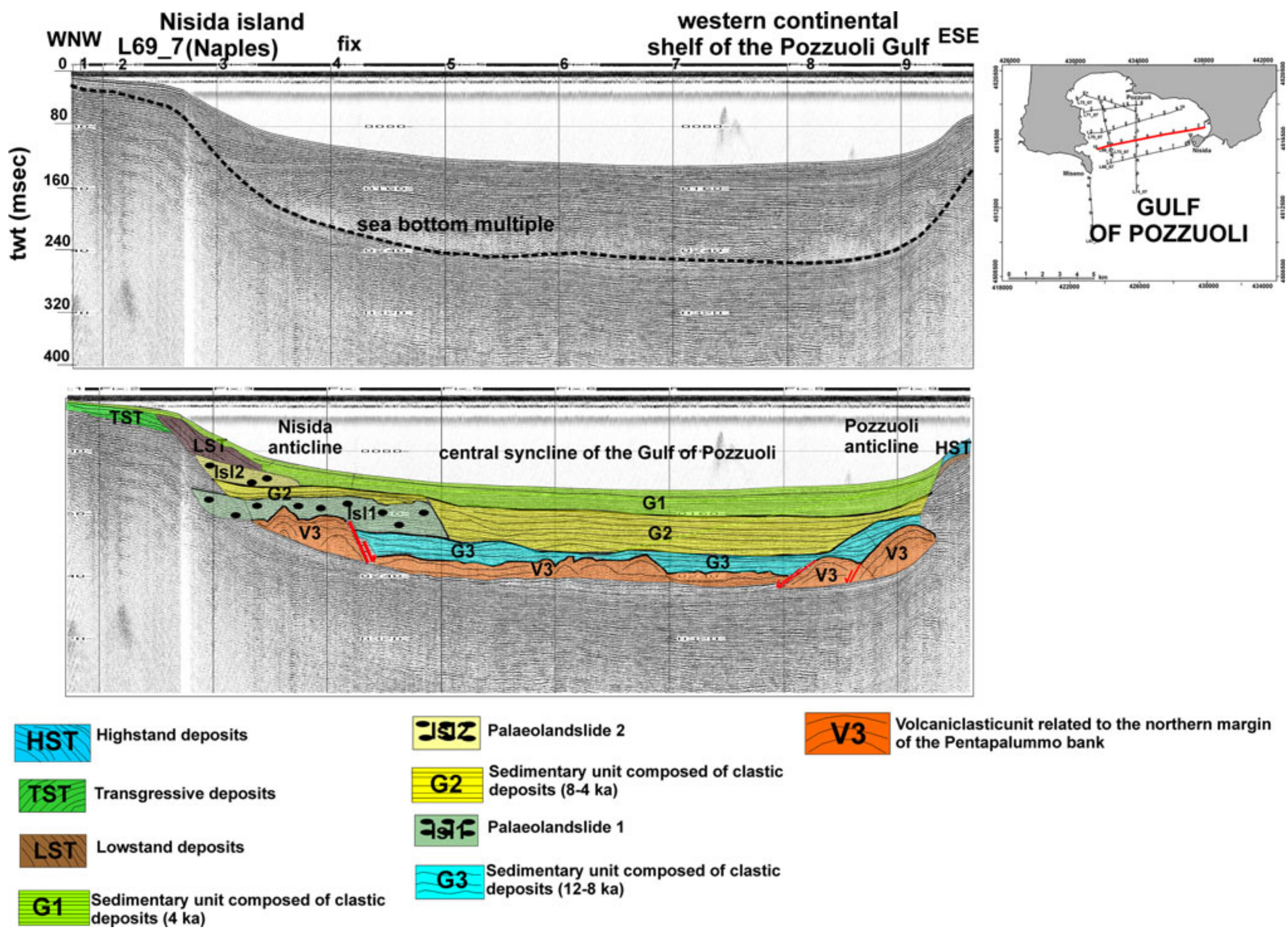

Fig. 13 Seismic profile L69_7 in the Pozzuoli Gulf and corresponding geological interpretation. The antiformal structure composed of the Nisida and Pozzuoli anticlines, separated by the central syncline of the Gulf of Pozzuoli has been recognized. Wide palaeolandslides occur in the stratigraphic record of the eastern continental shelf of the Gulf of Pozzuoli

bounded by normal faults and is limited on both sides by marine deposits. These units extend as far as the inner shelf, where they are deformed by normal faults. Highstand deposits are well developed and characterized by progradational seismic reflectors.

The seismic profiles L73_7 and L74_7 trend north–south. The line L73_7 runs from the inner to the outer shelf in correspondence with the Capo Miseno tuff cone (Figs. 4, 16). The seismo-stratigraphic analysis has allowed us to identify the V3, G1, G2 and G3 units. On the inner shelf the V3 unit is folded by the Punta Pennata anticline, and is slightly deformed by normal faulting. The corresponding syncline is located in the central basin of the Gulf of Pozzuoli, where the G3 unit reaches its depocenter. The G2 and G1 seismic units exhibit parallel seismic reflectors and constant thickness (Fig. 16).

The seismic profile L74_7 runs from the inner shelf off Pozzuoli to the eastern outer shelf off Pozzuoli (Fig. 17). Six main seismo-stratigraphic units have been identified through geological interpretation. The structural pattern of the V3 unit is characterized by two large anticlines (Punta dell'Epitaffio anticline and Punta Pennata anticline), intensively deformed by normal faulting, separated by a syncline, corresponding to the central Pozzuoli Gulf (Fig. 17). Two volcanic dykes correspond to sub-vertical volcanic bodies, acoustically transparent and locally bounded by normal faults. A palaeolandslide, characterized by a wedge-shaped external geometry and chaotic seismic reflectors, seems to be older than the emplacement of the G3 seismic unit (Fig. 17). The G3, G2 and G1 seismic units have also been recognized (Fig. 17).

The seismic stratigraphy offshore of the Capo Miseno volcanic edifice, which bounds the eastern flank of the Gulf of Pozzuoli, has been studied through the geological interpretation of the seismic profile L67_7 (Fig. 18). A tentative land-sea correlation of the volcanic sequences of Capo Miseno has been attempted based on seismo-stratigraphic criteria (Fig. 18).

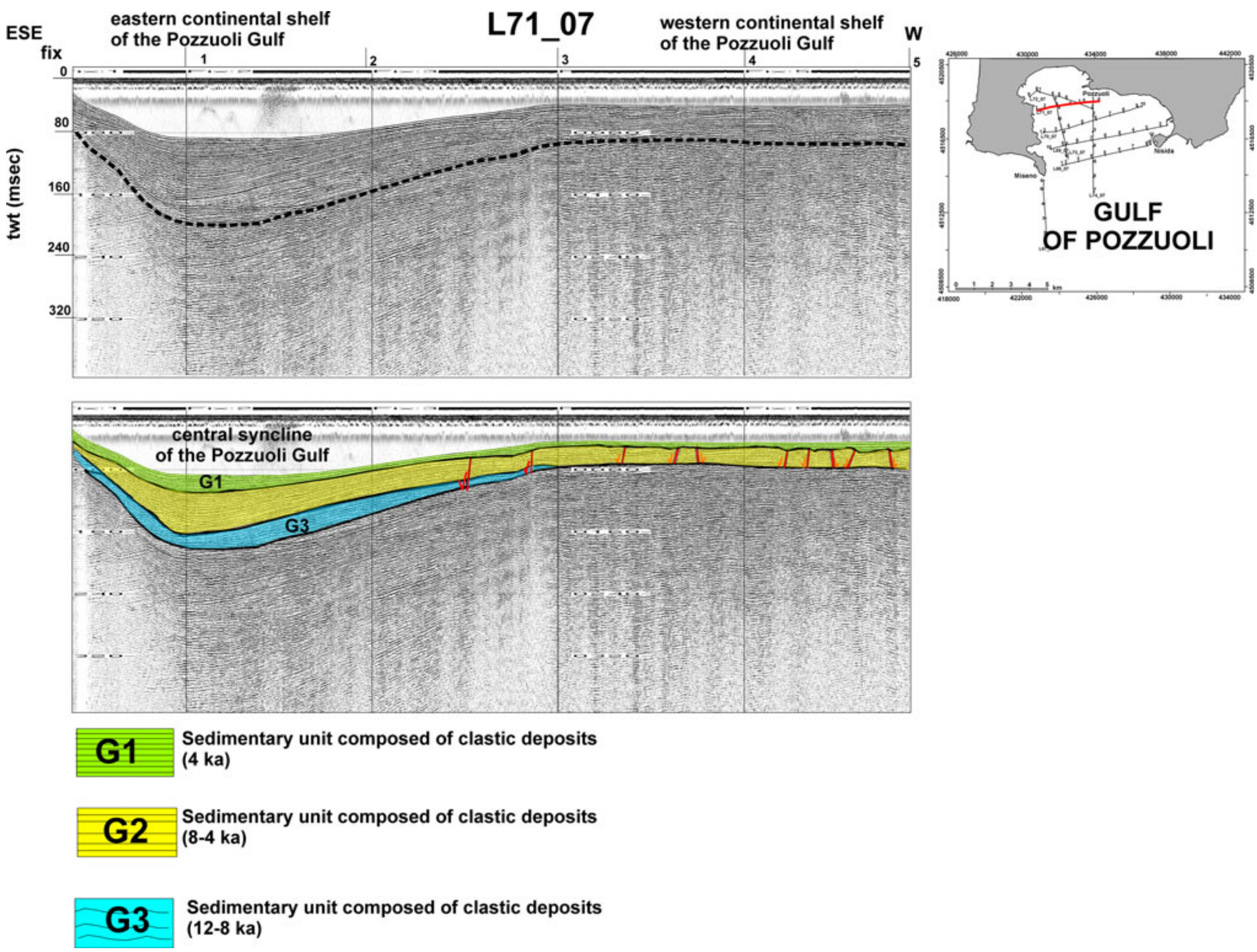

Fig. 14 Seismic profile L71_7 in the Pozzuoli Gulf and corresponding geological interpretation. The profile crosses the inner shelf of the gulf from Bacoli to Pozzuoli. Marine seismic units are significantly deformed by normal faults having little vertical throw

The Capo Miseno volcanic edifice is composed of stratified yellow tuffs, i.e., the "Bacoli-Isola Pennata-Capo Miseno" yellow tuffs (Rosi and Sbrana 1987). The field observations here reported have been carried out by Rosi and Sbrana (1987). These units consist of pumiceous tuffs regularly stratified and very highly lithified. The mass is formed by layers of pumice set in an altered ashy matrix, frequently vesiculated and pisolitic. Layers are medium to thickly bedded, and are poorly sorted with stratification ranging from subparallel to low-angle cross-bedding. At Capo Miseno tuff cone sedimentary structures include gravity flowage ripples and slumping. Volcanological field evidence suggests the emplacement of muddy material from wet eruptive clouds resulting from hydromagmatic activity (Rosi and Sbrana 1987). The presence of both massive and cross-bedded layers suggests the emplacement throughout the eruption of alternating pyroclastic flow and wet surges. The thickness above sea level is around 150 m for Capo Miseno and 20–30 m for Isola Pennata and Bacoli (Rosi and Sbrana 1987).

A thick volcanic seismic unit, acoustically transparent and exposed over a large area, has been identified offshore the Capo Miseno volcanic promontory (Fig. 18). The unit is interpreted as genetically related to the yellow tuffs cropping out at Capo Miseno, Bacoli and Isola Pennata, deposited during the post-caldera volcanic activity of the Phlegrean Fields volcanic complex (35–10.5 ka; Rosi and Sbrana 1987). In correspondence with the Miseno volcanic edifice the unit is deformed by normal faults, putting it in lateral contact with a thick pyroclastic unit (pyr1 in Fig. 18). The pyroclastic unit, uncertain in attribute, is characterized by discontinuous and sub-parallel seismic reflectors, deposited in a structural depression under the volcanic edifice of Capo Miseno. The pyroclastic unit is cut by a volcanic dyke, represented by an acoustically transparent and sub-vertical volcanic body (Fig. 18).

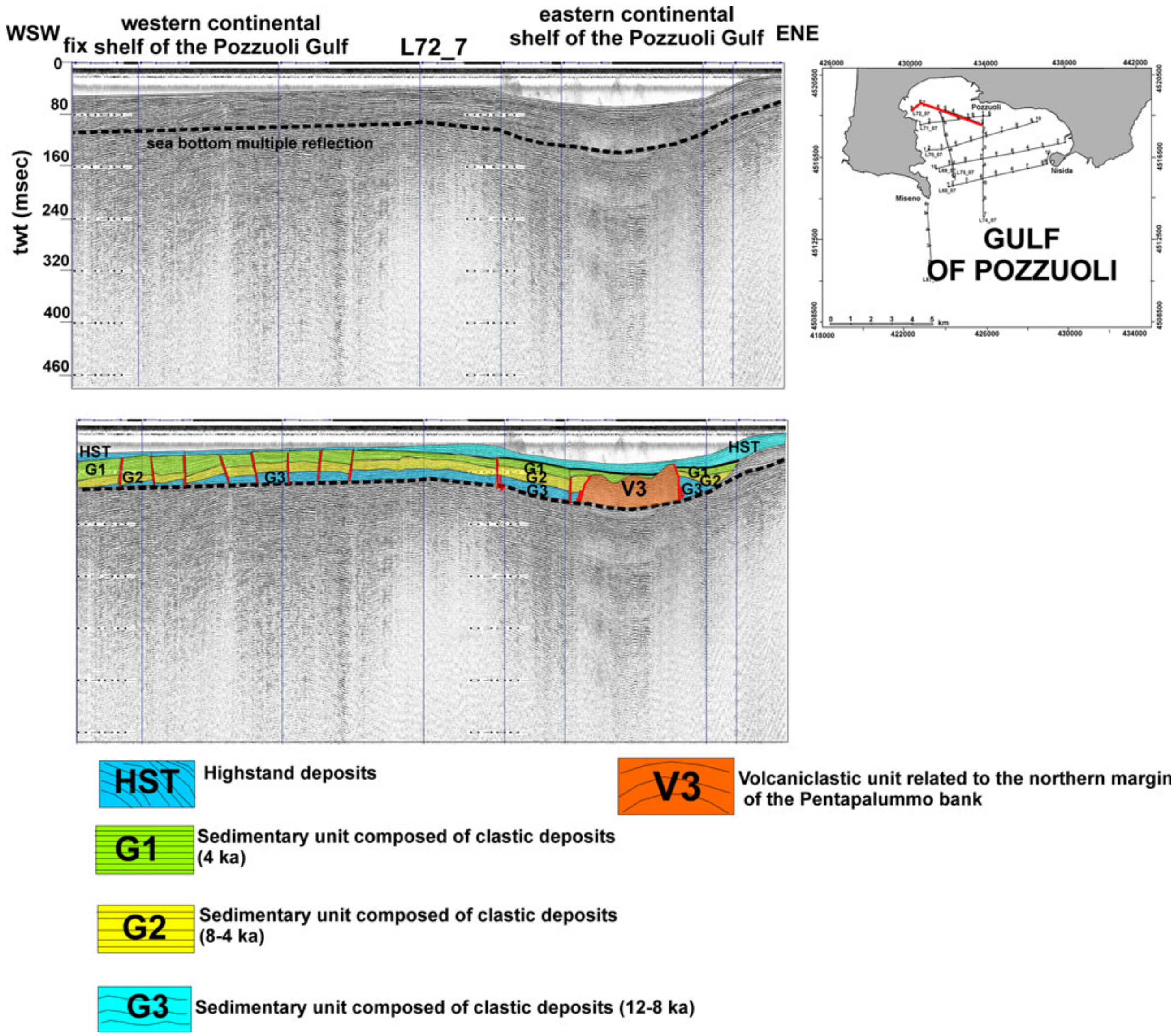

Fig. 15 Seismic profile L72_7 in the Pozzuoli Gulf and corresponding geological interpretation. The profile crosses the inner shelf of the gulf from Pozzuoli to Baia. Marine seismic units are significantly deformed by normal faults having a little vertical throw. An isolated outcrop of the V3 volcaniclastic unit has been recognized

Both the seismic unit genetically related with the Bacoli-Isola Pennata-Capo Miseno yellow tuffs and the pyr1 unit are overlain by a younger pyroclastic unit (pyr2 in Fig. 18). The pyroclastic unit, uncertain in attribute, is characterized by discontinuous progradational to parallel seismic reflectors, deposited from the offshore area surrounding Capo Miseno to the Miseno bank.

The deposits of the Late Quaternary depositional sequence have also been identified (Fig. 18). Lowstand deposits are characterized by discontinuous and sub-parallel seismic reflectors, occurring in the Gulf of Pozzuoli south of Capo Miseno (Fig. 18). Palaeolandslide deposits (lsll in Fig. 18), characterized by chaotic reflectors and locally incised by palaeochannels, are interstratified with the lowstand deposits. Transgressive deposits, branded by retrogradational seismic reflectors and highstand deposits, distinguished by progradational seismic reflectors, have been recognized close to the Capo Miseno volcanic edifice (Fig. 18).

Marine magnetics of the Gulf of Pozzuoli

Magnetic measurements for exploration are acquired from the ground, in the air, on the ocean, in space and down boreholes, covering a large range of scales and for a wide variety of purposes. Measurements acquired from all

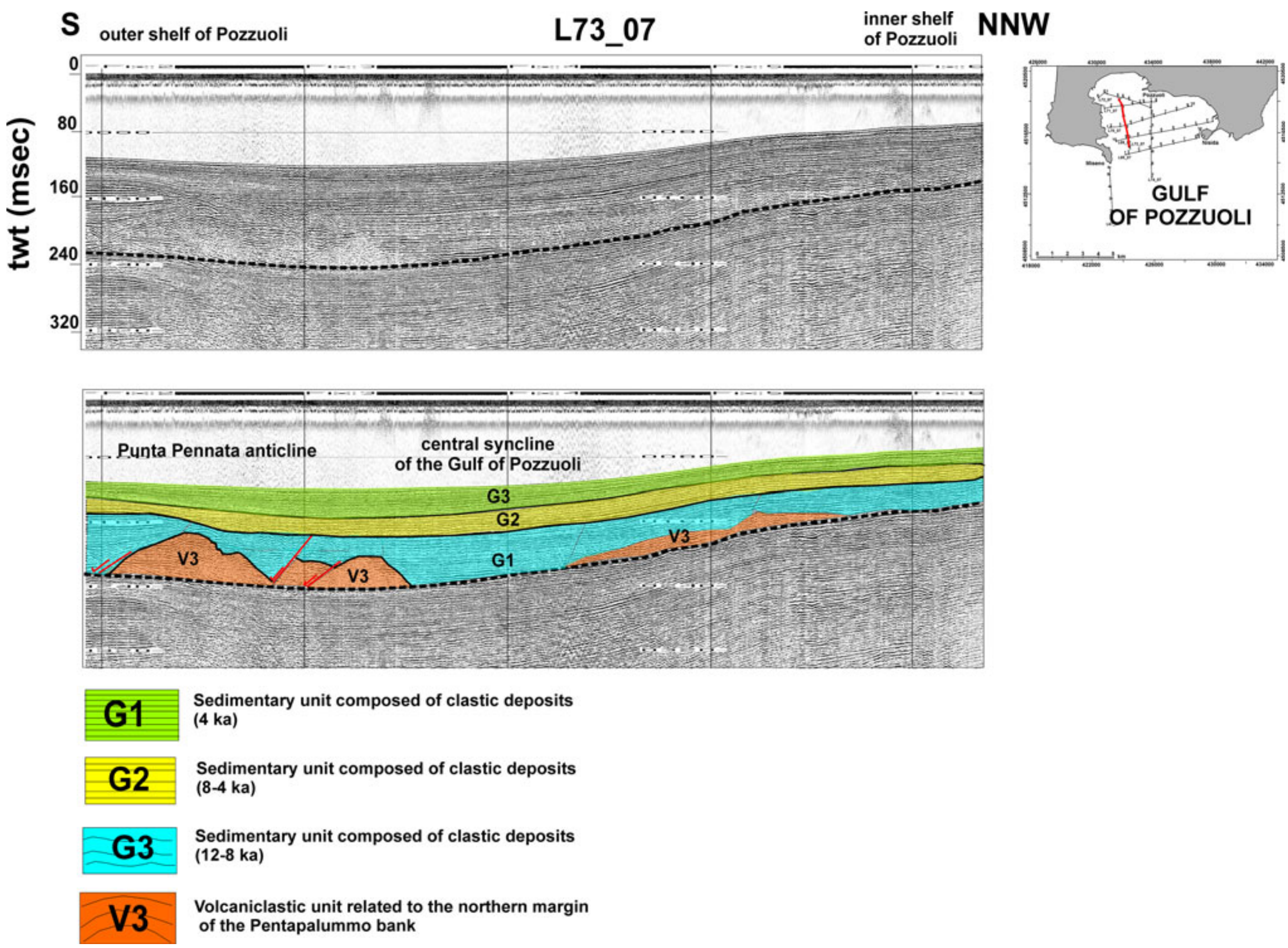

Fig. 16 Seismic profile L73_7 in the Pozzuoli Gulf and corresponding geological interpretation. On the inner continental shelf of the eastern gulf of Pozzuoli the profile has crossed the Punta Pennata anticlinal structure

instruments focus on variations in the magnetic field produced by lateral variations in the magnetization of the crust (Nabighian et al. 2005).

In geological interpretation of magnetic data, knowledge of rock magnetic properties for a study area requires an understanding of both magnetic susceptibility and remanent magnetization. Factors influencing rock-magnetic properties for various rock-types have been summarized by Reynolds et al. (1990) and Clark and Emerson (1991).

The aeromagnetic anomaly map of Italy produced by the Agip oil company (Agip 1981) has been the best reference point for many magnetic interpretations in this area to date. The revised and recent version of a magnetic anomaly map of Italy (Chiappini et al. 2000) outlines the lack of detailed magnetic measurements in the area covered by our survey. The map of Chiappini et al. (2000) is based on onshore measurements collected in the frame of the CNR-Progetto Finalizzato Geodinamica (1977–1981), while offshore magnetic measurements have been collected by the Osservatorio Geofisico Sperimentale (OGS; Trieste, Italy; 1965–1972). The most important result of the magnetic map published by Chiappini et al. (2000) is a new approach to the interpretation of the magnetic signature associated with the main regional tectonic structures in their geological framework. There is a good regional correlation between structural geology of shallow structures and magnetic anomalies.

Several magnetic studies have been carried out in the Neapolitan volcanic district (Nunziata and Rapolla 1987; Secomandi et al. 2003; Paoletti et al. 2005). In particular, Paoletti et al. (2005) presented a new detailed magnetic map of the whole Neapolitan active volcanic district, obtained by merging recently acquired airborne, land and marine magnetic measurements. The analysis of this magnetic dataset has enabled the characterization of the main buried volcanic structures, providing a better understanding of the connection between tectonism and volcanism in the study area.

Magnetic anomaly maps provide insights for a better understanding of the geologic, tectonic and geothermal

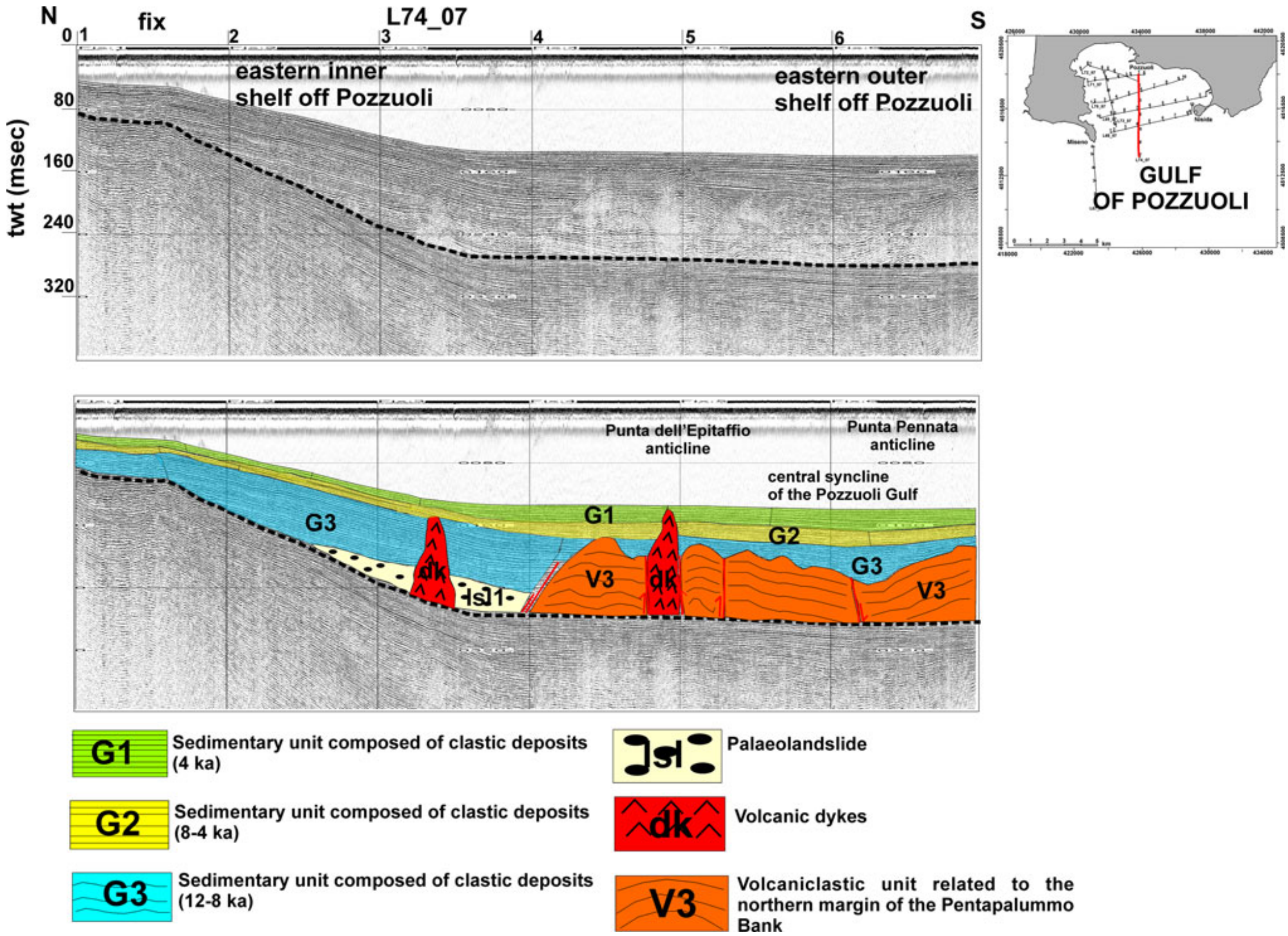

Fig. 17 Seismic profile L74_7 in the Pozzuoli Gulf and corresponding geological interpretation. The profile has crossed the eastern inner shelf off Pozzuoli towards the eastern outer shelf off Pozzuoli. A steep antiformal structure, probably down thrown by normal faults is constituted of the Punta dell'Epitaffio and Punta Pennata anticlines, separated by the central syncline of the Pozzuoli gulf

characteristics of an area, in particular for the volcanic areas, where recent tectonic activity and volcaniclastic deposits often cover important geological structures.

An interpreted map of the magnetic anomalies in the Gulf of Pozzuoli has been constructed (Fig. 19; Galdi et al. 1988). The interpretation of the magnetic anomaly map of the Gulf of Pozzuoli has allowed to distinguish areas characterized by positive anomalies (represented in yellow; Fig. 19) and areas characterized by negative anomalies (represented in light yellow; Fig. 19). The inner continental shelf of the Gulf of Pozzuoli is regarded as negative magnetic anomalies. The area surrounding the Pozzuoli harbour, from the Caligola pier to the Pirelli jetty, does not show significant magnetic anomalies The area adjacent the Lucrino-Punta Pennata resort is characterized by a negative anomaly, increasing southward up to the magnetic minimum located near the Baia Castle (−100 nT; Fig. 19).

Alternating magnetic maxima and minima have been observed on the outer shelf (Fig. 19). An area of magnetic maximum is located on a NE-SW oriented belt, about 1.7 km long (Fig. 19). The inner shelf from Bagnoli to Pozzuoli shows two strong magnetic anomalies, separated by a thin belt having a normal magnetic value (Fig. 19). Proceeding seaward, in the offshore region surrounding Bagnoli, two magnetic minima (−40 and −60 nT) are positioned, slightly E-W elongated, culminating with the absolute magnetic minimum (−100 nT) near the Baia Castle (Fig. 19).

Four magnetic sections, respectively NE-SW and NW–SE oriented, have also been constructed (Figs. 20, 21; Galdi et al. 1988). The magnetic section A–A′ (in the upper inset of Fig. 20) runs from Punta Pennata to the town of Pozzuoli (Via Napoli). The total magnetic intensity shows a trending with a magnetic minimum of −80 nT in the central area (corresponding to a water depth of 90 m) and a magnetic maximum of 70 nT near the Pozzuoli shoreline (Fig. 20).

The magnetic section B–B′ (in the lower inset of Fig. 20), translated 2.4 km toward the southeast, shows, starting from the southwest, a monotonous magnetic trend

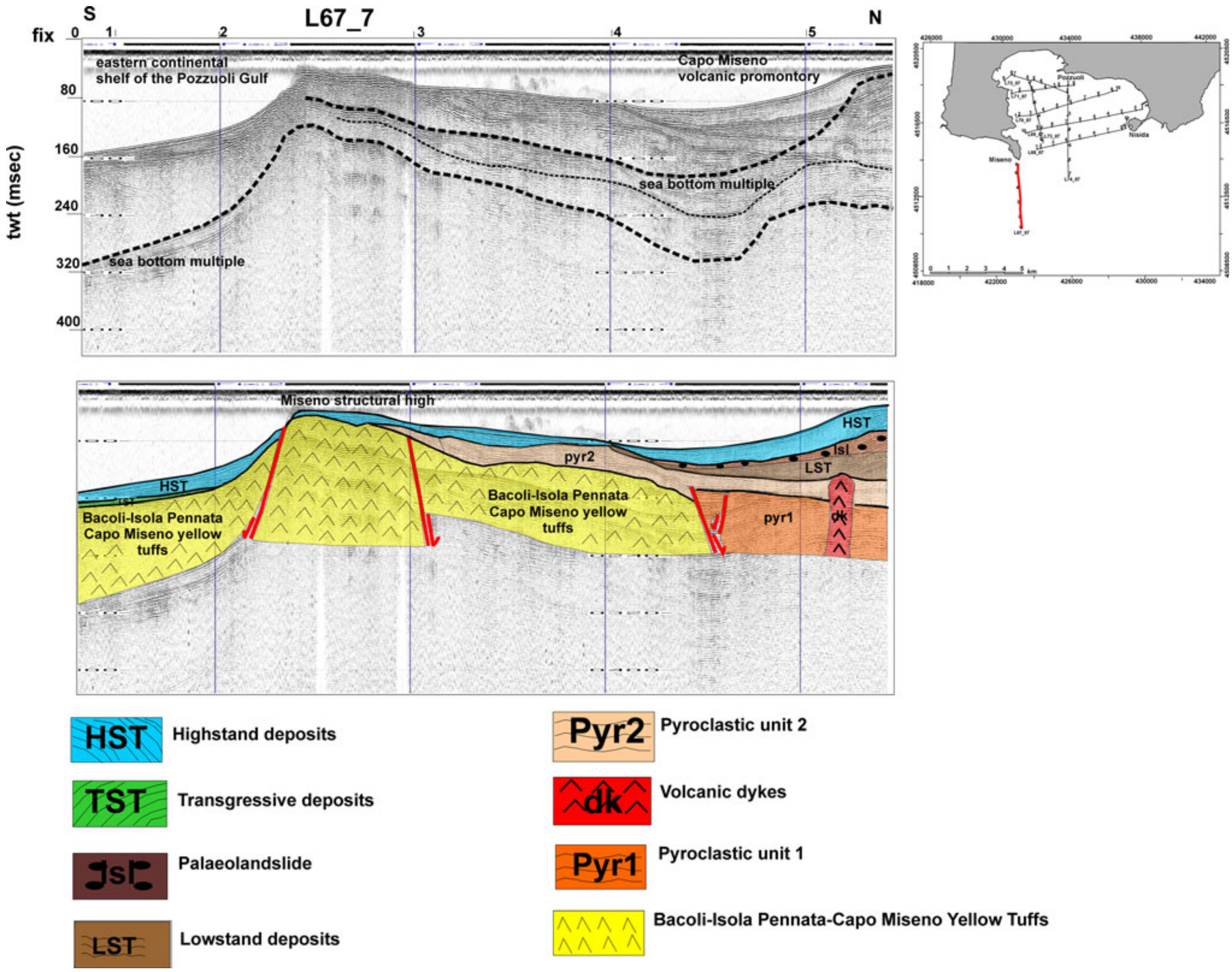

Fig. 18 Seismic profile L67_7 in the Pozzuoli Gulf and corresponding geological interpretation. The profile runs from the Miseno volcanic promontory to the eastern continental shelf off the Pozzuoli gulf. A volcanic seismic unit, acoustically transparent, is genetically related to the Miseno-Bacoli-Isola Pennata yellow tuffs cropping out at Capo Miseno, Bacoli and Isola Pennata, deposited during the post-caldera volcanic activity (35–10.5 ka)

up to the offshore surrounding Nisida, where a strong increase of gradient occurs. The magnetic highs occurring nearshore appear to be related not to the geology, but to the occurrence of the industrial system of Bagnoli. This industrial system has provoked a release in the environment mainly of metals derived by the burning of fossil coals (oil fields, etc.) and by remnants of industrial production, probably responsible for the observed magnetic anomalies. As an alternative hypothesis, the hydrothermal activity associated to the volcanic activity in the active volcanic area of the Phlegrean Fields should have been responsible for supplying in the environment of a large amount of metallic elements, causing the magnetic anomalies (Bodnar et al. 2007; De Vivo et al. 2008).

The magnetic section C–C′ runs from the Pentapalummo Bank in the Gulf of Pozzuoli to Punta dell'Epitaffio (in the upper inset of Fig. 21). A strong magnetic anomaly followed by a related maximum near Bagnoli is continued by a minimum near the island of Nisida.

The magnetic section D–D′ runs from Nisida to the historical centre of Pozzuoli (Rione Terra, in the lower inset of Fig. 21). A magnetic minimum has been recognized 1.2 km from Nisida; by continuing, the value of the intensity rapidly increases to reach the maximum value of 60 nT near the Rione Terra of Pozzuoli.

Offshore of the Phlegrean Fields volcanic complex significant magnetic anomalies are located in a belt of submarine volcanic banks in the external part of the Gulf of Pozzuoli (Fig. 22).

The map on the upper right in Fig. 22a shows that the Phlegrean Fields offshore represents a relatively complex magnetic anomaly area, characterized by several magnetic

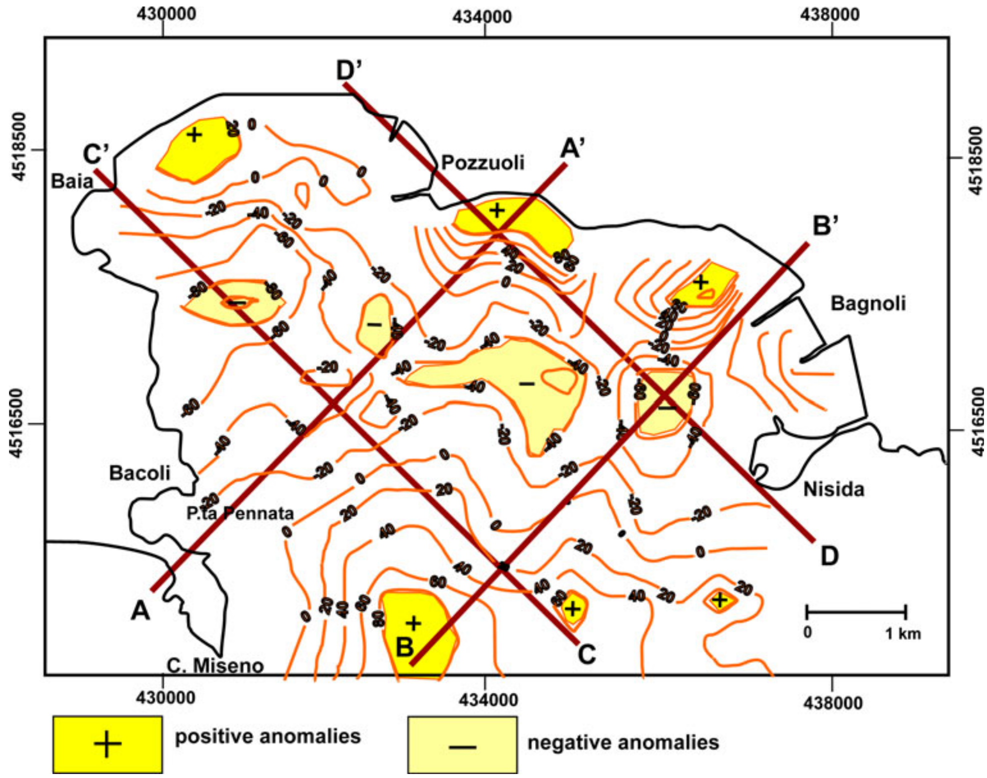

Fig. 19 Interpreted map of the magnetic anomalies in the Gulf of Pozzuoli (modified after Galdi et al. 1988). Note that the Gulf of Pozzuoli represents an area of negative anomaly, exceeding some areas of positive anomalies located off Baia, Pozzuoli and Bagnoli and some scattered positive anomalies on the continental shelf between Miseno and Nisida

anomaly fields with different intensity. Two dipolar anomalies, categorized by a maximum–minimum couple, have been identified. The first anomaly, E–W oriented and located in the northernmost part of the area, shows a minimum of −200 nT, associated with a maximum of +185 nT. Such values, which are relatively not very high, could be associated with volcanic bodies not cropping out at the sea floor but buried by sediment. The second anomaly, NW–SE oriented and located in the easternmost part of the area, 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, not dipolar and of lower intensity, ranging between 40 and 135 nT are due to the occurrence of small volcanic edifices (Fig. 22).

A significant magnetic anomaly on the order of 150 nT occurs at the Magnaghi canyon head (map on the lower right in Fig. 22b), deeply eroding the volcanic deposits of the continental slope of the island of Procida. The occurrence of this magnetic maximum seems to suggest highly magnetized lava bodies in the subsurface in correspondence with the Magnaghi canyon (Naples Bay; Fig. 22). As is already known, an important use of the magnetic method is the mapping of buried igneous bodies (Nabighian et al. 2005). These generally have higher susceptibilities than the rocks that they intrude, so it is often easy to map them in plan view. The approximate three-dimensional geometry of the body can also be determined. Because igneous bodies are frequently associated with mineralization, a magnetic interpretation can be a first step in finding areas favourable for the existence of a mineral deposit (Nabighian et al. 2005).

By concluding, the interpreted map of the magnetic anomalies in the Gulf of Pozzuoli (Fig. 19) has allowed us to distinguish both areas characterized by positive anomalies (represented in yellow; Fig. 19) and areas characterized by negative anomalies (represented in light yellow; Fig. 19).

The inner continental shelf of the Gulf of Pozzuoli is regarded as negative magnetic anomalies and the correlation with the volcanic structures evidenced by Sparker data is not clear. It is necessary to record a more densely-spaced magnetic survey, in order to identify on marine magnetics the volcanic dykes shown by seismic profiles. The volcaniclastic units identified on seismic profiles do not produce significant magnetic signatures, probably due to their composition (tuffs rather than lavas).

Discussion and concluding remarks

The Phlegrean Fields is a volcanic area featuring a shallow Moho, a high thermal gradient, bradyseismic movements and shallow seismicity. The offshore portion of the Phlegrean Fields (continental shelf of the Pozzuoli Bay)

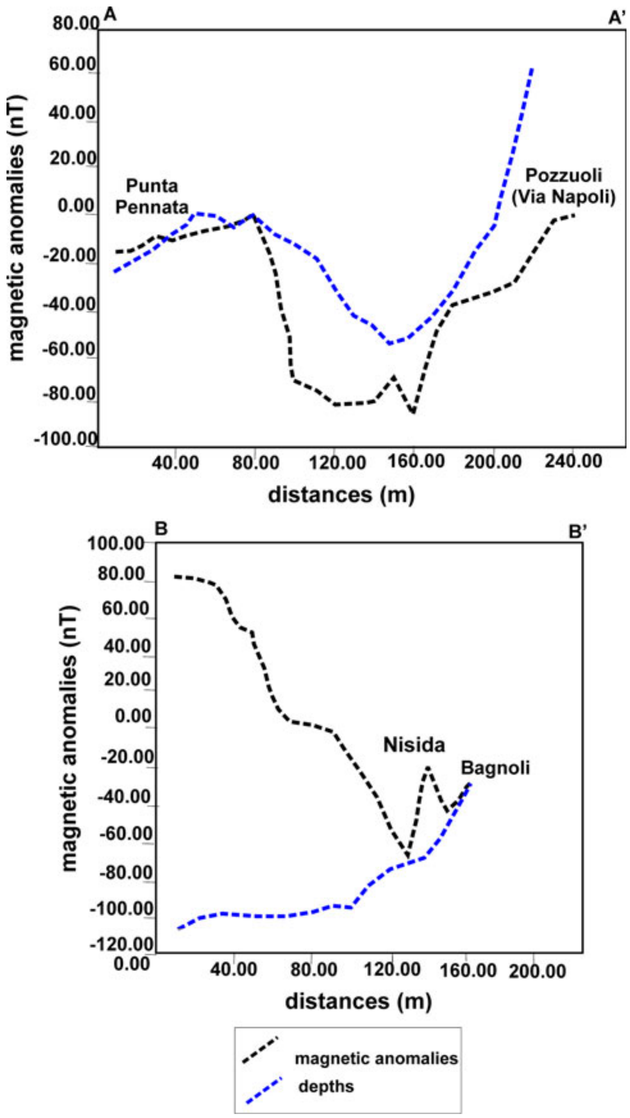

Fig. 20 Magnetic sections of the iso-anomalies NE–SW oriented in Pozzuoli Gulf (modified after Galdi et al. 1988)

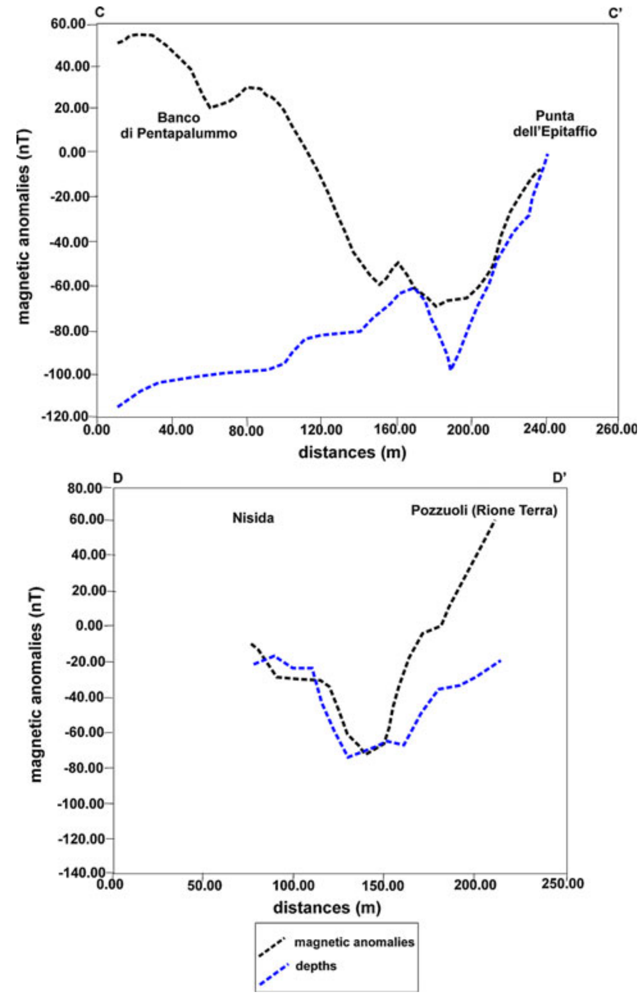

Fig. 21 Magnetic sections of the iso-anomalies NW–SE oriented in Pozzuoli Gulf (modified after Galdi et al. 1988)

has been investigated through high resolution seismic reflection profiles and volcanic and marine units are herein documented. An up-to-date geologic and stratigraphic setting of the seismic units is here furnished and discussed. Marine magnetic data in the study area are interpreted. Some implications of the interpreted data on the tectonics and magmatism of the Phlegrean Fields volcanic complex are discussed. Some regional geological concepts on the Phlegrean Fields in the framework of the Campania continental margin are recalled to support interpretations of the volcanic and tectonic context.

The rising of the magmas which characterize the Campania volcanic arc sets out on WSW–ENE and E–W trending tectonic lines in the Campania Plain and, as a general rule, in the structural depressions elongated on the Tyrrhenian margin (Turco and Zuppetta 1998; Turco et al. 2006).

Due to the effect of the rollback of the Adriatic slab, the migration of the volcanic activity carries on from west to east, giving rise to the volcanic edifices of the Phlegrean Fields and, in the final phases, to the volcanic edifice of Somma-Vesuvius.

Despite the overall extensional tectonic regime that characterizes the Tyrrhenian margin, compressional features have been observed in the Gulf of Pozzuoli, as anticlines and synclines. A working hypothesis to explain the tectonic structures observed in the study area was suggested by Milia and Torrente (2000). The limited longitudinal extent of the folds and their arcuate axial trends may be explained with an east-trending left transtensional shear zone that was active along the eastern Tyrrhenian sea during the Late Quaternary (Milia and Torrente 2000), in overall agreement with the results of our study.

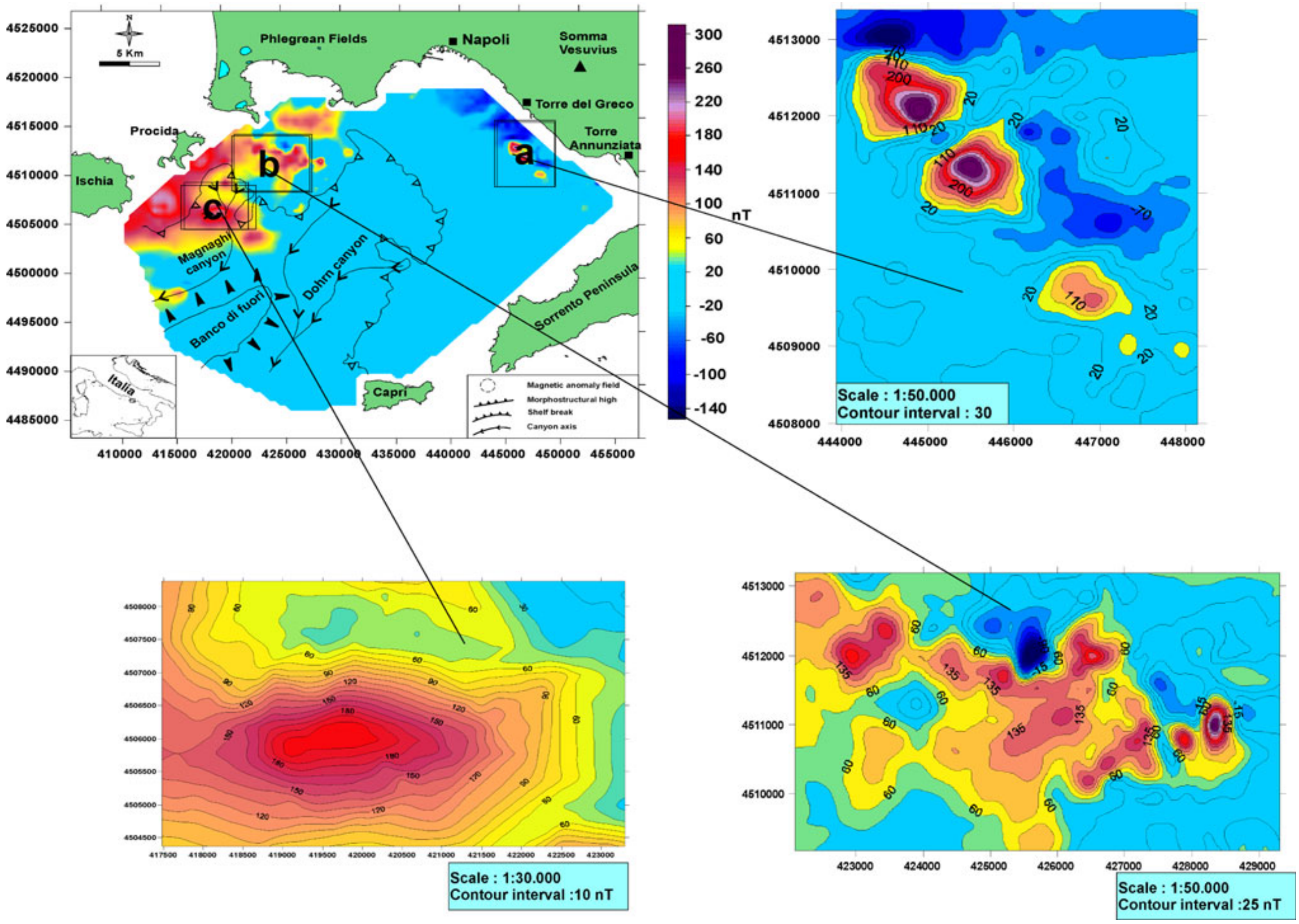

Fig. 22 High resolution magnetic anomaly map of Naples Bay (modified after Aiello et al. 2005). The *inset* "a" represents a magnetic anomaly area located offshore the Somma-Vesuvius volcanic complex, while the *inset* "b" represents another magnetic anomaly area located offshore the Phlegrean Fields volcanic complex. The *inset* "c" represents a magnetic anomaly area located on the continental slope of the gulf, at the Magnaghi canyon head

The Phlegrean Fields active volcanic field is located in a caldera structural depression, whose origin is still discussed. In fact, it is attributed to the eruption of the Campanian Ignimbrite (35 ka), or to the eruption of the Neapolitan Yellow Tuff (12 ka) or, more probably, to both those eruptions (Rosi and Sbrana 1987; Orsi et al. 1996). The caldera margin has been recognized based on different geophysical data, including gravimetry, magnetic and seismic data (Barberi et al. 1978; Zollo et al. 2003). Other authors think that the Campanian Ignimbrite is controlled by a single eruption coming from the Acerra graben (Scandone et al. 1991). These interpretations are in disagreement with those proposed by De Vivo et al. (2001) and Rolandi et al. (2003), who have recognized in the Campania Plain the occurrence of different ignimbritic events in the time interval ranging from 300 to 18 ka In particular, the ignimbritic event dated back by Rosi and Sbrana (1987) and by Orsi et al. (1996) to 35 ka and known in the geological literature as the Campanian Ignimbrite is dated to 39 ka (De Vivo et al. 2001; Rolandi et al. 2003). Those authors supposed that various ignimbritic events have been erupted through fractures located in the Campania Plain, corresponding to normal faults and having Apenninic (NW–SE) and counter-Apenninic (NE–SW) trends.

At the Phlegrean Fields the oldest volcanic products have been dated at about 50 ka and are composed of pyroclastic deposits and remnants of lava domes having a trachytic and alkali-trachytic composition (Alessio et al. 1973; Pappalardo et al. 1999). The Neapolitan Yellow Tuff is the most studied eruptive deposit between the Phlegrean products (Rosi and Sbrana 1987; Orsi et al. 1996; Di Vito et al. 1999; Pabst et al. 2008). Its eruption, having a variable character from phreato-plinian to phreato-magmatic (Scarpati et al. 1993; Orsi et al. 1996), emitted a large amount of magmas having a composition from alkali-trachytic to latitic (Pabst et al. 2008). The eruption has determined a caldera collapse, giving origin to a recent volcanic activity having an age younger than 12 ka. In the last 12 ka the Phlegrean caldera has been the site of about thirty eruptions, concentrated in three epochs, ranging between 12 and 10.5 ka, 8.6 and 8.2 ka, and 4.5 and 3.7 ka (Di Vito et al. 1999). During the most recent eruptive period the caldera was involved by ground deformations, which starting from 10 ka have allowed for the formation of the La Starza terrace (Cinque et al. 1985, 1997).

In light of the above-mentioned regional geological discussion on the Phlegrean Fields, there remains the problem of the existence or not of a relationship between the patterns of regional faults and the location and characterization of the volcanic products linked to main events of volcanic activity.

In conclusion, a stratigraphic setting of seismic units in the Gulf of Pozzuoli is here proposed based on seismic interpretation of high-resolution profiles. Fourteen seismic units, both volcanic and sedimentary, tectonically controlled due to contemporaneous folding and normal faulting, have been revealed by geological interpretation. In the Neapolitan volcanic district such a detailed seismic stratigraphy is completely new offshore the active volcanic area of the Phlegrean Fields.

Volcanic dykes, characterized by acoustically transparent sub-vertical bodies, locally bounded by normal faults, testify to the magma rising in correspondence with extensional structures. A large field of tuff cones interlayered with marine deposits off Nisida island, on the western rim of the Gulf, is related to the emplacement of the Neapolitan Yellow Tuff deposits (Nisida volcanic complex). A thick tabular volcanic unit off the Capo Miseno volcanic edifice, previously unknown is connected with the Bacoli-Isola Pennata-Capo Miseno yellow tuffs, cropping out in the northern Phlegrean Fields.

Large submarine slides, connected with significant submarine instability processes have been recognized on seismic profiles. These landslides should be hypothetically triggered by pyroclastic flow and surges, related to the A.D. 1538 Monte Nuovo and 3.8 ka-old Averno eruptions that entered the sea (Milia et al. 2000).

A table summarizing the main seismic units recognized in the Pozzuoli sector, their seismic facies, and geologic interpretation has been constructed to clarify the stratigraphic discussion of the results (Table 1). The order of the units reported in the table roughly reflects their stratigraphic position and, consequently, their qualitative age (Table 1). In this table the older units have been reported at the bottom of the table and the younger ones at its top.

The structural setting observed in the Gulf of Pozzuoli based on the interpretation of high-resolution seismic reflection profiles is in agreement with that shown by previous papers (Milia and Torrente 2000). An active kilometer-scale low amplitude anticline was recognized in the gulf, locally controlling the sea floor morphology and forming a bathymetric high. The sedimentation of the G1 and G2 marine units was contemporaneous with the deformation of this anticline, showing growth strata, thinning towards the hinge and a composite stacking pattern of the seismic units.

Structural and stratigraphic analyses of the Gulf of Pozzuoli provided data on the age of folding, their kinematics and the amount and rates of uplift. The folds extend over two kilometres, displaying a curve axial pattern and wedge-shaped packages of syntectonic strata. The rate of fold uplift ranges between 1 and 20 mm/year. A relative sea-level curve calculated for an anticline culminating in the city of Pozzuoli has highlighted the relationship between the deformation timing and the genesis of related abrupt changes in sedimentary facies and erosional surfaces (Milia and Torrente 2000). The overall uplift rates and geometry of the folds have suggested their tectonic origin as the product of local folding.

The relationships between the growth of low-amplitude buckle folds and associated syntectonic sedimentation have been examined in kinematic models (Torrente and Kligfield 1995). The experiments have revealed distinct geometric relationships of fold geometry to growth stratigraphy, which are determined by the relative relationships of fold uplift rate to sedimentation rate (Torrente and Kligfield 1995). The production of geometric features such as buried anticlines or emergent anticlines and their respective onlap patterns are interpreted in terms of interplay between the rates of uplift and sedimentation.

A sketch tectono-sedimentary model of the Punta Pennata anticline (Fig. 23) has been constructed based on the interpretation of Sparker profiles according to the structural model of the Pozzuoli anticlines (Torrente and Kligfield 1995). The Punta Pennata anticline represents a synsedimentary fold (Fig. 23). Pre-folding strata have been identified, coincident with the V3 volcaniclastic unit identified through seismic stratigraphy (V3 Fig. 23). A geometry with strata progressively superimposed by fossilizing the structure is indicated in Fig. 23, involving the G3 and G2 seismic units. An overlying geometry with strata which tend to overlie the older ones by migrating towards the crest of the anticline is also shown (Fig. 23).

In conclusion, the geometric features of the Punta Pennata anticline should be interpreted in terms of an interplay between the rate of uplift and the rate of sedimentation. The folds have been probably controlled by a bending due to the occurrence of volcanic intrusions, accordingly with the occurrence of the “dk” unit on the seismic profiles and the regional tectonics at the basin scale (tectonic inversion).

The limited longitudinal extent and arcuate axial trends of the observed folds well match with a E-trending left

Table 1 Seismic units in the Pozzuoli sector

Seismic unit	Seismic facies	Geologic interpretation	Location
(14) HST	Progradational to parallel seismic reflectors	Highstand system tract of the Late Quaternary depositional sequence	Eastern Pozzuoli Gulf
(13) TST	Retrogradational seismic reflectors	Transgressive system tract of the Late Quaternary depositional sequence	Eastern Pozzuoli Gulf
(12) lsl	Wedge-shaped, chaotic to discontinuous seismic unit	Landslide deposits intercalated in the upper part of the Lowstand System Tract; locally occurrence of palaeo-channels	Gulf of Pozzuoli south of Miseno Cape
(11) LST	Progradational seismic reflectors, erosionally truncated at their top	Lowstand system tract of the Late Quaternary depositional sequence	Inner continental shelf off Pozzuoli
(10) G1	Parallel and continuous seismic reflectors	Upper sedimentary unit of the basin fill, attaining maximum thickness in the depocenter of the central basin	Gulf of Pozzuoli
(9) lsl2	Wedge-shaped, chaotic to discontinuous seismic unit	Fossil landslide overlying the G2 marine unit and underlying the Lowstand System Tract of the Late Quaternary depositional sequence	Eastern Pozzuoli Gulf
(8) NYT/PC	NYT: Wedge-shaped acoustically transparent volcanic seismic unit PC: mound-shaped, acoustically transparent volcanic bodies interlayered with parallel reflectors	NYT: Pyroclastic deposits of the Neapolitan Yellow Tuff (12 ka) deposited in the Naples and Pozzuoli offshore PC. Tuff cones of the Nisida volcanic complex in facies hetheropy with the Neapolitan Yellow Tuffs and interstratified with the G3 marine deposits	Naples and Pozzuoli offshore
(7) G2	Parallel and continuous seismic reflectors	Intermediate sedimentary unit of the basin fill, probably composed of clastic deposits; deposited in the whole Pozzuoli Gulf; strongly involved by wedging and growth in correspondence to anticlines (Punta Pennata anticline, Pozzuoli anticline, Nisida anticline) and synclines (central syncline of the Pozzuoli Gulf; Epitaffio syncline)	Pozzuoli Gulf
(6) lsl1	Wedge-shaped, chaotic to discontinuous seismic unit	Wide palaeo-landslide overlying the V3 volcaniclastic unit and coeval with the basal part of the G2 marine unit	Eastern Pozzuoli Gulf
(5) pyr2	Continuous progradational to parallel seismic reflectors	Pyroclastic unit, uncertain in attribution, deposited from the offshore surrounding Capo Miseno to the Miseno volcanic bank, involved by wedging and growth, testifying its deposition during vertical down throwing of normal faults	Eastern Pozzuoli Gulf
(4) dk	Sub-vertical volcanic bodies, acoustically transparent and locally bounded by normal faults	Volcanic dykes due to magma uprising in correspondence to normal faults	Eastern and central Pozzuoli Gulf
(3) pyr1	Discontinuous to sub-parallel seismic reflectors	Pyroclastic unit, uncertain in attribute, deposited in a structural depression under the volcanic edifice of Capo Miseno	Eastern Pozzuoli Gulf
(2) G3	Discontinuous to parallel seismic reflectors	Lower sedimentary unit of the basin fill, composed of clastic deposits; strongly involved by wedging and growth in correspondence to anticlines (Punta Pennata anticline, Pozzuoli anticline, Nisida anticline) and synclines (central syncline of the Pozzuoli Gulf; Epitaffio syncline)	Pozzuoli Gulf
(1) V3	Acoustically transparent to discontinuous seismic unit; strongly eroded at its top	Volcaniclastic unit related to the northern margin of the Pentapalummo bank; intensively deformed by anticlines (Punta Pennata anticline, Pozzuoli anticline, Nisida anticline) and synclines (central syncline of the Pozzuoli Gulf; Epitaffio syncline) individuated due to compressional deformation genetically related to main magmatic events	Pozzuoli Gulf

transtensional shear zone, active along the eastern Tyrrhenian Sea during the Late Quaternary (Catalano and Milia 1990; Sacchi et al. 1994; Milia and Torrente 2000). Inversion tectonics along synsedimentary folds has been observed in the Gulf of Pozzuoli at the basin scale. On the Southern Italy continental margins this kind of tectonism has been already documented in the sedimentary basins of the south-eastern Tyrrhenian margin (Argnani

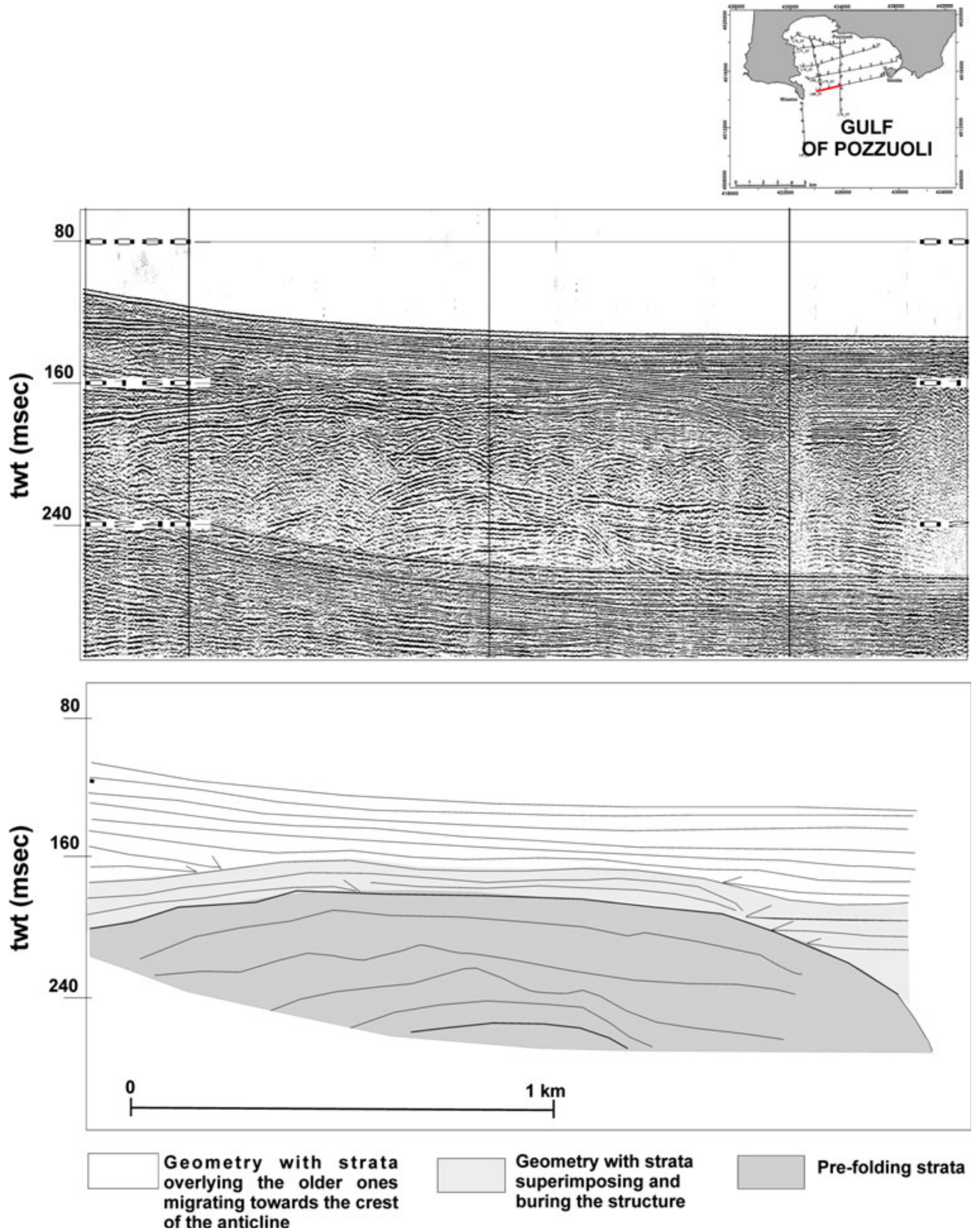

Fig. 23 Tectono-sedimentary model of the Punta Pennata anticline (according to Torrente and Kligfield 1995). (1) Pre-folding strata, (2) geometry with strata superimposing and buring the structure, (3) geometry with strata overlying the older ones migrating towards the crest of the anticline

and Trincardi 1990; Sacchi et al. 1994; Aiello et al. 2009) and offshore of western Sicily (Catalano and Milia 1990).

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