A NEW DETAILED SEISMIC STRATIGRAPHY OF THE GULF OF POZZUOLI (NAPLES BAY, SOUTHERN TYRRHENIAN SEA) BASED ON HIGH RESOLUTION SEISMIC REFLECTION PROFILES: INSIGHTS INTO THE OFFSHORE VOLCANOLOGY OF THE PHLEGREAN FIELD VOLCANIC COMPLEX

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Introduction. A new detailed seismic stratigraphy of the Gulf of Pozzuoli (Naples Bay, southern Tyrrhenian sea, Italy) is here purposed and discussed based on the geological interpretation of high resolution seismic reflection profiles, recently collected in the frame of research programmes of marine geological mapping. This offshore stratigraphy is utilized to put some new insights on the marine volcanology of the Phlegrean Fields volcanic complex, deeply studied onshore through field volcanological data. The new stratigraphic setting here purposed will improve the geological and geophysical knowledge on the active volcanic area of the Phlegrean Fields and the adjacent offshore sectors. The tectonic framework of the area will also be discussed based on seismic interpretation and identification of main fault systems and their relationships to the main regional unconformities in the Pozzuoli basin filling.

The stratigraphy and geology of volcanic areas, such as the Gulf of Pozzuoli, has been recently studied in detail (Groppelli and Goette, 2010), focussing on several aspects. Some results mainly deal with the types of mappable stratigraphic units and unconformity bounded units (Lucchi et al., 2010; Tibaldi, 2010; Bonomo and Ricci, 2010; Palladino et al., 2010), centering on Italian volcanoes and showing the use of different applications in the concept of mapping on the base of stratigraphic units, with the aim to define the evolution of a volcanic area. These studies have applied in the field survey the lithosomatic and synthemic units (or...
Unconformity Bounded Stratigraphic Units or UBSU) to synthesize the volcanic evolution of the area. The relative importance of a volcanic unconformity depends on its geographic extension, the duration of an associated hiatus, or its volcano-structural significance. The application of unconformity-bounded units to synthesize detailed lithostratigraphic units has been carried out in the south-western sector of the Phlegrean Fields volcanic complex (Perrotta et al., 2010). The integration of field data by seismo-stratigraphic analysis of the Bay of Naples and wells drilled in the city of Naples (Milia, 2010) has allowed the reconstruction of the stratigraphic evolution of the southern margin of the Phlegrean Fields, highlighting the close relationships among volcanic activity, marine sedimentation and sea level fluctuations. This allowed to distinguish magmatic features, such as dykes, domes and tuff cones, deciphering the complex stratal architecture as an interplay between the syneruptive and intereruptive stratigraphic units.

In this paper, a correlation with the onshore geology of the Phlegrean Fields has been carried out in order to highlight tectonic and magmatic implications in the geological evolution of the Phlegrean Fields volcanic complex, intensively studied through field geology (Rosi and Sbrana, 1987; Morhange et al., 2005; Bellucci et al., 2006; De Natale et al., 2007; Bodnar et al., 2007; Aiello et al., 2013).

Geologic setting. The Gulf of Pozzuoli, offshore the Phlegrean Fields volcanic complex (Naples Bay, southern Tyrrenian sea) is an inlet with limited dimensions, bounded seawards by several submerged volcanic banks (Pentapalummo Bank; Nisida Bank; Miseno Bank; Fig. 1; Aiello et al., 2012, 2013).

The Phlegrean Fields is an active volcanic center near Naples, Italy (Fig. 2). Numerous eruptions occurred in this volcanic complex during the Late Quaternary (Fig. 2) 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 market called “Serapeo” in the Pozzuoli town indicated a strong volcano-tectonic subsidence of the area (Dvorak and Mastrolorenzo, 1991; Morhange et al., 2005). The sea level measurements made within the Phlegrean Fields from 1819 to 1968 gave an average subsidence rate of 14 mm/yr. Thermal cooling and contraction of a large magmatic body beneath this caldera have been
proposed as a possible cause for local subsidence within the Phlegrean Fields volcanic complex (Dvorak and Mastrolorenzo, 1991). The episodic uplift of some sectors of the Phlegrean Fields is clearly indicated onshore. These sectors include the most recent eruptive vents, including the Monte Nuovo vent, historically erupted during the 1538. Geophysical evidence suggests that the uplift at the Phlegrean Fields is caused by the periodic reactivation of a shallow magmatic body, possibly by intrusion of additional magma or alternatively, hydrothermal mechanisms (Dvorak and Mastrolorenzo, 1991).

The Phlegrean Fields are a young explosive caldera having a diameter of about 12 km, created by the volcano-tectonic collapse during two main volcanic events (Rosi and Sbrana, 1987). This caldera was the source of two large volcanic deposits in the Campania Plain, i.e. the Campanian Ignimbrite (35 ky B.P.) and the Neapolitan Yellow Tuff (12 ky B.P.). After the formation of the Neapolitan Yellow Tuff, representing the main bulk of the Naples town, two periods of eruptive activity occurred in the Phlegrean Fields from 10 to 8 ky B.P. and again from 4.5 to 3.7 ky B.P. (Rosi and Sbrana, 1987). Each eruptive period was followed by a period of quiescence that lasted a few thousand years.

Some deep well data (Mofete and San Vito geothermal areas: Aiello et al., 2012) have been also taken into account for a better correlation with the volcanic products of the Phlegrean Fields volcanic complex. A deep stratigraphic section in the Mofete geothermal area (northern Phlegrean Fields: Aiello et al., 2012) has shown the occurrence of deep trachytic subvolcanic bodies, overlaying by siltites, sandstones and shales and then by tuffites, tuffs and lavas interbedded. Pre-calderic products superimpose on these ones and are represented by latitic and trachytic lavas, overlaying by the Campanian Ignimbrite. Post-calderic products, overlying the Campanian Ignimbrite are constituted of chaotic tuffites, the Mofete yellow tuffs and the Baia pyroclastites. Another stratigraphic section has been constructed in the San Vito geothermal area (Gulf of Pozzuoli: Aiello et al., 2012). The deep products are represented by silts and sandstones interbedded overlay by tuffites, tuffs and lavas interbedded, both in a submarine environment. Pre-calderic volcanites consist of trachytic lava domes, overlay by chaotic tuffs. Post-caldera products are represented by the Gauro yellow tuff, overlay by latitic scoria and pumices and then by incoherent pyroclastic rocks.

Data and methods. The interpreted Sparker grid consist of seven seismic sections recorded in the Pozzuoli Gulf, both parallel and perpendicular to the shoreline. Seismic acquisition was carried out by using a multielectrode sparker system (SAM96), including shorter pulse lengths for an equivalent energy discharge, increasing the peak pressure and the amplitude of the acoustic wave. The seismic sections were graphically recorded on continuous paper sheets with a vertical recording scale of 0.25. The resolution of the seismic data was about 1 m.

The ability of Multitip Sparker systems to record high resolution seismic data on continental shelf and deeper waters has been revealed and their technical characteristics have been measured in laboratory using different arrangements of energy storage and salinity of water (Rutgers and de Jong, 2003). Sparkers can be used for the production of acoustic pulses as seismic source for sub-bottom profiling in the sea. A multi-tip (200-800 tips) sparker has been developed, which makes high-resolution seismic profiling possible in deep water. The characteristics of the multi-tip sparker system have been measured in a basin in the laboratory using different arrangements of the capacitive energy storage and salinity of the water. A model in Matlab has been used to calculate the current waveform in the spark array for different layouts of the power supply (Rutgers and de Jong, 2003).

The geological techniques of high resolution seismic stratigraphy have been applied in the geological interpretation of seismic profiles (Mitchum et al., 1977; Vail et al., 1977). The stratigraphic interpretation of the seismic data for a particular geologic setting is based on the evaluation of variations in acoustic characteristics reflecting changes in sedimentary processes, tectonic setting and position of sea level. Parallel reflectors, usually continuous and distinct reflectors draping the sea floor typically indicate fine-grained pelagic and
hemipelagic sedimentation deposited during the last stages of a sea level rising or during sea level highstands. Discontinuous, more or less parallel reflectors often indicate mud turbidites deposited during a sea level rising, onlapping or draping depending on geological conditions. Acoustically transparent reflectors vary according to geological setting and sediment type and generally indicate silty-mud turbidites, debris flow deposits and small slumps and finally, channel fill deposits restricted within associated levees or structural walls. Unorganized chaotic reflectors indicate slump masses and possibly high density debris flow deposits, often onlapping but sometimes unconfined. Broken wavy seismic reflectors are typical of slump masses or sediment creep. Acoustical voids, characterized by an inverted U shape are usually acoustically transparent and occurring in the shallow subbottom and are interpreted as gas-charged sediments.

**High resolution seismic stratigraphy in the Gulf of Pozzuoli.** The seismic profile L68_07 (Fig. 3), running from the western continental shelf of Pozzuoli Gulf and Nisida island...
has been interpreted to show the main stratigraphic and structural features of the Pozzuoli Gulf, reported in the geologic interpretation (in the lower inset of the figure). The seismostratigraphic analysis has allowed to distinguish eight seismic units. The V3 unit is the oldest one (Fig. 3) and has been interpreted as a volcaniclastic unit genetically related to the northern margin of the Pentapalummo Bank, characterized by discontinuous seismic reflectors. It appears involved in compressional deformation in correspondence to the Punta Pennata and Nisida anticlines. The unit is overlain by the G3 unit, a sedimentary unit composed of clastic deposits, ranging in age from 12 and 8 ky B.P. It is characterized by discontinuous to parallel reflectors and synsedimentary wedging and growth contemporary with folding. The dk unit denominates volcanic dykes, categorized by acoustically transparent vertical bodies, locally bounded by normal faults. The overlying G2 unit is the second unit of the basin filling and is a sedimentary unit composed of clastic deposits, ranging in age from 8 and 4 ky B.P. The NYT/PC unit categorizes the pyroclastic deposits of the Neapolitan Yellow Tuff, while the PC unit represents the tuff cones of the Nisida volcanic complex. The G1 unit is represented by a sedimentary unit composed of clastic deposits (4 ky B.P.). The transgressive and highstand deposits have also been identified (Fig. 3).

High resolution seismic stratigraphy in correspondence to the Capo Miseno volcanic edifice has also been studied through the geological interpretation of the L67_7 seismic profile. A land-sea correlation of the volcanic sequences of Capo Miseno has been attempted based on seismo-stratigraphic criteria. 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). Field geo-volcanological survey of the Capo Miseno volcanic edifice (Rosi and Sbrana, 1987) has suggested that 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. The volcanic layers are medium to thickly bedded and are poorly sorted with a stratification ranging from subparallel to low-angle cross bedding. At the Capo Miseno tuff cone the sedimentary structures include gravity flowage ripples and slumping. Field observation 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 eruption of alternating pyroclastic flow and wet surges. The offshore elongment of the Capo Miseno-Isola Pennata and Bacoli yellow tuffs is represented by a thick volcanic unit, acoustically transparent and exposed over a large area and identified offshore the Capo Miseno volcanic promontory. The unit is interpreted as genetically related to the yellow tuffs cropping out onshore. On the slopes of the volcanic bank, deformed by normal faulting, the seismic unit is put in lateral contact with a pyroclastic unit, characterized by discontinuous and sub-parallel seismic reflectors.

Tectonic setting. The tectonic setting of the Pozzuoli seismic units is herein briefly discussed. The V3 volcaniclastic unit is intensively deformed in correspondence to three anticlinalic structures in the Gulf of Pozzuoli, respectively named the Punta Pennata anticline, the Pozzuoli anticline and the Nisida anticline. The same unit is deformed in correspondence to two synclines, namely the central syncline of the Pozzuoli Gulf and the Epitaffio syncline, individuated due to the compressional deformation genetically related to the main magmatic events of the Phlegrean Fields volcanic complex. The G3 sedimentary unit is strongly involved by wedging and growth in correspondence to older anticlines, involving the V3 unit and related synclines. The deposition of the pyr1 unit, pyroclastic in nature, is controlled by normal faulting, since it has been deposited in a structural depression located under the Capo Miseno volcanic edifice. The dk volcanic unit is represented by several dykes whose emplacement has been controlled by normal faulting in the eastern and central Pozzuoli Gulf, inducing the magma uprising along preferential pathways represented by tectonic lineaments. The pyr2 pyroclastic unit has been deposited in the eastern Pozzuoli Gulf, where it is involved by wedging and growth, testifying its deposition during vertical down throwing of normal
faults. The G2 marine seismic unit is characterized by wedging and growth in correspondence to the above mentioned anticlines and synclines. The Capo Miseno seismic unit is deformed in correspondence to both the slopes of the bank by normal faulting. A structural depression is individuated under the volcanic edifice of Capo Miseno, in which a thick pyroclastic unit deposits.

**Conclusions.** 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 ky B.P.). 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 geologic interpretation. These units are herein resumed, from the oldest to the youngest. The V3 unit, located in the Pozzuoli Gulf is characterized by acoustically transparent to discontinuous seismic facies and is strongly eroded at its top. It is a volcaniclastic unit related to the northern margin of the Pentapalummo bank. The G3 unit, located in the Pozzuoli Gulf is characterized by discontinuous to parallel seismic reflectors, representing the lower sedimentary unit of the basin fill, composed of clastic deposits. The pyr1 unit, located in the Eastern Pozzuoli Gulf, is characterized by discontinuous to sub-parallel seismic reflectors. It represents a pyroclastic unit, uncertain in attribution, deposited in a structural depression under the Capo Miseno volcanic edifice. The dk unit is represented by sub-vertical volcanic bodies, acoustically transparent and locally bounded by normal faults. This unit, detected in the eastern and central Pozzuoli Gulf, is represented by volcanic dykes due to magma uprising in correspondence to normal faults, as already suggested for the whole Naples Bay (Fusi, 1996; Fusi *et al.*, 1991). The pyr2 unit, interpreted in the eastern Pozzuoli Gulf, is characterized by a seismic facies with continuous progradational to parallel seismic reflectors. This pyroclastic unit, uncertain in attribution, has been deposited from the offshore surrounding the Capo Miseno volcanic edifice to the Miseno volcanic bank. The lsl1 unit is represented by a wedge-shaped, chaotic to discontinuous seismic unit, occurring in the eastern Pozzuoli Gulf. It is represented by a wide palaeo-landslide, overlying the V3 volcaniclastic unit and coeval with the basal part of the G2 marine unit. The G2 marine unit, identified in the Pozzuoli Gulf, is characterized by parallel and continuous seismic reflectors. It represents the intermediate unit of the basin fill, probably composed of clastic deposits. The NYT/PC seismic unit is a complex volcanic unit recognized in both the Naples and Pozzuoli Bays. The NYT unit is represented by the pyroclastic deposits of the Neapolitan Yellow Tuff (12 ky), showing a wedge-shaped, acoustically transparent, volcanic seismic unit. The PC unit is characterized by a seismic facies with mound-shaped, acoustically-transparent, volcanic bodies interlayered with parallel reflectors. The PC unit is represented by the tuff cones of the Nisida volcanic complex in facies hetheropy with the Neapolitan Yellow Tuffs and interstratified with the G3 marine deposits. The lsl2 unit is represented by a wedge-shaped, chaotic to discontinuous seismic unit. It is represented by a fossil landslide overlying the G2 marine unit and underlying the Lowstand System Tract of the Late Quaternary depositional sequence and has been interpreted in the eastern Pozzuoli Gulf. The G1 marine unit is characterized by a seismic facies with parallel and continuous seismic reflectors and has been detected in the whole Gulf of Pozzuoli. It represents the upper sedimentary unit of the basin fill, attaining a maximum thickness in the depocenter of the central basin. The LST seismic unit is characterized by progradational seismic reflectors, erosionally truncated at their top. It represents the lowstand system tract of the Late Quaternary depositional sequence and has been detected in the inner continental shelf off Pozzuoli. The lsl unit is a wedge-shaped, chaotic to discontinuous, seismic unit, detected in the Gulf of Pozzuoli, south of the Miseno Cape. It is represented by landslide...
deposits intercalated in the upper part of the lowstand system tract, locally characterized by the occurrence of palaeo-channels. The TST unit is characterized by the occurrence of retrogradational seismic reflectors. It has been detected in the eastern Pozzuoli Gulf and is represented by the transgressive system tract of the Late Quaternary depositional sequence. The HST unit, characterized by progradational to parallel seismic reflectors, has been detected in the Eastern Pozzuoli Gulf and represents the highstand system tract of the Late Quaternary depositional sequence.

References


