POST-OROGENIC EVOLUTION OF THE CENTRAL TYRRHENIAN MARGIN: INSIGHTS FROM HIGH PENETRATION AND HIGH RESOLUTION SEISMIC REFLECTION PROFILES

PhD Thesis

By

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Chapter 1

Introduction

The Tyrrhenian side of the central southern Apennines transition zone have experienced extensional processes since Late Miocene, occurring mainly along NE-SW and NW-SE main discontinuities (Liotta, 1991; Faccenna et al., 1994; De Rita & Giordano, 1996; Orsi et al., 1996; Acocella & Funiciello, 1999). NE-trending systems, cutting and interrupting the continuity of the main NW–SE striking planes, have been interpreted by several authors as transfer faults (Liotta, 1991; Faccenna et al., 1994), presumably related to the second order belt curvature (Oldow et al., 1993). Volcanic activity, aligned on a NW-SE direction, have been controlled by the same orthogonal systems of deformations (De Rita et al., 1994a; De Rita et al., 1994b; Faccenna et al., 1994; Acocella et al., 1996; De Rita & Giordano, 1996), predating and triggering magma rise (Acocella & Funiciello, 2002). The importance of NE-SW oriented transverse structures, has been also revealed by the seismic zonation of Italy (Meletti et al., 2000), individuating a NNE-SSW oriented discontinuity, representing, according to Di Bucci (2002), a barrier in the propagation of NW-SE trending active fault systems. Seismotectonic studies on this boundary sectors, within the Apennines, demonstrated the presence of NW–SE and NNE–SSW seismogenic structures, the latter still acting as transfer faults (De Luca et al., 2000; Pace et al., 2002; Milano et al., 2002, 2005). Records of strike-slip activity on NW-SE planes have been also reported by several authors in Plio-Quaternary times (Moussat et al., 1986; Sartori, 1990; Hyppolite et al, 1994; Cinque et al., 1993; Caiazzo et al., 2006; Cinque et al., 1993). The strike-slip activity on such planes has been ascribed to a broader geodynamical setting, related to the tectonic disjunction between Southern Apennines and a Calabrian arc retreating towards SE (Knott & Turco, 1991; Cinque et al., 1993; Doglioni et al., 1996).

Transverse structures acted as tear faults in compression, as transfer fault in extension, triggered volcanic activity and controlled earthquakes distribution. The occurrence from Early Pleistocene of a NW-SE directed extension, furtherly rearranged and complicated the structural pattern. The aim of this PhD thesis is to unravel the tectono-sedimentary evolution of the sector and to better understand the kinematic history of the main tectonic contacts, from Late Miocene to Holocene times. A seismostratigraphical approach is here proposed. The identification of structural styles by seismic reflection profiles is a difficult procedure that may lead to mistakes in the interpretation. Map distributions of seismically detected structures represents a fundamental tool in order to

directly observe the geometric pattern of the main faults and establish the regional stress field distribution. Three different seismic grids, located in the Gaeta Gulf, enabled structural and stratigraphical observations on the postorogenic evolution of the central Tyrrhenian margin, both on the onshore and on the offshore sectors. High penetration and high resolution seismic profiles provided different details of investigations, enabling us to better comprehend the structural pattern and the geometrical relationships between major tectonic discontinuities, merging in the study area in a complex accommodation zone.

This PhD thesis is built up as a collection of three scientific papers, presented in the next chapters, that are the result of the work done in the last three years. These complementary papers form a coherent work, pointing out relevant implications on the Neogene evolution of the central Tyrrhenian margin.

In the first of these papers data from high penetration seismic lines have been used to reconstruct the geometry and structural setting of the offshore sectors of the Latium and Campanian Tyrrhenian margin from Late Miocene to Quaternary times. The 3D modelling of the base of the Plio-Pleistocene seismic units revealed the occurrence of NNE-SSW and WNW-ESE right and left-lateral shear zones. Tulip, palm tree flower structures and other structural features have been seismically detected an mapped, in order to create a synthetic structural maps and a kinematic model of a relatively unexplored sector.

In the second paper, high penetration seismic reflection profiles, kindly provided by ENI s.p.a, enabled the reconstruction of the deep structural architecture of the Volturno Plain, where deep wells reported at least 3km of Pleistocene continental and marine deposits. Releasing bends, structural inversions and normal listric faults have been displayed by seismic profiles, enabling the reconstruction of the main principal displacement zones (PDZs) active in Pleistocene times.

In the third and last paper, the Late Quaternary-to Holocene evolution of the northern Campania continental shelf has been investigated by the interpretation of a grid of high resolution Sparker and Chirp sub-bottom profiles. Morphobathymetric maps were reconstructed by the interpolation of seismically detected horizons, enabling in this way structural observations. Igneous intrusions, degassing features and minor faulting have been seismically detected and interpreted in a more comprehensive regional framework.

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Chapter 2

Postorogenic evolution of the central Tyrrhenian continental margin (central Italy)

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Abstract

Data from high penetration seismic lines have been used to reconstruct the geometry and structural setting of the Latium and Campanian Tyrrhenian margin from Late Miocene to Quaternary times. At a regional scale, a high penetration seismic grid located in the offshore sector of the margin, enabled the recognition of three main seismic units. Seismic interpretation was calibrated using Mara1 and Mondragone 1 deep wells, coupled with analyses on coastal outcrops. The identification of three main acoustic units allowed us to create 3D surfaces representing their relative boundaries. The bottom of the Plio-Pleistocene seismic unit and the top of the highly deformed acoustic substratum (B and A horizons, respectively) have been modeled throughout the margin. This reconstruction enabled us to imagine structural and depositional features within the acoustic substratum and the post-orogenic covers, respectively. The base of the Plio-Pleistocene seismic unit revealed an articulated surface, where relative highs and lows appear to be shifted along NNE-SSW and WNW-ESE right and left-lateral shear zones. Tulip and palm tree flower structures have been observed and their location defined the strike-slip stepover geometry of the main structural planes. The youngest seismic unit, resting above horizon B, was distinguished in three depositional sequences, correlatable to the well-known Plio-Quaternary transgression-regression cycles that affected the eastern Tyrrhenian continental margin. A 3D modelling of their relative sequence boundaries revealed a general basinward migration of mainly NW-SE elongated maximal depocenters, separated by a major E-W ridge. The formation of this structure has been referred to the arrangement of two overstepping E-W discontinuities, locally creating a restraining bend and interpreted as synthetical planes to the observed WNW-ESE main displacement zone.

1. Introduction

The Southern–Central Apennines Transition zone is crossed by major tectonic boundaries whose role and kinematics was the result of distinctive tectonic events affecting the margin from Late

Miocene to Pleistocene times. Separating the arcuate northern-central Apennines and the mainly NW-SE oriented southern segment, the NNE–SSW striking Ortona–Roccamonfina tectonic line (Locardi, 1982; Patacca and Scandone, 1989;) represents a main structural discontinuity. Most authors are in accordance conferring to this line a right-lateral kinematics in post-Messinian times (Locardi et al., 1982; Patacca et al., 1990; Di Bucci &Tozzi, 1991; Ghisetti &Vezzani, 1991; Ghisetti, Vezzani &Follador, 1993). Different structural styles of deformations, both in thrust mechanisms and in extensional features, affected the northern and the southern sectors of the Apennine-tyrrhenian system. ESE of this crustal decoupling zone (Patacca et al., 1990), the stacking of tectonic units in thrusting processes (Scrocca et al., 2010) were influenced by the presence of pelagic units, resulting in thick and terrigenous sheets covering the Apulia units (Mostardini and Merlini, 1986; Corrado et al., 1997). A shallower trusting involving the Apulia units occurred instead in the northern sectors. The asymmetry in the opening of the Tyrrhenian Sea reflected also a difference in the resulting extensional tectonics. Subsidence rates related to the Messinian rifting phases, affecting the central-southern coastal plains, reported values of 5mm/yr, while records of 1.25mm/yr were reported for the northern domains (Cipollari et al., 1999). In Northern Apennines major listric E dipping and low angle normal faults with a staircase trajectory controlled the evolution of the resulted basin structures (Barchi et al., 1998a; Decandia et al., 1998; Barchi et al., 2010), recording an extension co-axial with the maximum shortening direction, related to the opening of the Tyrrhenian basin (Malinverno & Ryan, 1986; Kastens et al., 1988; Sartori, 1990; Lavecchia, 1987; Patacca & Scandone, 1989). The Late Miocene-Pliocene eastward migration of the Tyrrhenian extension was also recorded in the central-southern sectors, resulting in major high angle NW-SE normal faults (Patacca et al., 1990; Sartori, 1990). Starting from early Pleistocene a NW-SE stretching direction, creating major NE-SW normal faults (Moussat et al., 1986; Sartori et al., 1990; Hyppolite et al, 1994; Cinque et al., 1993; Caiazzo et al., 2006) superposed on the previous rifting stages. Records of an interrelated strike-slip regime (Angelier & Bergerat, 1983) creating NW-SE left-lateral transtensive faults were observed in the Cilento and Sorrento regions (Cinque et al., 1993; Caiazzo et al., 2006), dating back to Pliocene times (Turco et al., 1990; Ascione & Cinque, 1996) and in the Pollino Ridge, dissecting also lower-middle Pleistocene deposits (Monaco & Tansi, 1992; Schiattarella, 1998). The Cilento-Pollino shear zone is another major tectonic discontinuity whose northern tip seems to affect also this sector of the Tyrrhenian margin. The strike-slip activity on such planes has been ascribed to a broader geodynamical setting, related to the tectonic disjunction between Southern Apennines and a

Calabrian arc retreating towards SE (Knott & Turco, 1991; Cinque et al., 1993; Doglioni et al., 1994). Many authors suggest also the presence of an E-W structural discontinuity separating the Northern Tyrrhenian domain from the Southern, known as the '41st Parallel Line'. The structural meaning of this discontinuity is still debated. Some authors (Lavecchia, 1987; Boccaletti et al., 1990; Oldow et al., 1993; Ferranti et al., 1996; Carminati et al., 1998) suggested that this tectonic line should have acted as a transfer fault characterized by left-lateral movements resulted by the asymmetry in the opening of the Tyrrhenian Sea. The merging area of all these major structural discontinuities corresponds to the northern Campania-southern Latium margin (Fig.1).

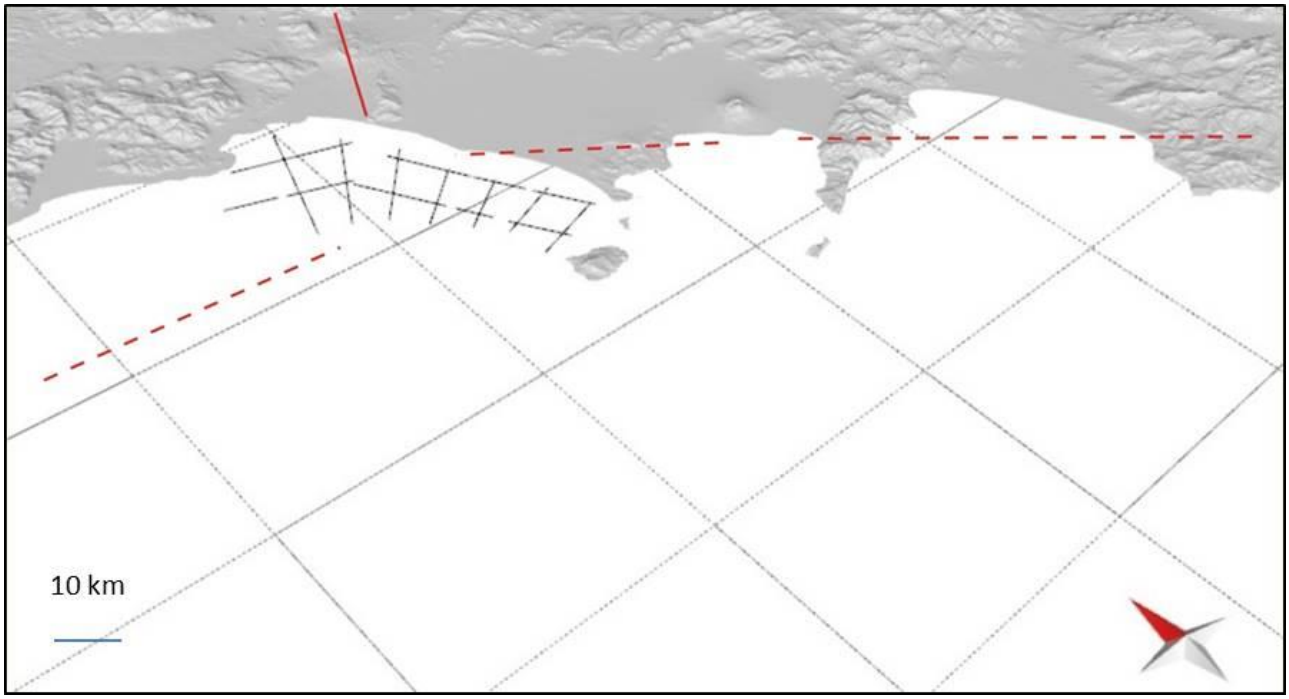

Figure 1: Synthetic sketch representing the area of study, evidencing how it corresponds to the merging area of the 41st parallel, ORL and Pollino-Cilento discontinuities tips.

The present study has been carried out in order to unravel the structural pattern of the area and the geometrical relationships between these tectonic lines in a complex accommodation zone. A grid of high penetration seismic reflection profiles enabled structural and stratigraphical observations finalized to improve the general knowledge on the Late Tertiary-Quaternary evolution of the offshore sectors of this key area.

2. Geological framework

The inner sectors of the Central-Southern Apennines have been involved in the tectonic wedge during Late Tortonian times (Fig.2), as revealed by thrust top and foredeep basins cropping out in

the Lepini-Ausoni-Aurunci tectonic Unit and in the Massico Mt (Cipollari and Cosentino, 1995a, b; Cosentino et al., 2003).

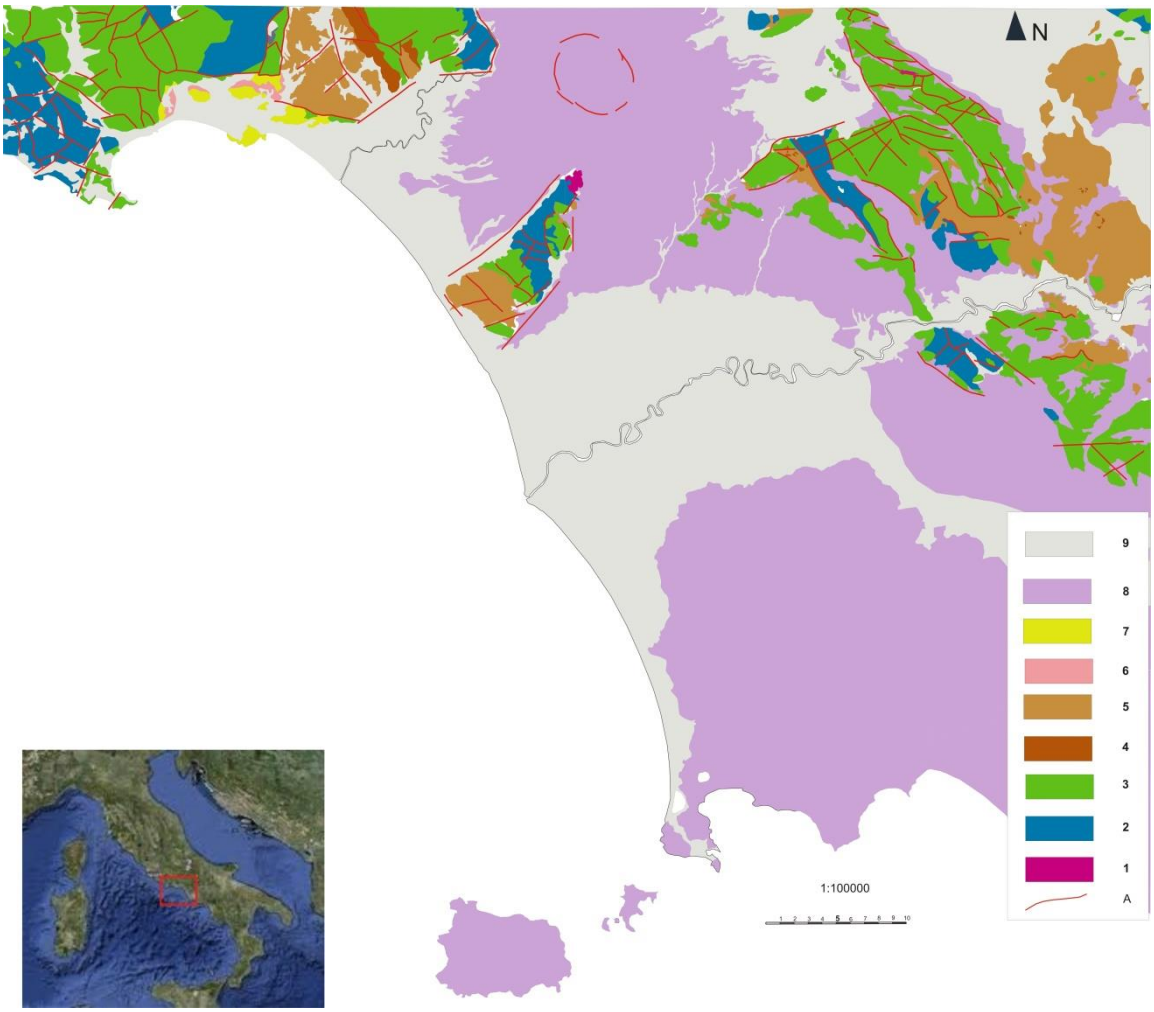

Figure 2: Structural sketch map of central-southern Apennines. Legend: 9) Pleistocene-Holocene alluvial deposits; 8) Quaternary volcanic deposits; 7) Early Pleistocene conglomeratic deposits; 6) Upper Messinian gypsum-bearing clays; 5) Late Tortonian siliciclastic foredeep deposits; 4) Langhian-Serravalian *Calcari a Briozoi e Litotamni* Fm; 3) Cretaceous shallow water limestones; 2) Jurassic shallow water limestones and dolomites; Triassic dolomites and limestones; A) undifferentiated faults.

The shifting of the related extensional back arc area at the rear of the orogenic system (Malinverno & Ryan, 1986; Kastens and Mascle, 1990; Boccaletti et al., 1990; Patacca et al., 1992; Carmignani et al., 1995; Faccenna et al., 1996; Jolivet et al., 1999; Pascucci et al., 1999; Cipollari et al., 1999; Mattei et al., 2002) resulted in late Messinian syn-rift deposits, as testified in the area by the outcrops, in the northwestern sectors of the Formia Plain, of gypsum-bearing clays (Cipollari et al., 1999). Evidence of late Messinian extensional tectonics have been recognized in the offshore on the Tyrrhenian ODP sites (Cita et al., 1990; Kastens and Mascle, 1990; Mascle and Rehault, 1990; Robertson et al., 1990; Sartori, 1990). Resting above upper Messinian sediments in the

Mondragone deep well, Pleistocene deposits characterized by cyclical alternations of marls, calcareous marls with frequent intercalations of sands and conglomerates bodies, correlated with the so colled “Conglomerati di Minturno” Auct., (Catenacci &Molinari, 1965; Naso & Tallini, 1993; Giordano et al., 1995; Cosentino et al., 2006) have been found. Three main depositional sequences related to major transgressive-regressive cycles affected the whole eastern Tyrrhenian margin from Pliocene to Quaternary times (Barberi et al., 1994). Two depositional sequences separated by an erosional unconformity characterize the Pliocene succession. From 4.9 to 3.2 My, extending from the *Sphaerodinaellopsis seminulina* to the *G. puncticulata* Zone, the first cycle is erosionally truncated by the transgressive calcareous sandstones corresponding to the *G. aemiliana* Zone of the second sedimentary cycle. Pleistocene marine clayey sands constitute the third depositional sequence. The unconformities between these depositional sequences have been related to major tectonic events producing hiatuses proportional to the resulted vertical movements affecting the eastern Tyrrhenian margin in Plio-Quaternary times. Starting from middle Pleistocene the onset of the Roccamonfina volcanic activity lead to the deposition of volcanoclastic and lava bodies (Giordano et al.,1995). The study area is located on the offshore sector of the Garigliano and the Volturno basins, in the Gaeta Gulf. The mentioned structures are separated by the Massico Mt., a roughly NE-SW trending horst located at the southern tip of the Ortona-Roccamofina tectonic line (Patacca et al., 1990; Mantovani et al., 1996; Billi et al., 1997). Two NE-SW Pleistocene normal faults bound respectively to the NW and to the SE the structure, individuating the Garigliano and the Volturno half-graben (Billi et al., 1997). Data from boreholes revealed different thickness in the quaternary infillings for the two basins. Cellole Aurunci deep well, located in the Garigliano basin, pointed out 700 m of Quaternary infralittoral to delta plain deposits, while subsidence rates much more intense have been recorded by deep boreholes located in the Volturno basin, where Castelvoturno 1, 2 and 3 recorded 3000 m of Quaternary marine to continental deposits (Ippolito et al., 1973; Giordano et al., 1995).

2.1. Succession of deformational events

A chronology of literature reported deformational events affecting the Tyrrhenian side of Central-Southern Apennines from Late Miocene to Late Pleistocene times is here proposed. According to Caiazzo et al. (2006), conducting a morphotectonic study on the carbonate promontories of Sorrento peninsula and Bulgheria Mt, four different deformational events controlled the evolution of the area. During middle-late Miocene, a strike-slip to subordinately compressional event with a

NW-SE maximum shortening direction was responsible for the main right-lateral NW-SE faults cropping out in the Sorrento peninsula. The successive deformational event, taking place in Pliocene times, was characterized by a N-S oriented σ_1 producing both strike-slip and an interrelated homoaxial extensional regime with an E-W oriented stretching direction. It was responsible for the creation of transpressive structures, normal to oblique NW-SE faults and the reactivation of previous E-W striking faults. Thus, from Mid-Late Miocene to Pliocene times the σ_1 changed from a NW-SE striking direction to a N-S main trend. According to Capotorti & Tozzi (1991), this major change in the structural pattern of deformations should invoke "block faulting rotations" processes instead of major changes in the stress field orientation. According to Caiazzo et al. (2006) a 60° counterclockwise rotation recognized by Gattacceca & Speranza (2002) affecting Mt. Bulgheria during Late Miocene, should explain a change in the orientation of the observed structures. An anticlockwise rotation, induced by the progressive arcuation of the belt, has been also proposed by Ferranti et al. (1996). According to the author this process has been accompanied by a NW-SE extension recorded in the internal sectors of Southern Apennines during Mio-Pliocene times (D'argenio et al., 1987; 1993; Oldow et al., 1993). This orogen-parallel extension, following the interpretation proposed by the author, ceased in Pleistocene times, with the onset of a NE-SW extension direction (Oldow et al., 1993; Ferranti et al., 1996). Several authors recognized instead a NW-SE stretching direction with an interrelated strike-slip regime taking place in the area since early Pleistocene times (Moussat et al., 1986; Sartori, 1990; Savelli and Schreider, 1991; Hyppolite et al., 1994; Milia &Torrente, 1999; Caiazzo et al., 2006). This event, corresponding to the third deformational event recognized by Caiazzo et al. (2006), was responsible for the formation of coastal graben bounded by NE-SW normal faults, as observed in the Garigliano, Volturno and Sele basins (Giordano et al., 1995; Aiello et al., 1997; Bruno et al., 1998) and for the formation of major left-lateral transtensive faults observed mainly in the Cilento-Pollino region (Turco et al., 1990; Monaco & Tansi, 1992; Cinque et al., 1993; Ascione & Cinque, 1996; Schiattarella, 1998; Caiazzo et al., 2006;). The fourth and final Late Quaternary extensional event recognized by the author was characterized by a NE-SW oriented σ_3 resulting in NW-SE normal faults with medium to small scale vertical offsets and seems to be still active (Caiazzo et al., 2006). Fault planes have been reactivated several times by distinctive deformational events affecting the margin. Several studies pointed out the importance of strike-slip movements in this sector of the Tyrrhenian margin where tectonic inversions started to occur during Pliocene times, mainly with a right-lateral kinematic and continued in early middle

Pleistocene with a major transtensive regime with a left-lateral kinematic on NW-SE faults (Turco et al., 1990; Monaco & Tansi, 1992; Cinque et al., 1993; Ascione & Cinque, 1996; Schiattarella, 1998; Saitto et al., 2002; Caiazzo et al., 2006;).

3. Methods

We have interpreted a grid of 15 high penetration seismic reflection profiles acquired by the Western Geophysical Company in 1968, documents accessible on Ministry of Economic Development website. Seismic sections have been calibrated with Mara1 and Mondragone deep wells, located respectively offshore and onshore the Gaeta gulf (Fig.3). To better calibrate the interpretation of the deep seismic sections some field works were carried out in the Garigliano and Volturno plains, as well on the Massico Mts. The approach here used is based on seismo-stratigraphic techniques. Criteria involved in this method mainly consist in the individuation of main discontinuities in the stratal architecture, in order to identify external shapes and internal configurations, attributable to already interpreted geometries and stratal patterns (Mitchum et al. 1977, Vail et al. 1977). Map distribution of the more relevant structures, a 3D modelling of sequence boundaries and the observation of the migration of depositional depocenters enabled the reconstruction of a kinematic model.

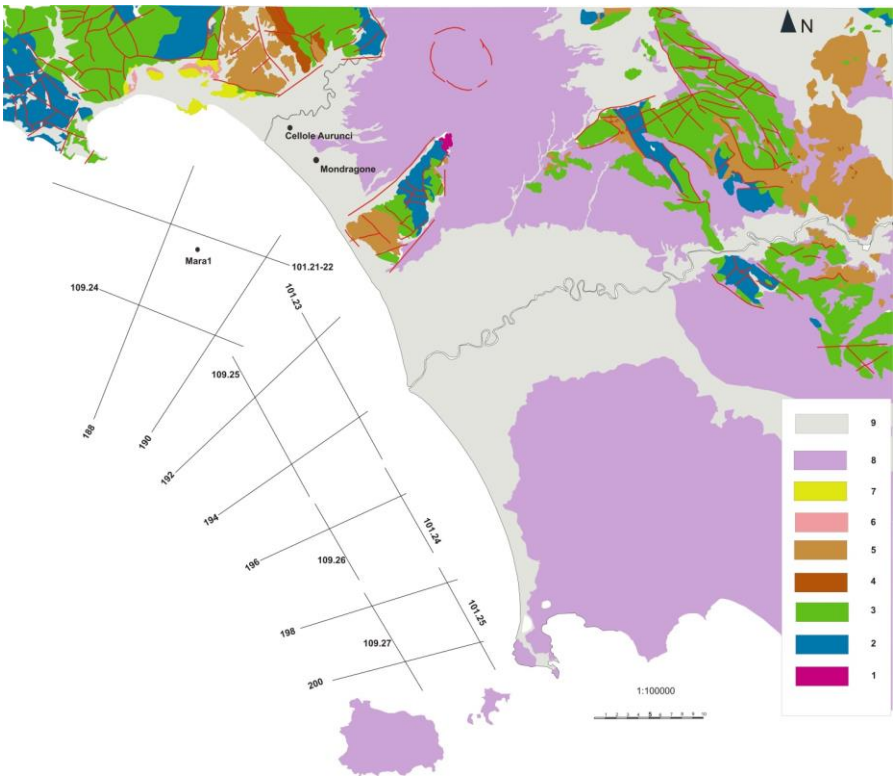

Figure 3: Location of the 15 high penetration profiles interpreted and of Mara1, Cellole Aurunci and Mondragone deep wells.

4. Seismic dataset presentation

4.1. Seismic units

We have recognized 3 major seismic units throughout the margin distinguished by two horizons. The top seismic sequence (unit3) has been further divided in three subunits separated by two main boundaries. A lenticular external shape and an internal prograding reflection configuration have been recognized for this seismic unit (Fig.4).

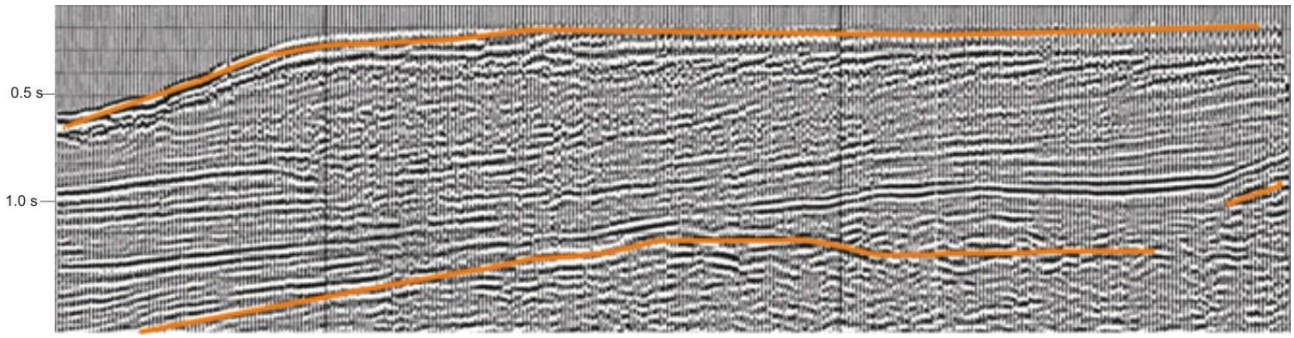

Figure 4: Seismic unit 3: evidence of its lenticular external configuration and progradational internal pattern.

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Unit 3 is characterized by generally continuous reflections of middle-high amplitude, with parallel and sometimes divergent geometries. Three subunits constitute seismic unit3, corresponding, bottom to top, to Unit 3a, 3b and 3c. The top subunit displays a sigmoid progradational pattern with gently dipping reflections. The preservation of topsets, reaching at very low angles the surface, suggest processes of upbuilding in stratal architecture (Mithcum et al., 1977). Low angle downlap terminations have been revealed by its bottomsets. Unit 3b shows S-shaped clinoforms with gently dipping upper and lower segments and more steep middle segments. Toplap in the upper reflections and onlap-downlap terminations of middle to low amplitude reflections have been observed. Unit 3a displays medium to high amplitude reflections in a prograding configuration, with stratal reflections exhibiting a less clear lateral continuity. Disrupted reflectors, toplap terminations and a subparallel to divergent geometry characterize the bottom subunit 3a. A synthetic image (Fig. 5a, 5b) shows the stratigraphical features described for above presented seismic subunits. We pass down to a different acoustic signal, with stratal reflection arranged in a more chaotic pattern. Seismic horizon B constitute the upper boundary of Unit2 and is clearly traceable all over seismic profiles. The transition to the below unit is marked by high amplitude disrupted reflectors. A lenticular and sometimes wedge shaped external configuration characterize

the second seismic unit. Its internal reflection pattern varies from more or less bedded diverging stratal architecture with medium to high amplitude reflectors, to chaotic and disorganized configurations (Fig.6). The transition to the below unit 1 is marked by an irregular horizon (Horizon A). Discontinuous and disrupted low amplitude reflections characterize this bottom unit (Fig.7).

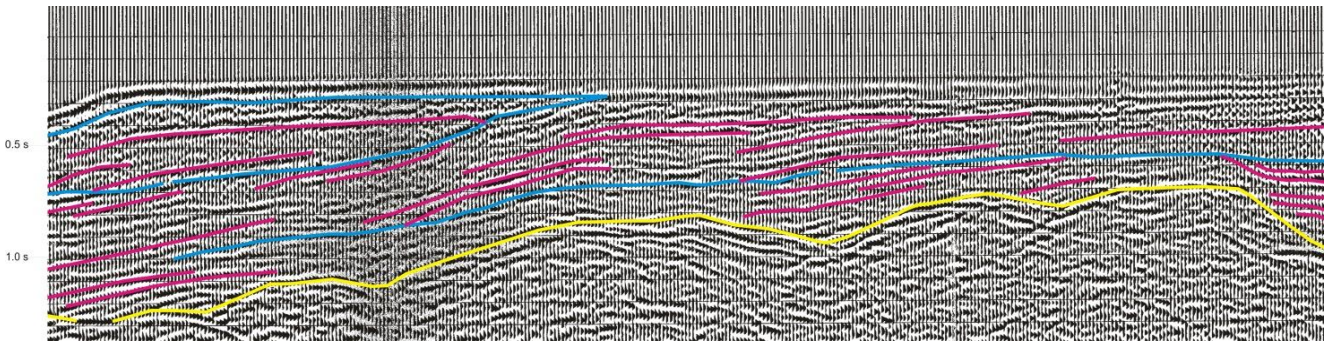

Figure 5a: Seismic unit3: in yellow we have represented the base of the Plio-Quaternary sequences, in blue the unconformities (U1, U2) bounding the imaged subunits 3a, 3b and 3c. Unit 3b shows S-shaped clinoforms with gently dipping upper and lower segments and steeper middle segments.

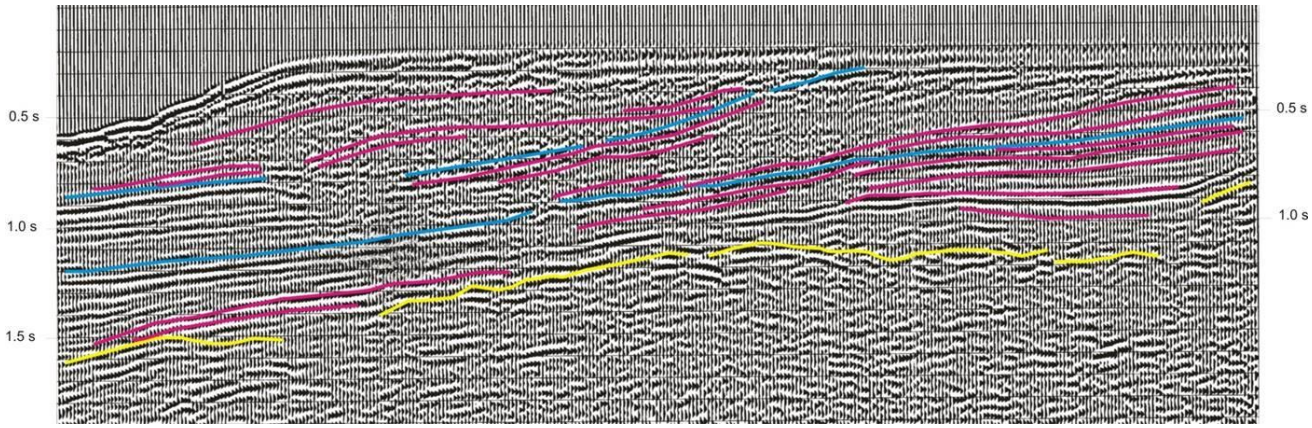

Figure 5b: Seismic unit3: in yellow we have represented the base of the Plio-Quaternary sequences, in blue the unconformities (U1, U2) bounding the imaged subunits 3a, 3b and 3c. Disrupted reflectors, toplap terminations and a subparallel to divergent geometry characterize the bottom subunit 3a.

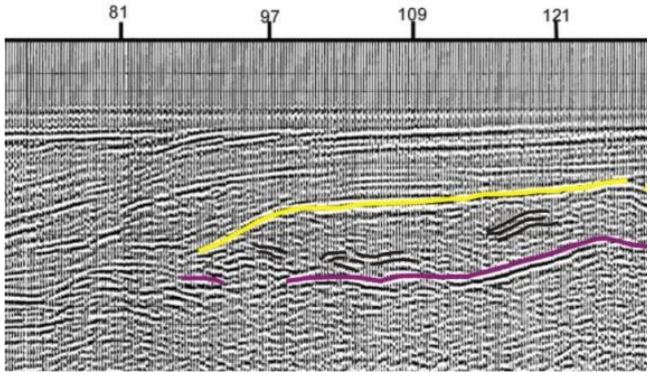

Figure 6: In yellow we have represented the base of the Plio-Quaternary sequences (B horizon) and in violet the top of the Apennine chain units (A horizon). Seismic facies of Unit2: internal pattern characterized by more or less bedded to chaotic stratal reflections.

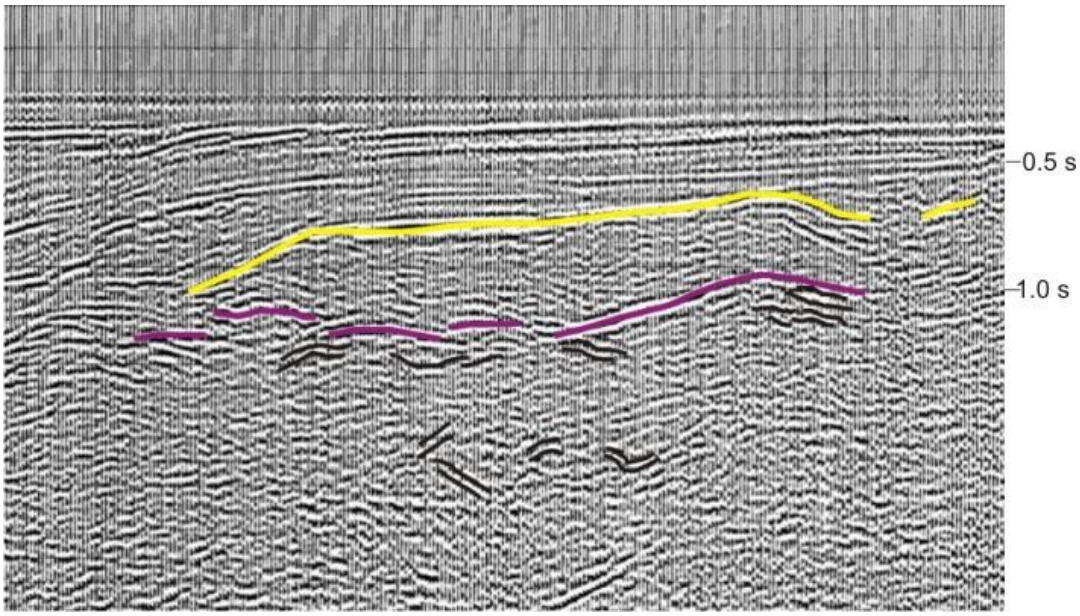

Figure 7: In yellow we have represented the base of the Plio-Quaternary sequences (B horizon) and in violet the top of the Apennine chain units (A horizon). Seismic facies of unit1: disrupted high amplitude reflectors characterize this acoustic unit.

5. Seismic calibration

Boreholes data coming from Mondragone and Mara deep wells and field works performed in the Garigliano and Volturno plains, as well on the Massico Mts, enabled the calibration of deep seismic profiles.

5.1. Wells description

5.1.1. Mondragone1

The Mondragone 1 well is located in the Garigliano coastal plain (AGIP-DIMI, 1969). Reaching a total depth of 2002 meters (Fig.8), the deep well recorded a Late Miocene to Quaternary succession (Cosentino et al., 2006). According to the reinterpretation of the composite-log proposed by the author, the first 200m of sands and clayey sands sediments, with frequent intercalations of volcanic deposits, are attributable to an upper Pleistocene-Holocene succession. The following interval individuated by the author consists of a 370m thick marly zone, passing down at 570m to coarse-grained deposits characterized by 100 m of sands , gravels and conglomerates bodies correlated with “Conglomerato di Minturno” Auctt. This succession has been correlated with an early-middle Pleistocene interval. An angular unconformity, as suggested

by the dipmeter measurements, occurred at 675m separating the above described succession from the underlying deposits. Siltstones, marly clays, sandstones and frequent intercalations of conglomeratic bodies characterize the following interval continuing until 2002m of depth. The ostracod assemblages recognized in the interval observed from 675m downward, pointed out a Late Messinian *Lago-Mare* succession (Grekoff and Molinari, 1963; Gramann, 1969; Molinari Paganelli, 1977; Benson, 1976; Roep and van Harten, 1979; Krstic and Stancheva, 1990; Gliozzi, 1999; Cipollari et al., 1999; Bonaduce and Sgarrella, 1999; Gliozzi et al., 2002). The 675 m depth unconformity recognized by Cosentino et al. (2006) and seismically detected by the same author on several high penetration profiles covering the basin, seems to separate a Pleistocene from a Late Miocene successions, without recording any Pliocene marker. The Late Messinian deposition suggests an initial increase in accommodation space followed by a decrease in water depth (Cosentino et al., 2006). Uplifted and tilted blocks could have been responsible for the lacking of Pliocene recordings (Cosentino et al., 2006). The Late Messinian succession drilled in Mondragone 1 deep well has been correlated with the pre-Pliocene deposits recognized in the Tyrrhenian bathyal plain at the ODP Site 652 (Cosentino et al., 2006).

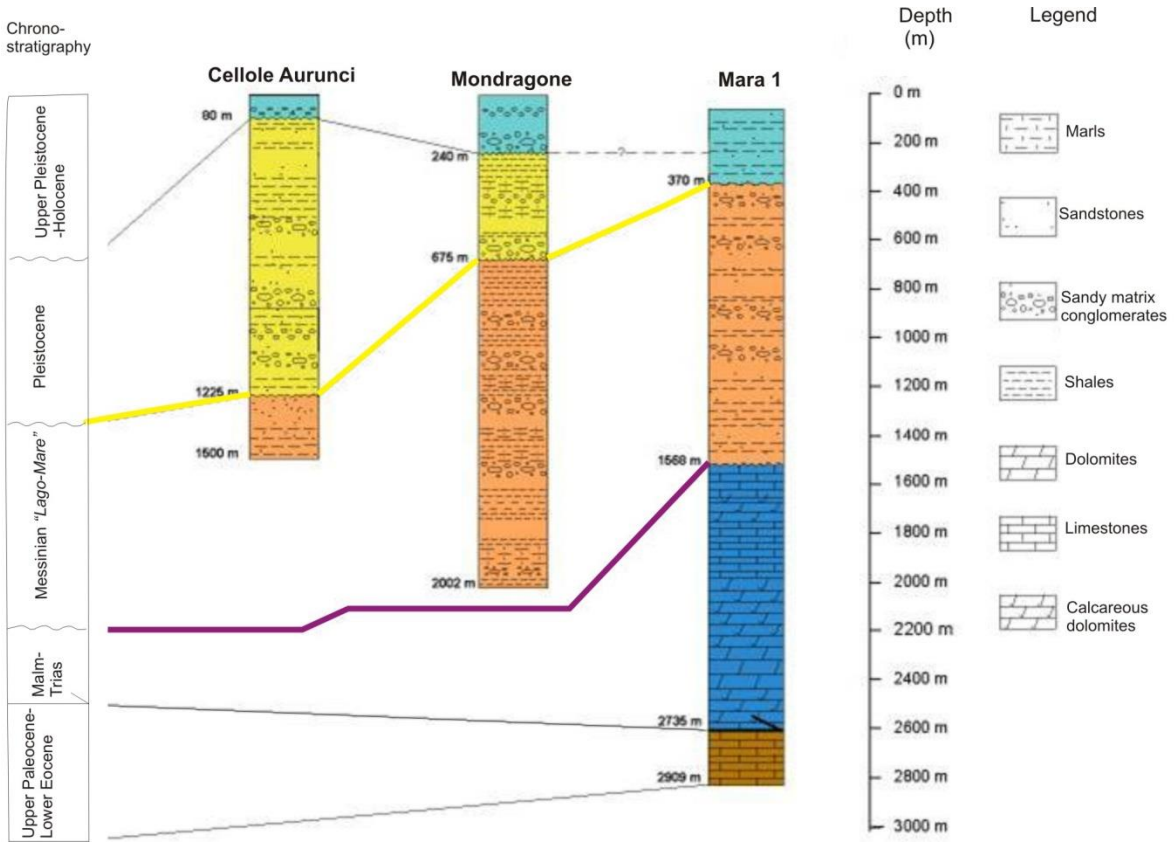

Figure 8: Reinterpretation of the Mondragone 1 well, proposed by Consentino (2006) and tentative correlation with Mara1 and Cellole Aurunci deep well, calibrating seismic data.

5.1.2. Mara1

Mara 001 well is a 2909m long core (Fig.8) located in the immediate offshore of the Garigliano basin (AGIP-DIMI, 1969). The first 350m are characterised by Pleistocene clayey sands passing down to 1200m of siltstones, marly clays, sandstones and frequent intercalations of conglomeratic bodies. An indicative and general Miocene age has been attributed to this interval by the authors of the borehole stratigraphy, referring the last 325m to the "Frosinone Flysch" Auctt (AGIP-DIMI, 1969). Downward, from 1568m to 2735m, the borehole stratigraphic description pointed out Mesozoic carbonates thrusting onto Meso-Cenozoic carbonatic and siliciclastic deposits, closing the recorded succession. Lithologic analogies in the Miocene alternations of marly-clays, sandstones and mega-beds of polygenic conglomerates have been recognized with the reinterpreted Late Messinian succession observed in the Mondragone 1 deep well (Cosentino et al., 2006). Similarities in the spontaneous potential log, characterizing rock formation properties of such intervals, have been recognized (Ilaria Federici, unpublished thesis, 2005), suggesting a possible correlation of the Late Messinian Lago-Mare succession recognized in Mondragone 1 well with the 1200m thick Miocene siliclastic deposits reported in Mara1 long core.

5.2. Field work

The highly deformed carbonatic Meso-Cenozoic shallow-water carbonate substratum succession of the Massico Mts ends with the Middle Miocene carbonate-ramp deposits (*Calcari a briozoi e litotamni* Fm). Conformably on those shallow-water limestones, Massico Mt. show marls rich in planktonic foraminifera (*Marne a Orbulina* Fm). On a clear erosional surface cutting down the Meso-Cenozoic substratum, we observed a coarse-grained siliciclastic succession containing olistostromes with allochthounous materials (marbles) and carbonate from the substratum (Fig.9). The basal unconformity and the occurrence of some compressional deformation within this unconformable bounded stratigraphic unit, point to interpret this deposit as sedimented into a thrust-top basin. Biostratigraphical analyses on the calcareous nannofossil assemblages of the *Marne a Orbulina* Formation were carried out in order to find a chronostratigraphical constrain to define the maximum age of the thrust top basin. Unfortunately no useful markers were found. A possible post-Tortonian age for the deposit was suggested by analogy with the Torrice, Gavignano and Caiazzo units, located nearby the study area (Cosentino et al., 2003).

Figure 9: Picture took on the Massico Mts showing a coarse-grained siliciclastic succession containing olistostromes.

5.3. Seismic units calibration

The first seismic unit (Unit3) showing a sigmoidal external configuration has been furtherly subdivided in minor subunits constituted by an internal progradational stratal pattern. Data from literature reported at least three main depositional sequences related to major transgressive-regressive cycles affecting the whole eastern Tyrrhenian margin from Pliocene to Quaternary times (Barberi et al., 1994). Following the stratigraphic reconstruction offered by the author, top to bottom the first seismic subunit 3c could be correlated with Pleistocene marine clayey sands constituting the third cycle individuated by the author along the central eastern Tyrrhenian margin. Piacenzian calcareous sandstones characterizing the second transgressive-regressive cycle could be referred to our seismic subunit 3b. In this way the bottom subunit 3a should be correlated with Clays and marly clays related to the lower Pliocene (Zanclean) marine transgression. The unconformities separating the cycles previously discussed seem to have been controlled by major tectonic events, producing main erosional surfaces. The offshore calibration covered only the upper part of seismic subunit 3c, recording 300 m of upper Pleistocene marine clayey sands directly deposited above Upper Messinian sediments. A more continuous record was offered by Mondragone 1 deep well, constraining also the lower part of seismic subunit 3c. 675 m

of Pleistocene deposits characterized by cyclical alternations of marls, calcareous marls with frequent intercalations of sands and conglomerates rested above Upper Messinian sediments in the 2002m deep borehole. The lacking of a clear datum to calibrate seismic subunit 3b and 3a led us to refer our subunits to the depositional sequences related to Pliocene transgressive-regressive cycles individuated by Barberi (1994). Below B horizon separating the first and the second seismic unit we have an acoustic body characterized by different internal configurations. The geological interpretation of Unit 2 is still uncertain lacking a clear datum to calibrate it. On land it was partially drilled by Mondragone 1 and Cellole Aurunci wells and offshore Mara 1 well offered a stratigraphical description for that interval. The original litholog of those boreholes reports the deposits corresponding to this seismic unit as Frosinone Flysch (Agip-Dimi, 1969). Biostratigraphical analyses carried out on a new sampling on Mondragone deep well cores (Cosentino et al., 2006) allowed to better characterize the fauna and to update the description of the stratigraphy. The deposit drilled below the 675 m depth unconformity found in Mondragone 1 well is characterized by an alternation of clay and sands with intercalations of conglomerate beds and corresponds to the uppermost portion of post-evaporitic succession (p-ev2). A possible correlation of that deposit with the interval 350-1568m depth in Mara 1 well was also suggested. In the study area on land geology shows the presence, on top of the deformed substratum, of Late Messinian syn-rift basins (Cipollari & Cosentino 1992; Cipollari et al., 1999). In the vicinity of the study area it is also well documented the presence of early Messinian thrust-top basins, such as Torrice, Gavignano and Caiazzo Units (Cosentino et al., 2003). Seismic lenticular bodies on top of the Apennine units have been seismically detected, though the complexity in the internal organization, a low quality of signal and the absence of a certain datum to calibrate our seismic lines, led us to give for that unit only a general seismostratigraphical description. The bottom unit (Unit1) has been correlated with the Apennine chain units. It represents the acoustic substratum, characterized in the area by shallow-and deep-water carbonates and siliciclastic foredeep deposits as suggested by the control offered by Mara 1 deep well.

6. Structural analysis

6.1. Seismic profiles

The stratigraphic interpretation of high penetration seismic reflection profiles pointed out the presence of three sequences distinguished by two major horizons (A, B). Within Unit 3 we have recognized three sigmoidal depositional sequences bounded by two erosional surfaces (U1, U2).

Seismic lines (188, 192, 101.21-22, 101.23, 109.25) enabled also structural observations revealing deformations resulted from distinctive tectonic events from Late Miocene to Pleistocene times. Seismic lines 188 (Fig.10) and 101.21.22 (Fig.11), dip and strike sections respectively, showed the occurrence of lateral ramps of NE verging thrusts deforming Unit 1. Different positions in frontal thrust sheets have been displayed for the northern and southern sectors.

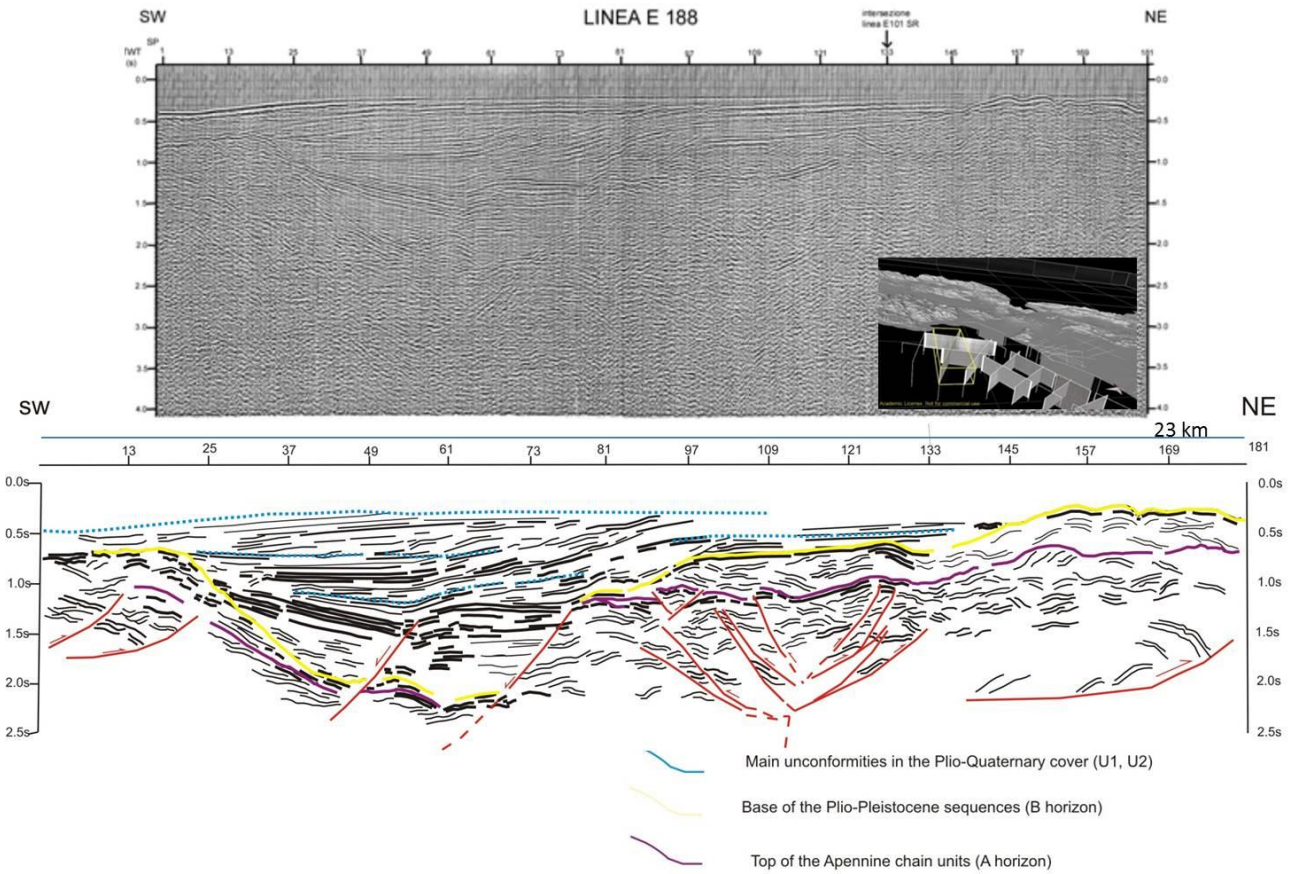

Figure 10: seismic profile 188: a dip section showing NE Verging thrusts, SW dipping normal faults, affecting seismic subunit 3a and a palm tree like flower structure, deforming seismic units 1 and 2.

Strike Seismic sections 101.23 (Fig.12) and 101.21-22 revealed the presence of mainly NW dipping NE-SW normal listric faults, cutting A horizon and characterizing the wedge like external configuration of Unit2. E-NE and W-SW verging thrusts affecting Unit 1 and Unit 2 have been observed in northern sectors of the interpreted grid, describing an upward spreading structural pattern, observed in seismic dip and strike sections 188 and 101.21-22. The same trending upward spreading system of deformations have been recognized in the southern sector. Seismic section 101.23 allowed the recognition of downward linking WNW-ESE main thrusts deforming Unit 1 and Unit2, up and down-throwning the related A and B horizon. In the same section NE-SW normal

faults control the wedging geometry of Unit2 and seem to correspond to lateral ramps of NE verging thrusts, later reactivated in extension.

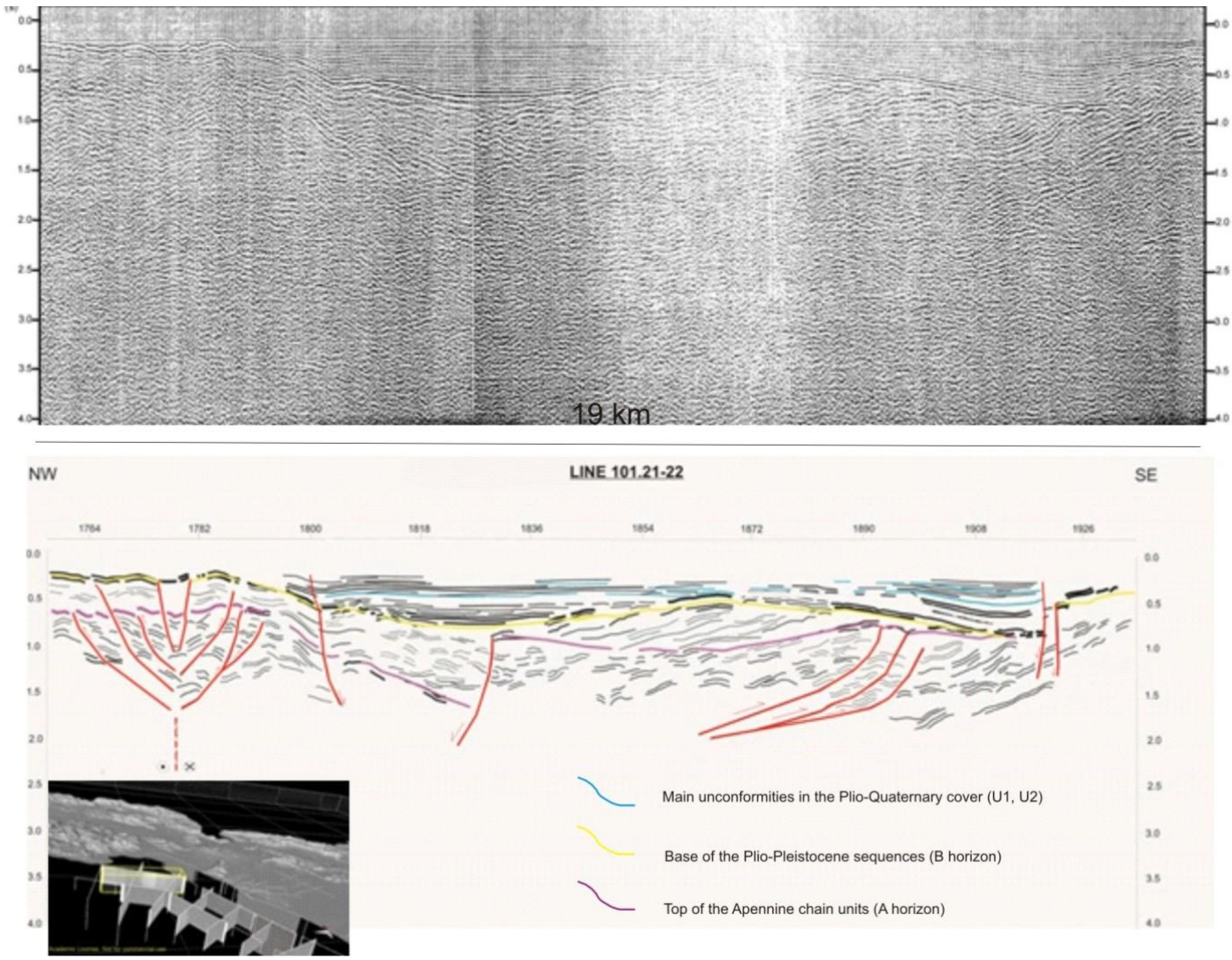

Figure 11: seismic section 101.21-22: a strike profile showing the occurrence of lateral ramps of NE verging thrusts, NW dipping normal faults, controlling the wedge like external form of Unit2 and evidencing the presence of a tulip like structure, affecting unit 1 and 2. Finally, NW and SE dipping normal faults cut all the imaged units.

This profile showed the occurrence of an inversion in the polarity of structural relief controlled by a fault plane, traced also on seismic section 192 (Fig.13), initially controlling in extension the late Messinian deposition of Unit 2 and later upthrowing the individuated block, as testified by kinks and digitisation in the stratal reflections of the above Unit3. Similar kinkings in the Plio-Pleistocene stratal reflections constituting seismic Unit3 have been also observed in section 192. This dip section revealed a system of deformations characterised by ENE-WSW verging thrusts accommodating the growth of a structure. The same system of deformations have been observed on seismic profile 109.25 (Fig.14), a strike section cutting the structure along another direction and

intersecting the above described seismic profile. NW and SE verging and downward linking thrusts, deforming Unit 1 and Unit 2, seem to affect also sub unit 3c, revealing kinks above the growing structure. NE-SW normal faults cut all the mentioned units, as testified by seismic section 101.21-22.

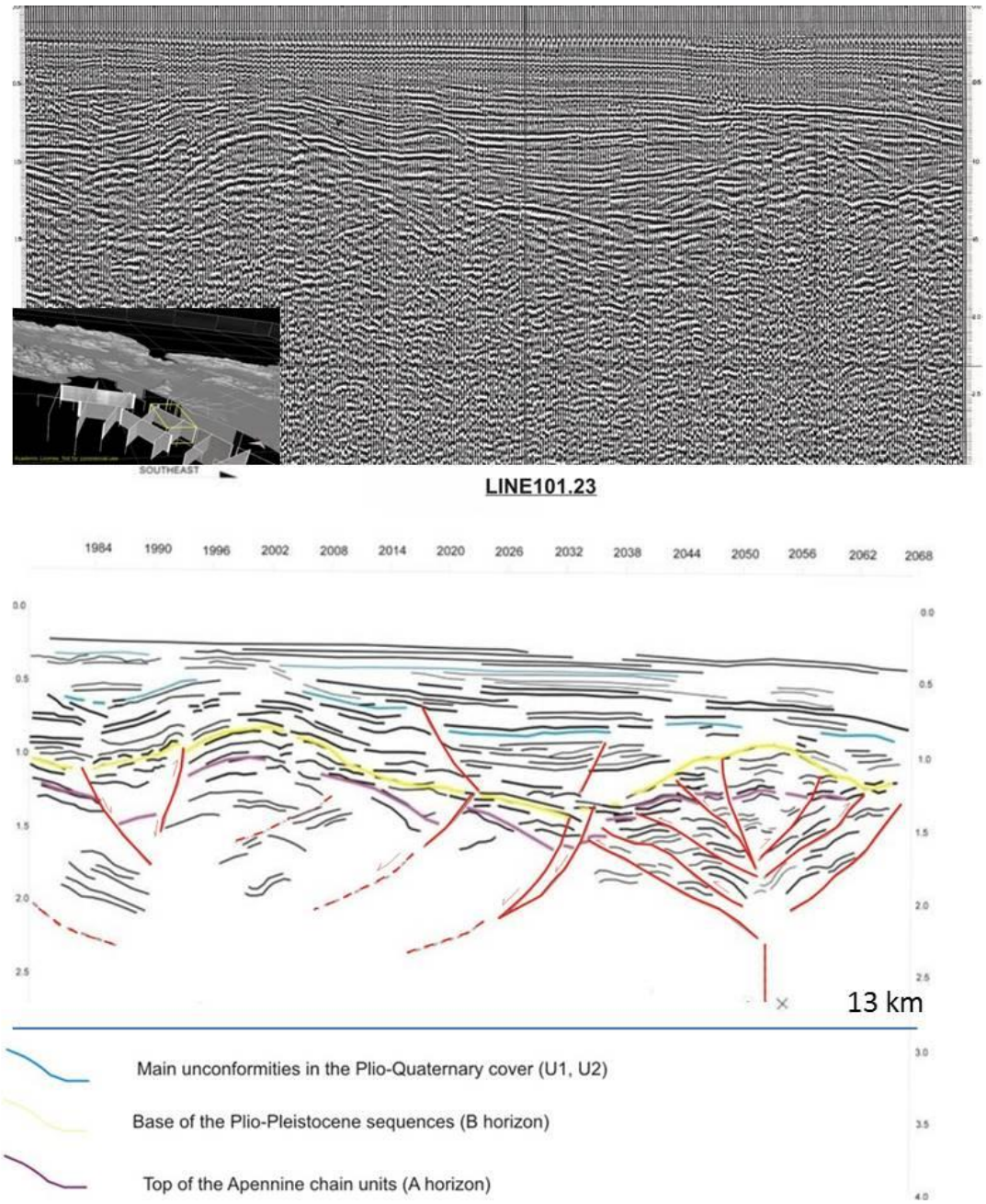

Figure 12: seismic profile 101.23: a strike section revealing lateral ramps of thrusts later reactivated in extension and controlling the deposition of unit2. Evidence of downward linking thrusts, deforming unit 1 and 2 and occurrence of positive structural inversions: a late Messinian normal fault seem to have been reactivated in compression in Pliocene times.

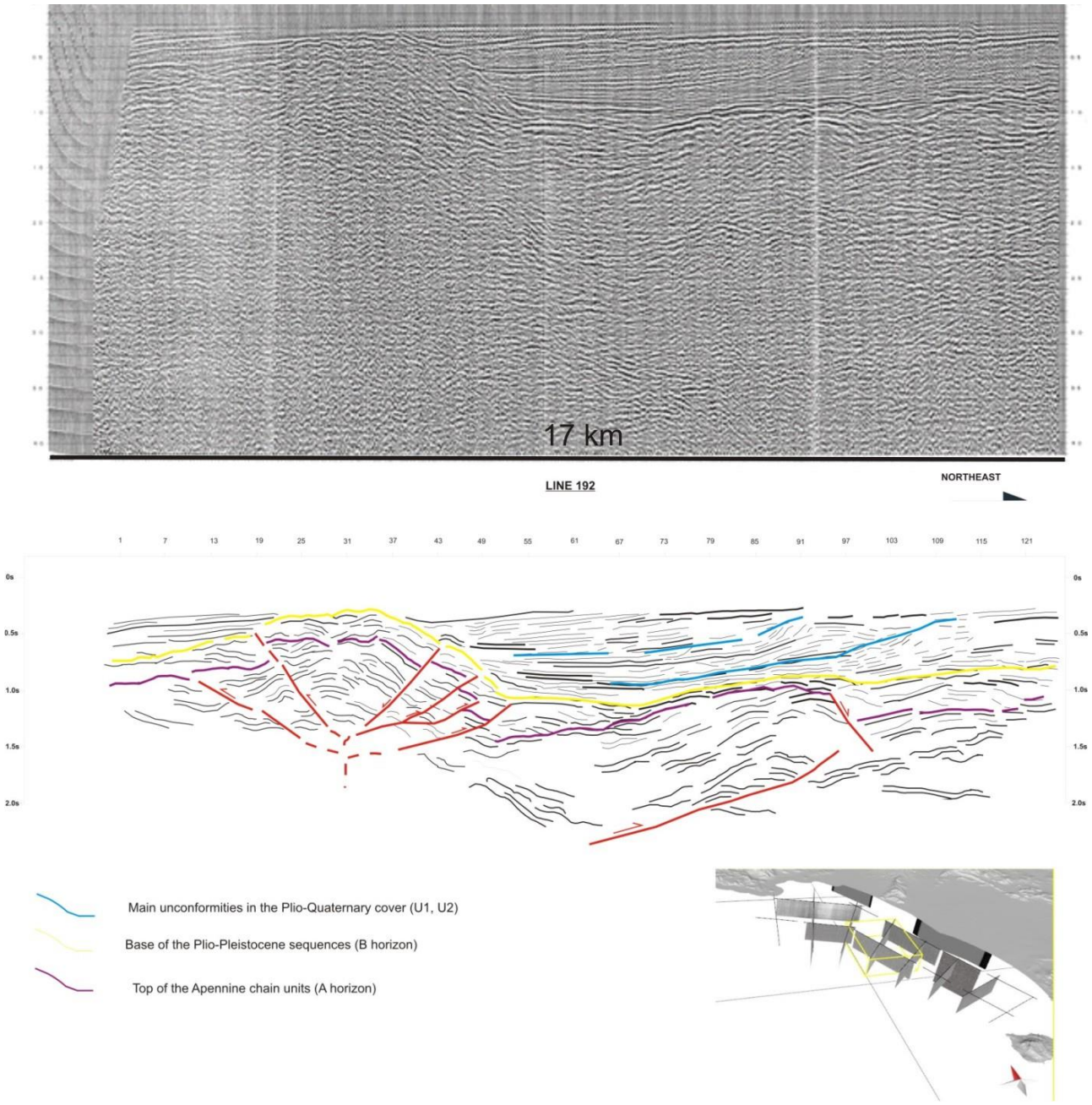

Figure 13: seismic profile 192: a dip seismic section revealing the presence of a NE verging thrust, of a NE dipping normal fault and showing the occurrence of a positive flower structure. Evidence of kinks in the Plio-Pleistocene stratal reflections of Unit3.

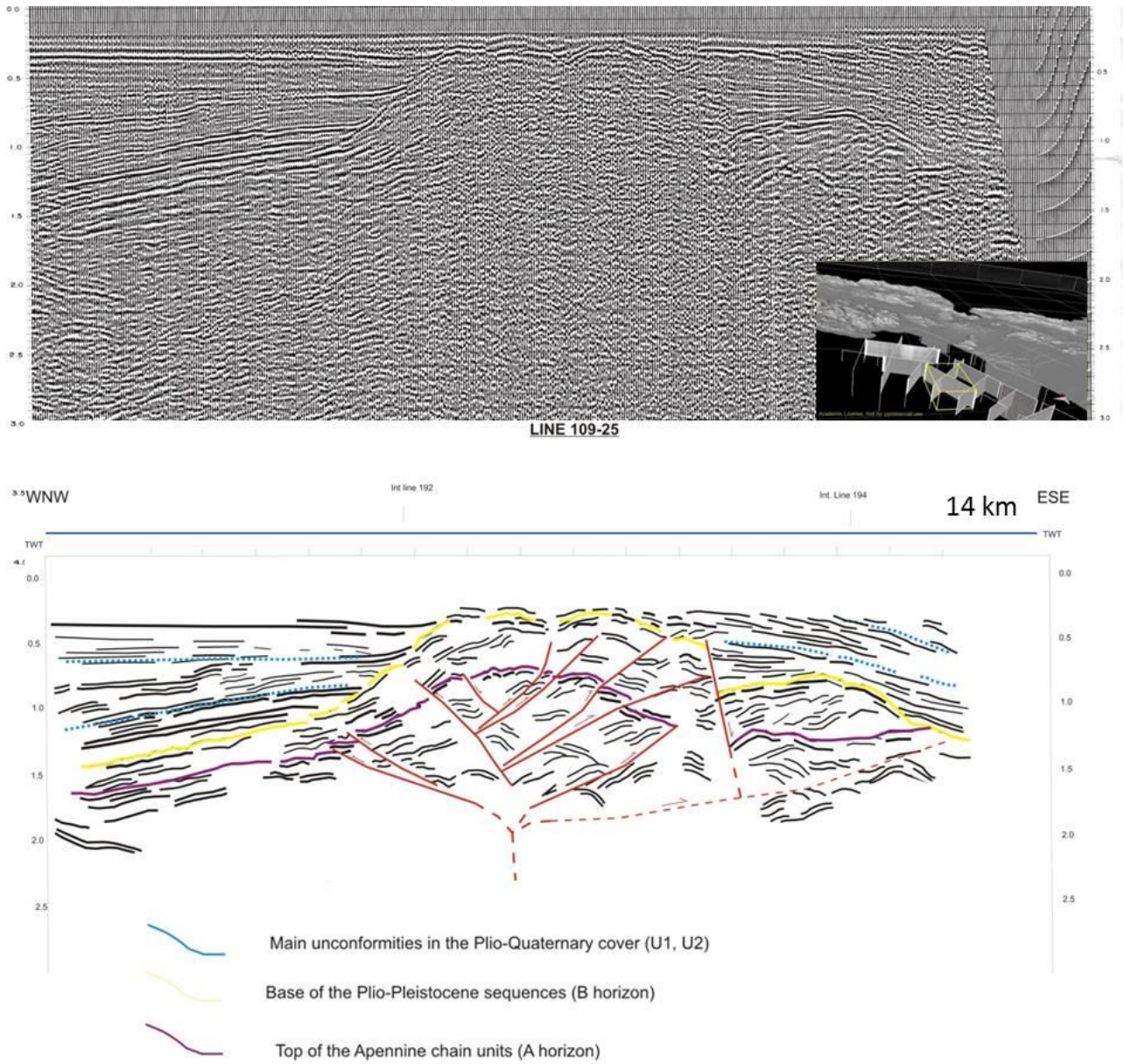

Figure 14: seismic profile 109.25: a strike secton revealing a system of upward spreading thrusts and the occurrence of an ESE dipping normal fault, controlling the wedge like external form of subunit 3a.

6.2. Distribution of deformations and margin geometry

The geometry revealed by the modeling of A (Fig.15) and B horizon (Fig.16) and the map distribution of the seismically detected structures defined the direction of the main discontinuities controlling the architecture of the margin. Relative highs and lows appear to be shifted along N30E right-lateral and NW-SE left-lateral strike slip faults, constituting in our interpretation the main principal displacement zones defining the geometry of the margin. The individuation of structures

and the distribution of deformational patterns on the interpreted grid, enabled the building of a kinematic model and the reconstruction of a structural synthetic map, reflecting the timing of tectonic events affecting the margin form Miocene to Pleistocene times (Fig.17).

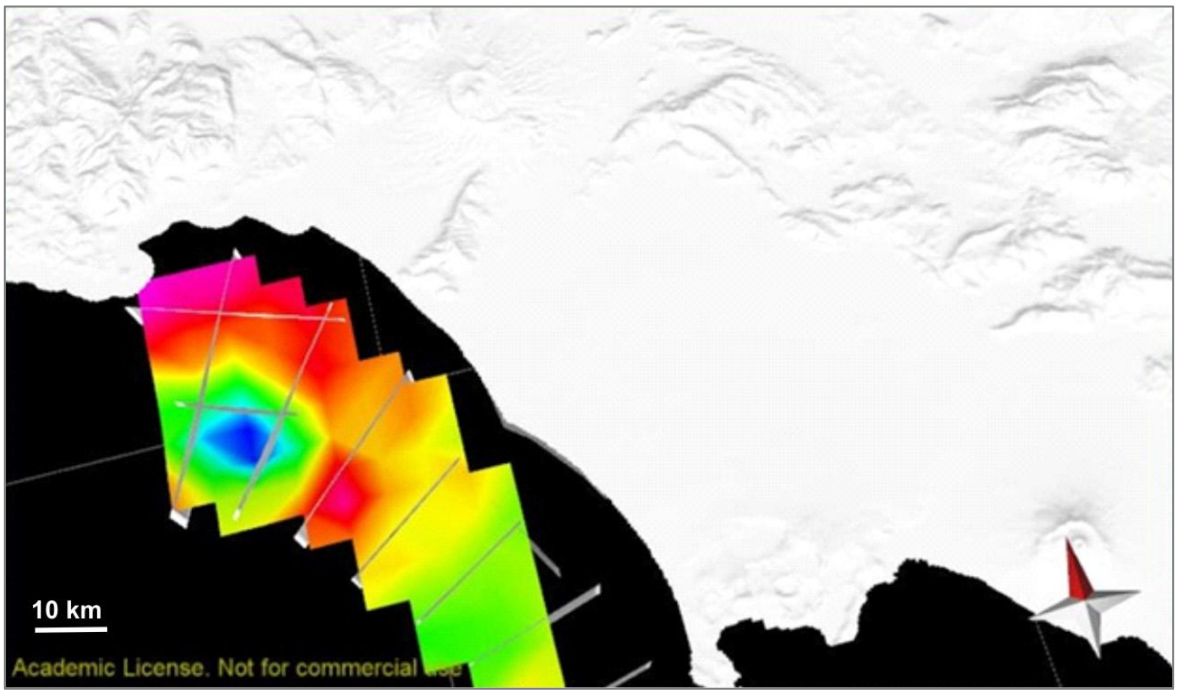

Figure 15: modelled A horizon: TWT surface showing the geometry of the top of the Apennine chain units.

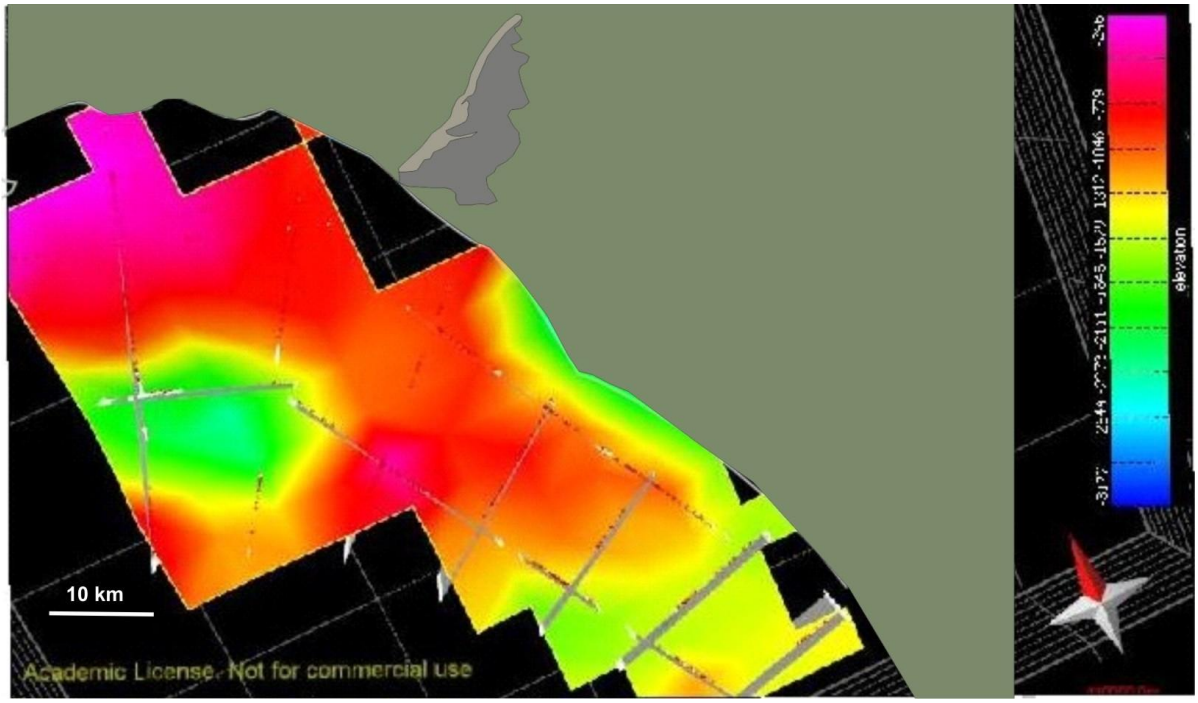

Figure 16: modelled B horizon: TWT surface representing the base of the Plio-Quaternary cover. A shift in the offshore prolongation of the Massico Mts has been here observed. . Relative highs and lows appear to be shifted along N30E right-lateral and NW-SE left-lateral strike slip faults, in our interpretation.

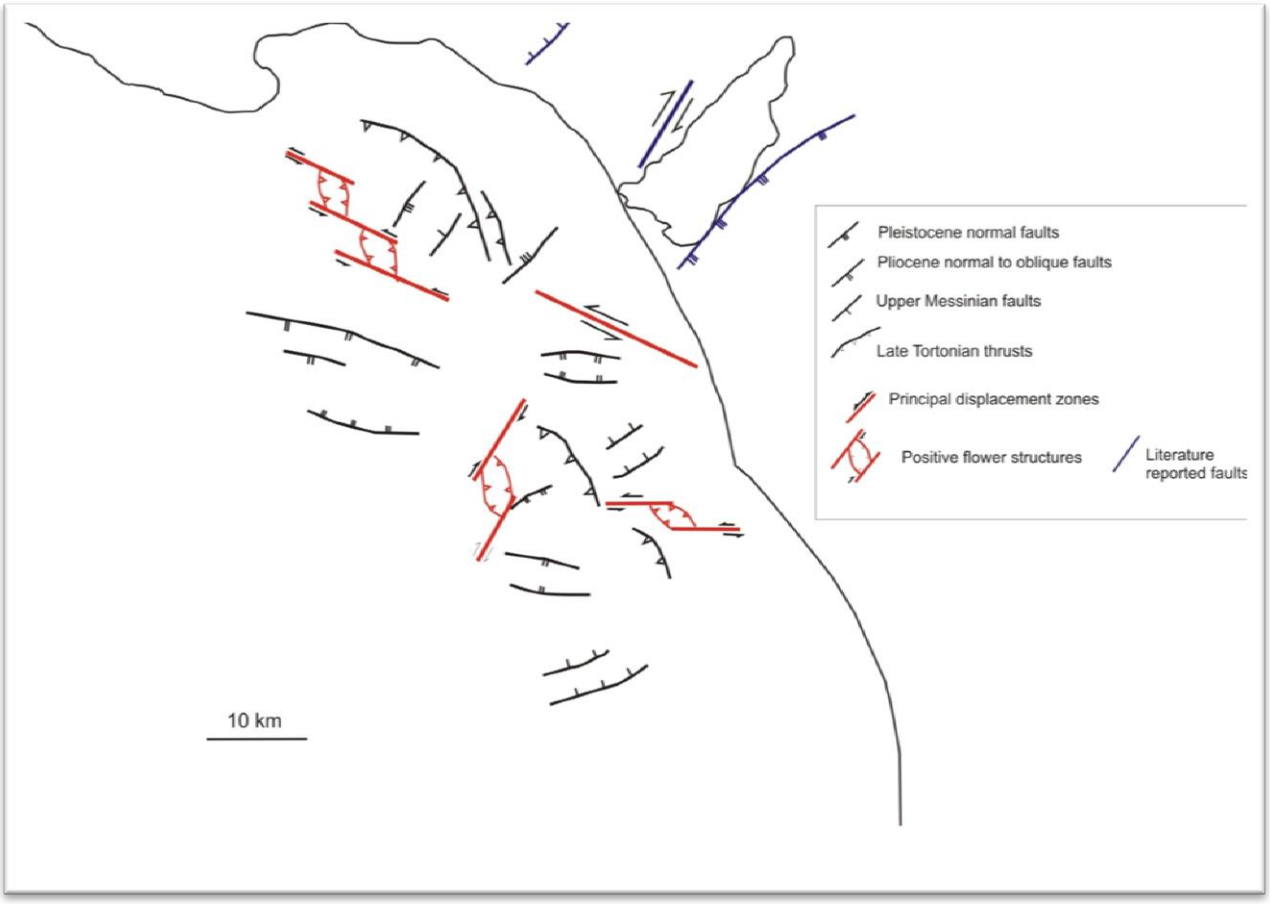

Figure 17: proposed structural synthetic map, reflecting the timing of tectonic events affecting the margin form Miocene to Pleistocene times. Location of seismically detected positive flower structures and suggested kinematic model.

NE verging thrusts affecting the Meso-Cenozoic acoustic substratum seem to be shifted along a NE-SW striking discontinuity with a right-lateral kinematic. NE-SW normal faults mainly NW dipping, dissect the orogenic structures controlling the deposition of Upper Messinian sediments arranged in wedge shaped acoustic bodies. NW-SE oriented structural planes seem to coincide with previous contractional fronts reactivated in extension in Lower Pliocene. These discontinuities controlled the wedge-like geometries of subunit 3a in the northern sector and produced tectonic inversions in the southern one. Then NE-SW normal faults controlled the Pleistocene evolution of the margin, as observed on seismic profiles and reported in literature (Moussat et al., 1986; Sartori, 1990; Hyppolite et al, 1994; Cinque et al., 1993; Caiazzo et al., 2006). Tectonic inversions on normal faults and strike slip faulting, producing on the overstepping regions upthrown blocks in a flower type geometry, started to occur in Pliocene times. The Meso-Cenozoic acoustic substratum and the Messinian lenticular bodies on top of it are involved in palm-tree and tulip-like structures. Positive structural inversions are also testified by changes in the polarity of structural reliefs, as shown in section 101-23, giving the main constrain to the occurrence of this

strike-slip regime, influencing the arrangement of the margin also in Pleistocene times. The sigmoidal progradational pattern characterizing the Plio-Pleistocene sedimentation of Unit3 in fact displays kinks and digitizations, testifying tectonic inversions on pure dip-slip components (Harding, 1985). Strata related to Upper Pleistocene subunit 3c seem to be deformed by the tulip like growing structure, showing kinkings in the upper stratal reflections. Both on A and B surfaces we have observed an offset in the offshore prolongation of the Massico Mts, suggesting left-lateral movements on a NW-SE striking principal displacement zone active since Early Pliocene times, as testified by the first tectonic inversions displayed on seismic data. The location of the upward spreading systems of deformations recognized on seismic lines and interpreted as the occurrence of positive flower structures, defined the strike-slip stepover geometry of the main structural planes.

6.3. Modeling of Sequence boundaries and timing of tectonic events

We have modeled the unconformities (B horizon and U1, U2 unconformities) bounding the three Plio-Quaternary depositional sequences and described the observed patterns. The surfaces modeled represent, bottom to top, the erosional unconformity predating the onset of the lower Pliocene marine ingression (B horizon), a second erosional unconformity, predating the Piacenzian deposits of the second transgressive-regressive cycle and an erosional surface predating the late Gelasian-Early Calabrian marine ingression. The results show us a general basinward migration of mainly NW-SE elongated maximal depocenters separated by a major E-W ridge. The first seismic subunit 3a, lying on top of the modelled B horizon, seems to be controlled by major NW-SE normal to oblique faults generating wedge-like geometries in the northern sector, individuating its NW-SE oriented maximum depocenter. Tectonic inversions start to occur within subunit 3a, which appear to be bent and deformed by NW and SE verging and downward linking thrusts, organized in a positive flower like geometry as observed on seismic section 101-23. The erosional surface representing the base of the second depositional sequence enabled the observation of this upthrown structure, revealing its ENE-WSW trending direction, separating two WNW-ESE elongated morphological lows (Fig.18). The second depositional sequence shows a more clearly progradational configuration pattern, displaying onlap terminations on the modeled and previously described sequence boundary U1. In section 192 little kinks against an upthrown growing structure testify the deformation occurring on it. The surface representing the base of the third depositional sequence reveal two morphological lows elongated in a NW-SE direction

(Fig.19). Their position revealed a basinward migration of depositional depocenter, suggesting a decrease in the accommodation space occurring during the last transgressive-regressive cycle. Also in this case an E-W trending structure separates two observed sequence depocenters. Kinks and digitisations against an upthrown flower structure on the upper Pleistocene stratal reflections observed in section 109.25, revealed a deformation still active affecting seismic subunit 3c.

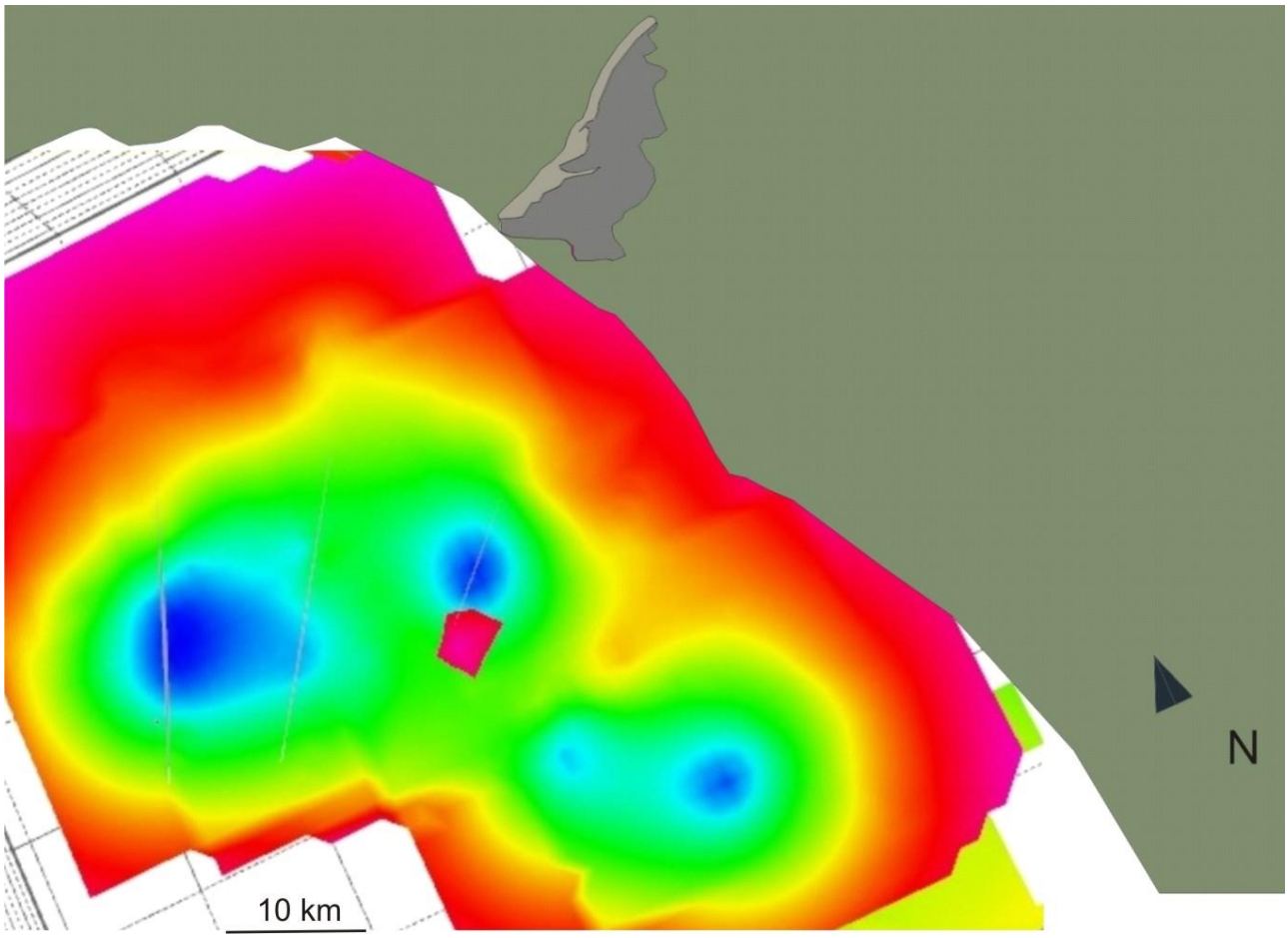

Figure 18: 3D modelling of U1 unconformity, representing the base of the second depositional sequence. In pink and red we have represented morphological highs and in green and blue, we have the lowest values. Evidence of an ENE-WSW oriented rodge separating two WNW-ESE oriented morphological lows.

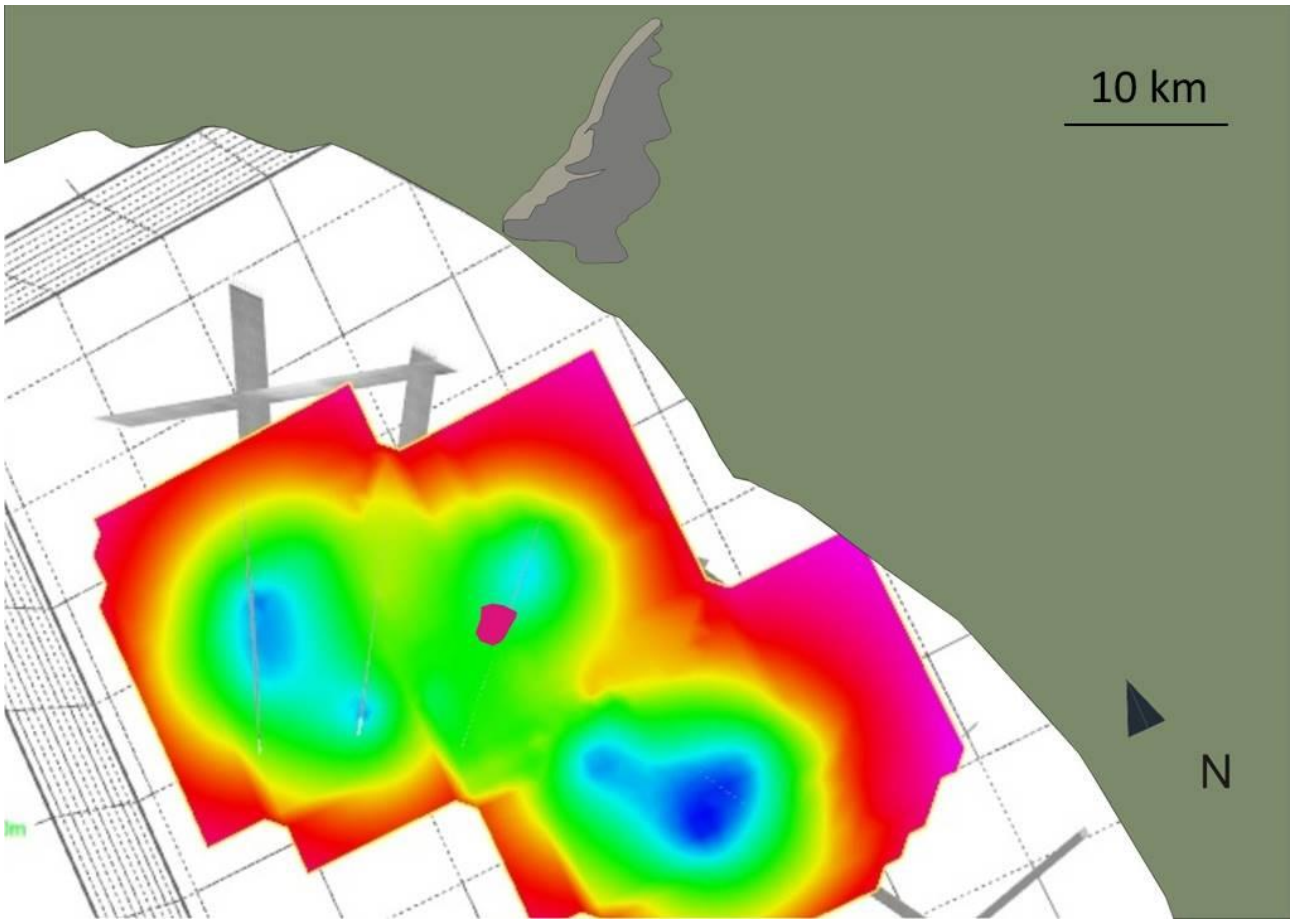

Figure 19: modelling of U2 unconformity, representing the base of the third depositional sequence. In pink and red we have represented morphological highs and in green and blue, we have the lowest values. NW-SE oriented morphological lows seem to be separated by an ENE-WSW oriented ridge.

6.4. Distribution of stress trough time and block rotations processes

PDZs have not been directly observed but inferred by the mapped distribution of strike-slip related structures and by the modelling of sequence boundaries, revealing the more relevant discontinuities. The 3D modelling of the base of Plio-Quaternary infillings revealed NE-SW and NW-SE main discontinuities controlling the geometry of the margin. An E-W oriented ridge has been recognized by the 3D modelling of Plio-Quaternary sequence boundaries. Seismic profile 101.23 revealed the transpressive nature of this upthrown structure. Such an E-W trending structure could be interpreted as the result of different processes: 1) it could be attributed to deformations occurring on E-W trending left-lateral planes, interpreted as R synthetic planes to the WNW-ESE main faults, 2) to changes in stress field orientations creating new discontinuities 3) to block rotation processes results and 4) to reactivation of previously formed structural planes. Four states of stress have been recognized analysing the structural features affecting the margin from Late Miocene to Pleistocene times (Fig.20): 1) a Tortonian NE-SW oriented σ_1 responsible for

the thrust sheets emplacement, 2) a Late Messinian NW-SE oriented σ_3 responsible for the NE-SW faulting, 3) a Lower Pliocene NNE-SSW oriented σ_3 producing WNW-ESE normal to oblique faults and 4) a NW-SE oriented σ_3 causing major Pleistocene NE-SW normal faults. The first event was characterized by a reverse regime and was followed by the onset of an extensional event.

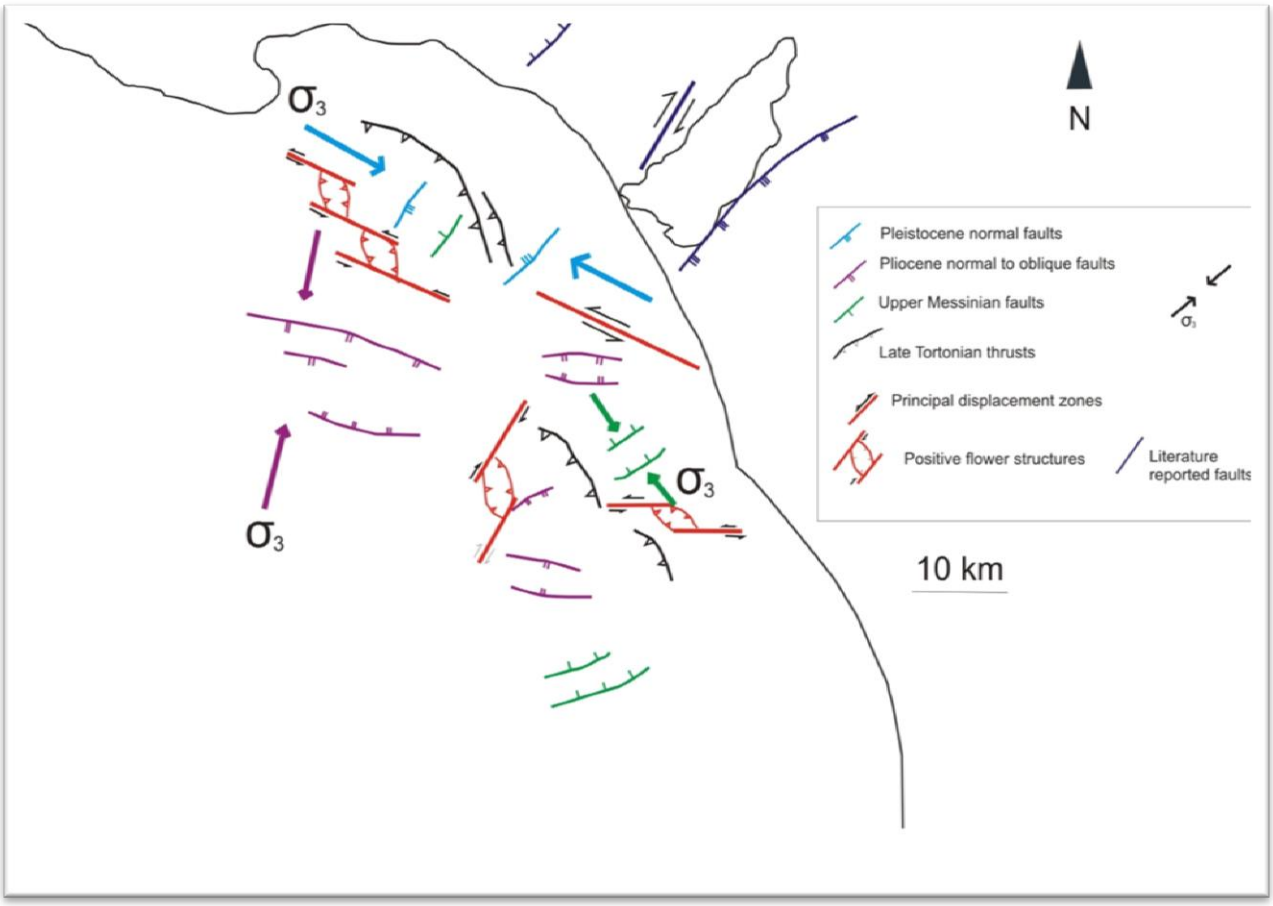

Figure 20: recognized states of stress analysing the structural features affecting the margin from Late Miocene to Pleistocene times.

A change in the stress field orientation has been recorded by the structural features related to the third tectonic event. Local permutations among σ_1 and σ_2 axis in an homoaxial stress regime, characterized by an oriented NNE-SSW σ_3, produced an extensional with and interrelated strike-slip regime. In Pleistocene times the fourth deformational event resulted in NE-SW normal faults with a NW-SE oriented σ_3. These results invoke major changes in stress field orientations or block fault rotations. The structural pattern is mainly constituted by NE-SW and WNW-ESE fault planes probably reactivated several times with different kinematics. This tectonic style, characterized by the presence of main blocks bounded by strike-slip faults and with deformations mainly located at the boundary of the imaged structural blocks, suggests the occurrence of rotations. Gattacceca & Speranza (2006) report a 60° counterclockwise rotation during Late Miocene times for Monte

Bulgheria. Capotorti & Tozzi (1991) suggest that similar processes should have rearranged the Sorrento peninsula in post Messinian times. Nevertheless records of mainly left-lateral movements on NW-SE planes should suggest, following the hypothesis of the authors, a clockwise preferred rotation. In this scenario overlaps, corresponding to area of reverse faulting and gaps, coinciding with sectors in extension, should form and match the observed trend (Fig.21). In any case data from literature report stretching directions changing from an E-W orientation in the initial rifting stages during Late Miocene-Pliocene times to a NW-SE orientation in post-Pliocene times (Sartori, 1990; Moussat et al., 1986), without invoking block fault rotations. The absence of paleomagnetic data avoid to build a model, allowing only working preliminary hypothesis. Our hypothesis is that E-W structural planes should represent synthetical planes to the WNW-ESE main displacement zone.

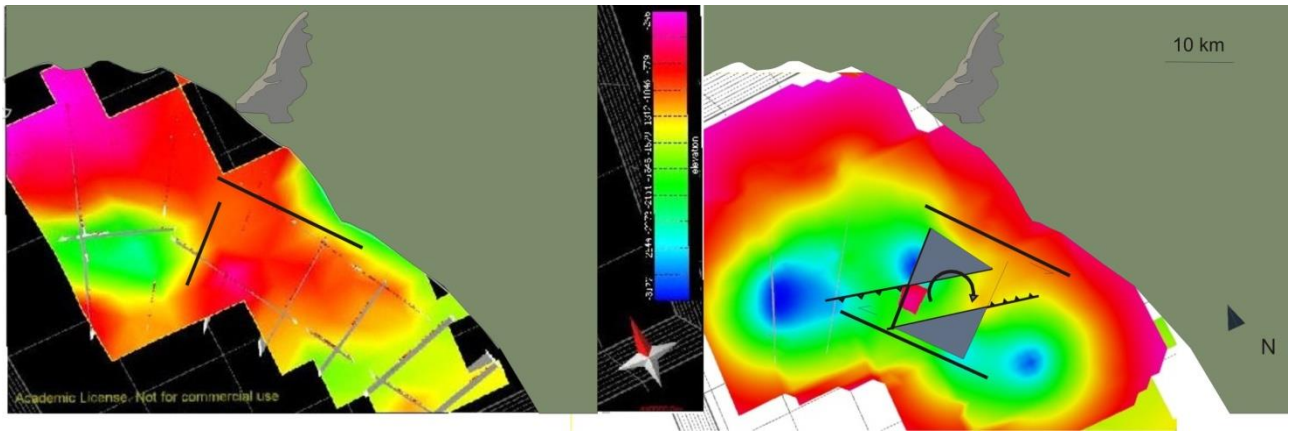

Figure 21: main structural discontinuities recognized by the modelling of sequence boundaries: B horizon (on the left side). Modelling of U1 unconformity, representing the base of the second depositional sequence: overlaps, corresponding to area of reverse faulting and gaps, coinciding with sectors in extension (in grey in the figure), should match the observed trend (on the right side).

7. Conclusions

The geometry of the margin has been controlled by NW-SE, NE-SW and E-W structural discontinuities, reactivated several times in different kinematic contexts. A NE-SW oriented σ_1 responsible for the thrust sheets emplacement in Late Tortonian times, has been followed by the onset of an extensional regime, taking place in the study area with NE-SW Late Messinian listric faults, reactivating in extension lateral ramps of Late Tortonian thrust sheets. Starting from early Pliocene, local permutations among σ_1 and σ_2 axis in an homoaxial stress regime characterized by an oriented NNE-SSW σ_3, produced an extensional with and interrelated strike-slip regime. A similar state of stress has been recognized by Caiazzo et al. (2006), conducting structural and morphotectonic analysis on the Tyrrhenian side of Southern Apennines. The author recognized

major NW-SE trending strike-slip faults, locally creating palm-tree and other transpressive structures, from Late Miocene to Early Pliocene times. This event, corresponding to the "D2 deformational event" individuated by Caiazzo et al. (2006), was responsible, following the interpretation of the author, for the reactivation as transfer faults of older E-W oriented segments. In our grid tectonic inversions, palm-tree and tulip-like flower structures, expression of NW-SE and NE-SW segmented principal displacement zones, have been detected. E-W trending discontinuities, active in Pliocene times and creating push-up structures in the stepover region, have also been recognized. Our interpretation distances itself from the one proposed by the author for the deducted sense of shear. The elaborated modelling of the base of Plio-Quaternary infillings revealed a shift of the Massico Mts offshore prolongation, compatible with a left-lateral kinematics, as already pointed out by Bruno et al. (2000). The antithetical plane of this NW-SE left-lateral plane corresponded in our interpretation to NE-SW right-lateral striking planes, already recognized in the onshore sector of the study area and correlatable with segments of the ORL tectonic line (Patacca et al., 1990; Mantovano et al., 1996; Billi et al., 1997; Bruno et al., 2000). Starting from early Pleistocene times, a NW-SE oriented σ_3 created major NE-SW normal faults influencing the present day morphology of the margin with the formation of coastal graben. Our grid offered the opportunity to visualize the early Pleistocene faulting on such NE-SW normal faults. Evidence of tectonic inversions on the main discontinuities affecting the margin, coinciding with kinks and digitisations against flower-like structures have been pointed out also in Pleistocene times. Records of an interrelated strike-slip regime (Angelier & Bergerat, 1983) creating NW-SE left-lateral transtensive faults (Cinque et al., 1993; Caiazzo et al., 2006) were reported for early-Middle Pleistocene times.

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Chapter 3

Transtensional tectonics along the southern Tyrrhenian margin: an example from the Volturno basin (central Italy)

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Abstract

High penetration seismic reflection profiles enabled the reconstruction of the deep structural architecture of the Volturno Plain. Data from boreholes revealed an highly subsiding structure recording 3000m of Quaternary continental and marine deposits, resulting in a subsidence rate, once decompacted and corrected, with an average value of tectonic signature of 0,8 mm/yr. The area is located at the boundary between Central and Southern Apennines and is crossed by the N120° striking Cilento-Pollino shear zone and the NNE-SSW striking Ortona-Roccamonfina tectonic line. Releasing bends, structural inversion and normal listric faults were displayed by seismic profiles enabling the reconstruction of the main principal displacement zones (PDZs) active in Pleistocene times. The results are compatible with the regional stress field distribution, pointing out a NW-SE stretching direction for early-middle Pleistocene. Local permutations among the σ1 and σ2 axes, as suggested by previous authors, produced an interrelated strike-slip regime, resulted in NNE-SSW and E-W normal to oblique faults. This splaying system of deformations has been interpreted as the response of synthetic and antithetic planes of a main N120° left-lateral shear zone. Data from boreholes and seismic profiles have also allowed the individuation, calibration and the 3D modeling of 5 main depositional sequences for the last 1.8 My.

1. Introduction

The most recurrent discontinuities observed along the inner domains of the southern portion of the Apennine tectonic belt seem to have a N120°±10° striking direction, as observed in the Sorrento and in the Cilento-Pollino region (Turco et al., 1990; Capotorti & Tozzi 1991; Catalano et al., 1993; Cinque et al., 1993; Ascione & Cinque, 1996; Saitto et al., 2002; Caiazzo et al., 2006). The kinematic of these faults responded to distinctive rifting episodes with different orientations affecting the margin from late Miocene to Pleistocene times (Bartole et al., 1984; Moussat et al., 1986; Sartori, 1990; Cinque et al., 1993; Hyppolite et al., 1994; Ferranti et al., 1996; Caiazzo et al.,

2006). The initial rifting phases mainly followed an E-W trending direction (Bartole et al., 1984; Sartori, 1990; Hyppolite et al., 1994b; Giordano et al., 1995; Caiazzo et al., 2006) producing a mainly dip-slip component on the NW-SE striking faults. Starting from Early Pleistocene a tectonic event with a NW-SE stretching direction, creating major NE-SW normal faults (Moussat et al., 1986; Sartori, 1990; Hyppolite et al, 1994b; Cinque et al., 1993; Caiazzo et al., 2006), induced on such planes mainly horizontal offsets (Cinque et al., 1993; Saitto et al., 2002; Caiazzo et al., 2006). This latter rifting phase led to the formation, in the Campanian sector, of coastal half grabens hosting infilling successions of up to 3000 m in thickness. This is the case of the Volturno basin, recording at least 3 km of Quaternary deposits. Intense subsidence rates of up to 2-3 mm/yr were recorded by deep well data pointing out to an early-middle Pleistocene starting age in this sector (Ippolito et al., 1973; Bigi et al., 1983; Brancaccio et al., 1991; Aiello et al., 1997; Brocchini et al., 2001). During this tectonic event stress permutations among the σ1 and σ2 axes produced an interrelated strike-slip regime (Angelier & Bergerat, 1983), creating NW-SE left-lateral and ENE-WSW dextral transtensive faults (Cinque et al., 1993; Caiazzo et al., 2006). Records of left-lateral strike-slip activity on N120° fault planes were observed in the Cilento region, dating back to Late Pliocene times (Turco et al., 1990; Ascione & Cinque, 1996) and in the Pollino Ridge, dissecting also lower-middle Pleistocene deposits (Monaco & Tansi, 1992; Schiattarella, 1998). The strike-slip activity on such planes has been ascribed to a broader geodynamical setting, related to the tectonic disjunction between Southern Apennines and a Calabrian arc retreating towards SE (Knott & Turco, 1991; Cinque et al., 1993; Doglioni et al., 1996) . In this tectonic scenario, a high penetration seismic reflection still uninterpreted grid, located on the highly subsiding Volturno basin, could help to unravel the complex tectono-sedimentary evolution of the sector. The identification of structural styles by high penetration seismic profiles is a difficult procedure that may lead to mistakes in the interpretation. Map distributions of seismically detected structures represents a fundamental tool in order to directly observe the geometric pattern of the main faults and establish the regional stress field distribution.

2. Geologic framework

The forelandward migration of the compressional front of the Apennine orogenic system was accompanied, from early Miocene, by an eastward migration of the related Tyrrhenian back-arc extension (Malinverno and Ryan, 1986; Boccaletti et al., 1990; Kastens and Mascle, 1990; Butler et al., 1992 Patacca et al., 1992b; Carmignani et al., 1995; Robertson and Grasso, 1995; Cipollari et

al., 1999; Catalano et al., 2000). The initial stages of the rifting phases acted mainly on low angle normal faults (LANF) (Barchi et al., 1998; Jolivet et al., 1999; Mattei et al., 2002; Brogi, 2004). On a second stage higher normal faults dissected the previous structures, shaping the present day morphology of the margin (Sartori, 1990). The opening of the Tyrrhenian basin, from Late Serravalian (Mattei et al., 2002) until early Pleistocene, gave rise to several extension-related basins (Boccaletti et al., 1990; Patacca et al., 1992a,b; Cipollari et al., 1999), younging their age following an E-W oriented stretching direction and, in domain of hyper-extension in the inner sectors, migrating also along the axis of the chain (Hyppolite et al., 1994b; Ferranti et al., 1996). The rifting phases allowed the formation of basins repeatedly submerged and exposed and the deposition of sedimentary sequences, whose thickness was a consequence of the sedimentation and subsidence rates. Their stratigraphical architecture resulted from a complex interplay between tectonics, eustatism and sedimentary influx. The Campania Plain, located in the Tyrrhenian side of Central-Southern Apennines, is the result of extension-related processes started, in that area, in lower Pleistocene times (Brancaccio et al., 1991; Ippolito et al., 1973). The plain has a very flat morphology and is bounded, in its northern sector, respectively to the NE and to the NW by the Maggiore Mts and by the Massico Mts Meso-Cenozoic carbonatic and siliciclastic successions (Fig.1).

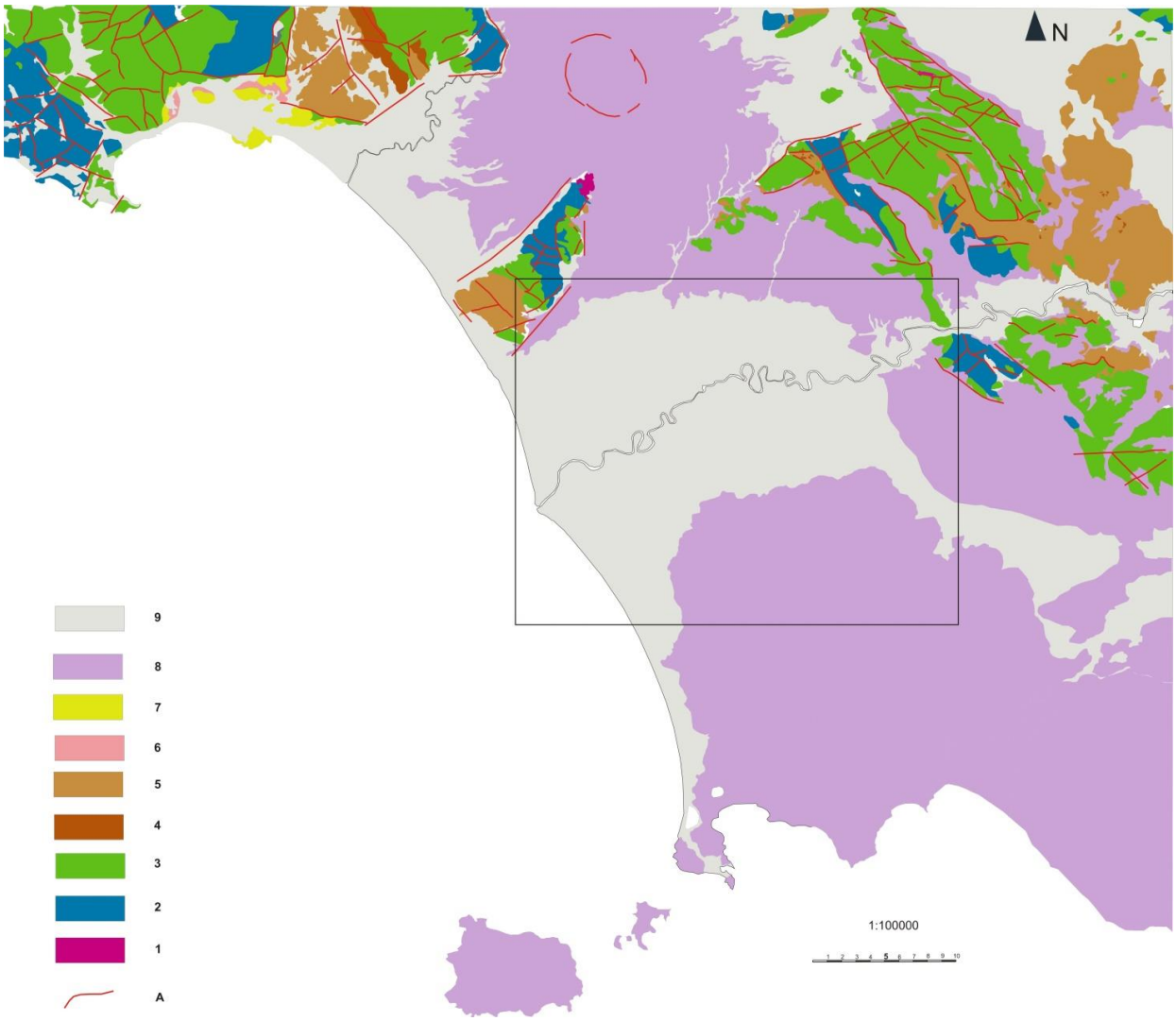

Figure 1: Structural sketch map of central-southern Apennines. Location of the study area. Legend: 9) Pleistocene-Holocene alluvial deposits; 8) Quaternary volcanic deposits; 7) Early Pleistocene conglomeratic deposits; 6) Upper Messinian gypsum-bearing clays; 5) Late Tortonian siliciclastic foredeep deposits; 4) Langhian-Serravalian *Calcari a Briozoi e Litotamni* Fm; 3) Cretaceous shallow water limestones; 2) Jurassic shallow water limestones and dolomites; Triassic dolomites and limestones; A) undifferentiated faults.

The compressional wave affected the study area during Late Tortonian, as revealed by the foredeep deposits outcropping on the Volsci Range, in the Latina Valley (Cipollari and Cosentino, 1995; Cipollari et al., 1995; Cosentino et al., 2003) and on the Caserta Mts (Pescatore & Sgrosso, 1973; Sgrosso, 1988). Evidence of the Messinian syn-rift deposition widely described in the Garigliano basin in the Gaeta Gulf (Cipollari and Cosentino, 1995; Cipollari et al., 1995; Cosentino et al., 2006) have not been found in the study area, highly subsiding and intensely deformed by the final stages of the Tyrrhenian extension. Several authors suggested a period of emersion of the area, presumably standing above sea level during Pliocene times (Brancaccio et al., 1991; Cinque et al., 1993; Caiazzo et al., 2006). The deepest boreholes drilled in the Plain recorded only Quaternary continental and marine deposits, not reaching any older deposits. The development of several palaeosurfaces suggested an intense erosion taking place during Pliocene times (Ascione

and Cinque, 1999; Caiazzo et al., 2006). Starting from Early-Middle Pleistocene severe subsidence, reaching values of 2mm/y in the Volturno basin, associated with strike-slip faulting affected the entire area, as reported by data from literature (Ippolito et al., 1973; Cinque et al., 1993; Caiazzo et al., 2006). During this tectonic event Early-Middle Pleistocene NE-SW trending normal faults (Moussat et al., 1986; Sartori, 1990; Hyppolite et al, 1994b; Cinque et al., 1993; Caiazzo et al., 2006), bounding to the South the Massico Mts (Billi et al., 1997) defined the half graben geometry of the Volturno Basin. Evidence of a strike-slip regime interrelated with this mainly extensional tectonic event have been detected in the bay of Naples, as reported by Milia and Torrente (2003), describing Quaternary E-W trending left-lateral faults and in the Garigliano basin, where Giordano et al. (1995) reported the same left-lateral E-W trending faults cutting early Pleistocene deposits (*Congl. Di Minturno Auctt)*. Volcanic deposits related to different districts, interbedded with marine and continental deposits and arranged in an asymmetric half graben geometry, constitute the bulk of the Volturno basin succession (Ippolito et al., 1973; Aprile & Ortolani, 1978; Mariani and Prato, 1988; Brancaccio et al., 1991; 1995; De Vivo et al., 2001; Santangelo, 2010).

3. Methods

The approach here used for the reconstruction of the tectono-stratigraphic evolution of the Volturno basin consisted in the interpretation of 19 high penetration seismic reflection profiles which have been kindly provided by ENI S.p.A (Fig.2).

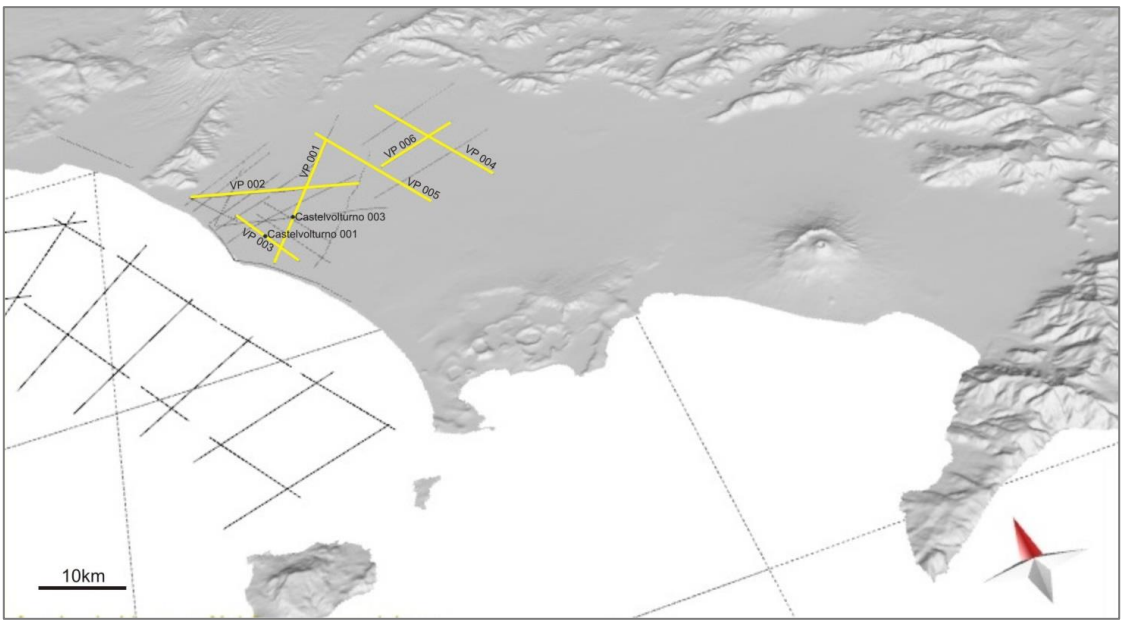

Figure 2: Location of the onshore interpreted seismic grid (19 seismic sections) and of the two deep wells used for the calibration (Castelvolturno 001 and 003). In yellow we have represented the six high penetration profiles here presented.

Boreholes data proveining from deep well Castelvolturno1 (SAMET 1954) have been used for the seismic calibration. Pattern of deformations and structural styles affecting the basin have been reconstructed and identified with exploration data. Map distribution of seismically detected structures and overstepping geometries in interpreted strike-to oblique slip faults, enabled the reconstruction of a kinematic model. Starting from the CV1 deep borehole stratigraphic description, we have calculated cumulative subsidence, then decompacted and later partitioned in sedimentary loading and tectonic components (Allen & Allen, 2005). The decompaction technique followed the procedure described by Sclater & Christie (1980), with a stratigraphic succession divided in five intervals with specific surface porosity and grain size density parameters. Once decompacted the sedimentary column, the backstripping procedure impose paleobathymetric and eustatic corrections (Miller et al., 2005), in order to calculate, assuming local Airy isostasy, the tectonic component. Tectonic subsidence was calculated using equation (A) from Steckler & Watts (1978):

$$Y = S\left\{\left(\frac{\rho_m - \rho_s}{\rho_m - \rho_w}\right) - \Delta_{SL}\frac{\rho_w}{\rho_m - \rho_w}\right\} + [W_d - \Delta_{SL}]$$

where Y is the tectonic subsidence, S is the total thickness of the sedimentary column corrected for compaction, ρ_m, ρ_s, ρ_w are mantle, mean sedimentary column and water densities, W_d is the paleo-water depth, and Δ_{SL} is the paleo-sea level relative to the present. The mean sedimentary column density (ρ_s) was obtained using sediment grain density from Sclater & Christie (1980).

4. Presentation of seismic data

4.1. Seismic units

Seismo-stratigraphical observations enabled the recognition of a total of 8 acoustic units in the Volturno basin (Fig.3). The poor seismic resolution of these high penetration profiles doesn't allow a good acoustic characterization for the first seismic unit (*Unit1*). The lower boundary of *Unit 1* (*a horizon*) marks an abrupt change in the acoustic response. High to medium amplitude wavy reflectors, characterizing the first seismic unit, pass down to low amplitude reflectors with a good lateral continuity (*Unit2*). Crossing an highly irregular *b horizon* we pass down to acoustic *Unit 3* characterised by parallel medium to high amplitude reflectors. Onlap and toplap terminations have been observed within this seismic unit which shows a wedge shaped external configuration. The top of the fourth unit seem to be cutted by an articulated c horizon. *Unit 4* displays thick

hummocky high amplitude sometimes diverging seismic reflectors, showing mound type and V-shaped structures onlapping on *d Horizon*. Parallel reflection configurations with a medium to high amplitude and frequently eteropic reflectors characterize *Unit 5,* displaying onlap terminations on *e horizon* and erosionally truncated at its top. The below unit (*Unit 6*) is characterised by hummocky sub-parallel medium amplitude reflections, locally creating V-shaped structures. The top of this acoustic unit seems to be cutted, showing also in this case toplap terminations. *Horizon f* separates *Unit 6* and *Unit 7*, the latter showing downlap and onlap terminations above the *g Horizon*. The amplitude is medium to low and the reflectors have a wavy to parallel reflection configuration. The last seismic unit observed (*Unit 8*) shows low continuity and medium to high amplitude disrupted reflectors.

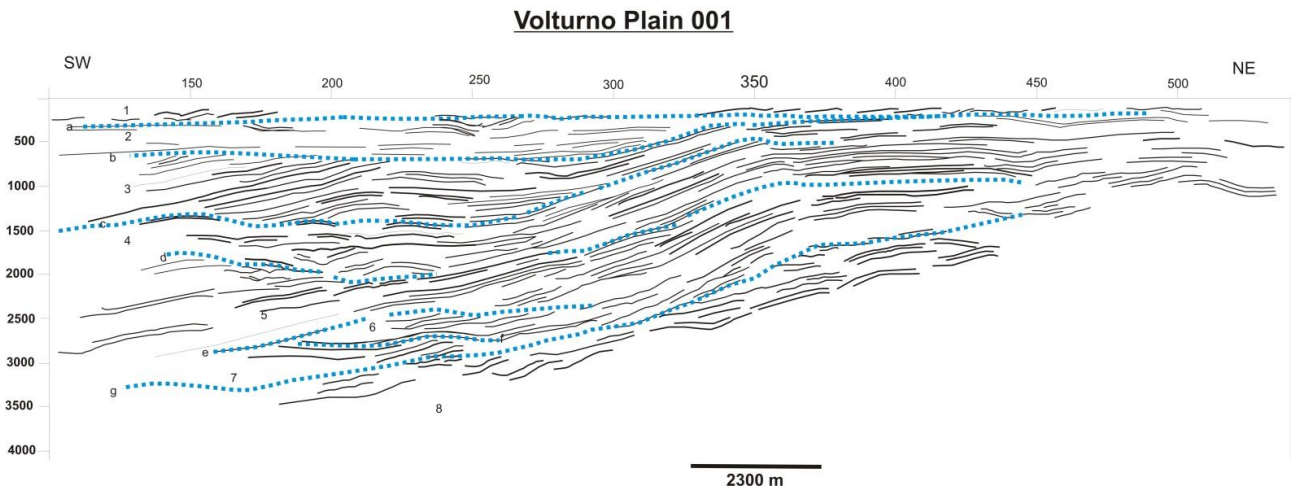

Figure 3: Volturno Plain 001 profile has been here used to show all the 8 acoustic units recognized.

The bottom unit is marked at its top by two high amplitude reflectors frequently truncated and marking a transition to a different acoustic domain. The others seismic units above the lowest one show a more continuous reflection configuration. Above *Unit 8*, displayed in all seismic profiles, non-depositional and erosional features influencing the stacking of depositional units, locally rearranged the pattern described above.

5. Seismic calibration

A revised stratigraphy, based on studies of microfaunal associations, proposed by Ippolito et al. (1973) pointed out for Castelvolturno 1 and Castelvolturno3 deep wells (3001m and 3006m respectively) a Pleistocene record for all the reached depths. From Ippolito et al. (1973) sedimentological descriptions of CV1 (Fig.4), the first change in lithology occurs at 75m of depth, where from a continental environment the deposits pass down to an infralittoral system until

200m depth. The successive interval, from 200 to 700m, has been referred to a deeper marine depositional environment by the same author. In seismic reflection profiles the shift from continental to marine conditions is marked by an abrupt change in acoustic impedance from high to low amplitude reflectors. Here we have located our *a horizon*, separating seismic *Unit 1* from *Unit 2*. From 75 to 700m the acoustic signal remain basically invariated, allowing us to calibrate *Unit 2* with a major sequence, passing, bottom to top. from deep marine to shallow water conditions, marking in this way a transgressive-regressive (T-R) cycle. Sand and shale characterize the following interval, starting from 700m to 1000m, referred by the author to an infralittoral depositional environment. Then we find 240m of deeper marine sediments passing down, at 1240m of depth, to coastal deposits until a depth of 1720m. From 700m (*b horizon*) to 1720 reflectors show a similar acoustic signal with medium to high amplitude reflectors. This interval calibrated *Unit3*, interpreted as a major sequence, referred also in this case to a T-R cycle. Strong acoustic impedance contrasts mark this sand-shale alternations within the sequence. From 1720 to 2150m of depth conglomerates, coal and sands characterize the delta plain composing that interval. Such deposits calibrate *Unit 4* bounded at its top by *c horizon*. Seismically observed V-shaped structures characterizing this unit have been interpreted as fluvial incisions affecting an emerged plain. An infralittoral depositional system constitute the following 350m. From thick hummocky reflectors characterizing *Unit 4*, crossing *d horizon*, we pass down to a parallel reflection configuration, characterising seismic *Unit 5*. Acoustic *unit 4* and *5* have been interpreted as sub-units composing a major depositional sequence corresponding to a T-R cycle. From 2500 to 2840m of depth delta plain conditions describe the deposits found in that interval. An infralittoral depositional environment characterize the last 161m recorded by the well. From 2500m (*e horizon*) we have a thick subparallel reflection configuration (*Unit 6*) passing down, across *f horizon* to parallel and medium to low amplitude reflections. *Unit 6* and *7* correspond also in this case to sub units composing a major depositional sequence related to a T-R cycle. A calibration for seismic *g horizon* and *Unit 8* is not possible by the well stratigraphy. CV1 and CV3 have not reached the acoustic substratum. Data from literature suggest that the Campania Plain was above sea level during Pliocene times (Brancaccio et al., 1991; Cinque et al., 1993). In this scenario *Unit 8* could represent the Meso-Cenozoic substratum and *g horizon* could be interpreted as a polygenic surface recording the uplift responsible for the emersion, later reworked by the onset of a Pleistocene transgression. *Hyalinea balthica*, a benthic foraminifera whose FCO dates back to

Calabrian age, costrain the first 2153m of the well. The remaining 848m have been attributed to Pleistocene for the lacking of species possibly attributing to Pliocene times (Ippolito et al., 1973).

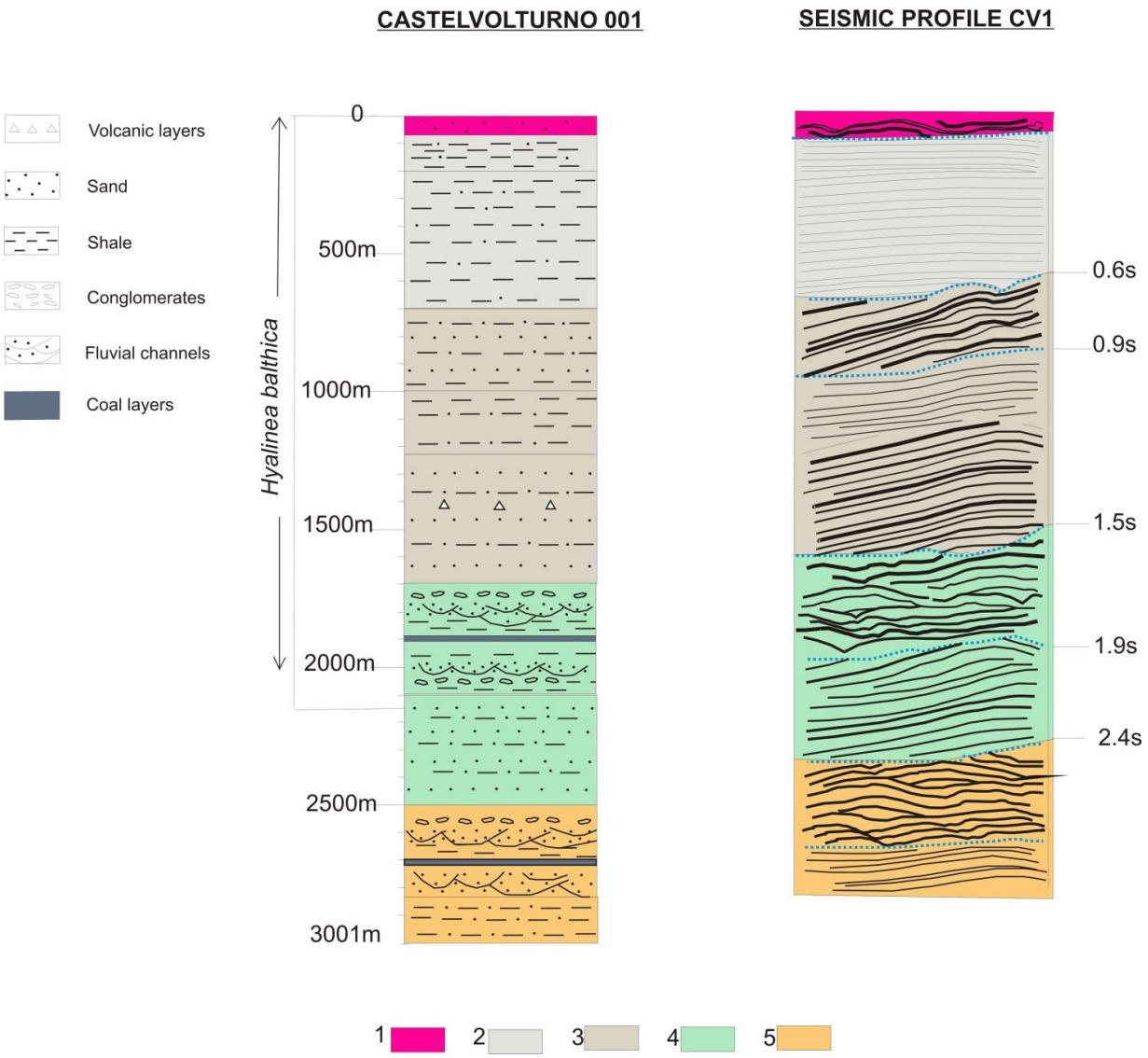

Figure 4: Seismic calibration: a comparison between Castelvolturno 001 lithologic description offered by Ippolito (1973) and the observed seismic reponse on Volturno Plain 003 profile. Legend: 1) depositional sequence A; 2) depositional sequence B; 3) depositional sequence C; 4) depositional sequence D; 5) depositional sequence E.

5.1. Depositional sequences and age constraints

Starting from early Pleistocene, deep seismic profiles in the Volturno basin recorded bottom to top 5 depositional sequences (E, D, C, B, A respectively) corresponding to 5 major T-R cycle. *Hyalinea balthica* has been found until a depth of 2153m in CV1. The first occurrence of this benthic foraminifera in the CV1 well coincides with the infralittoral deposits characterizing the base of the fourth T-R cycle (depositional sequence D). The fifth cycle, lacking clear Pliocene marker species

and characterized by a microfaunal association remained almost invariated with the exception of the occurrence of *Hyalinea balthica* in the cycle deposited above, has also been attributed to a Pleistocene age by Ippolito (1973). The author referred all the succession to a Pleistocene age in a period in which the Plio-Pleistocene boundary coincided with the base of the Italian Calabrian Stage, in the Vrica section, at 1.8 My (e.g. Tauxe et al., 1983). The fifth and the fourth transgressive-regressive cycles showed similar depositional environments and have been attributed both to a Pleistocene age. If we interpret the occurrence of *Hyalinea balthica* at 2153 m of depth, at the base of the fourth T-R cycle as its FCO we have an age costrain of 1.5 My for the infralittoral deposits, marking the transition to the *Hyalinea balthica* zone (Fig.5).

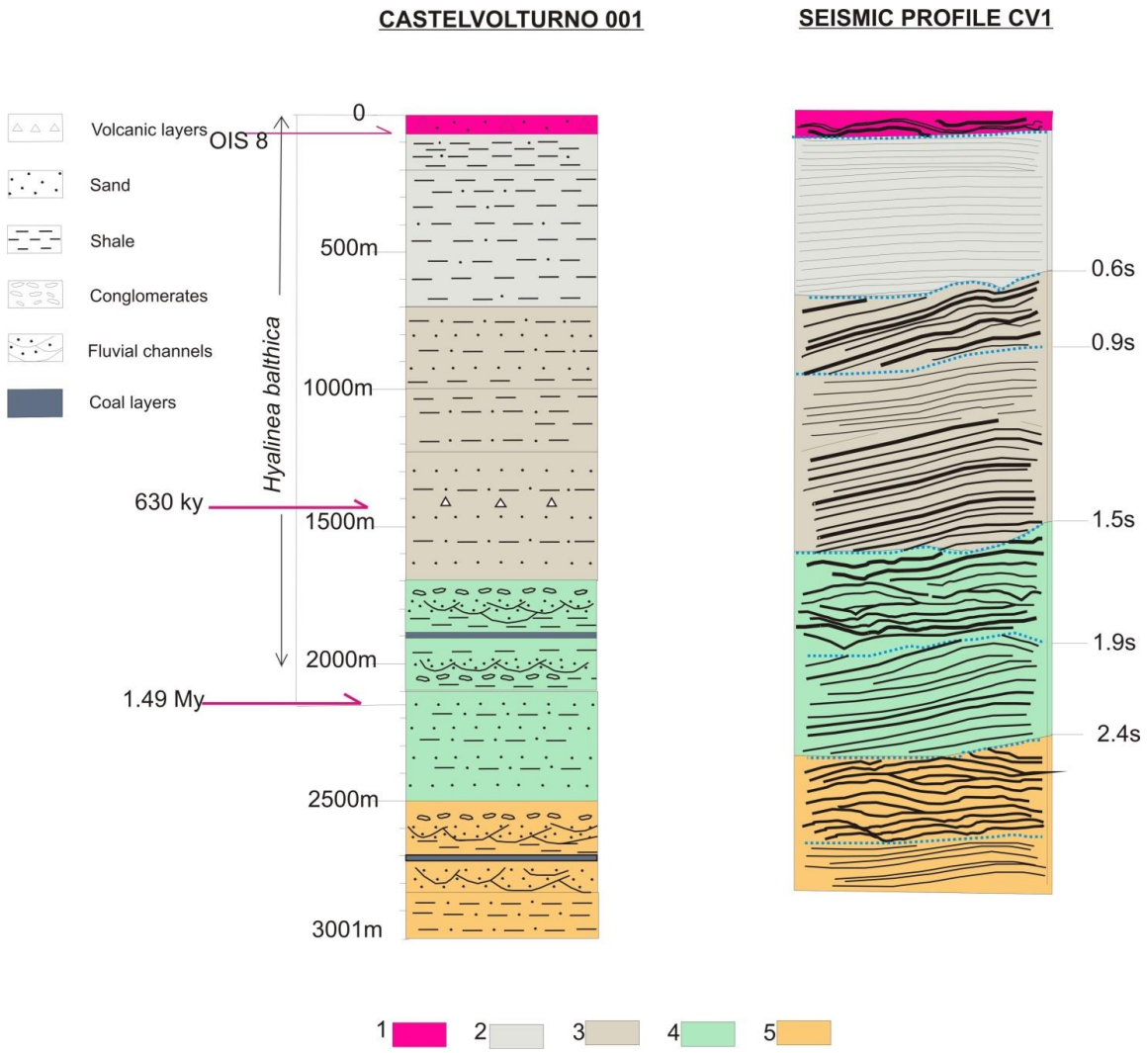

Figure 5: Presumed age constraints: in the lower part of seismic D sequence, the interpreted FCO of Hyalinea balthica give an age constraint of 1.5 My. The volcanic layer reported by Ippolito (1973) at about 1400 m depth, in our C sequence, should correspond to the onset of the Roccamonfina volcanic activity, giving an age constraint of 630ky. The shift from marine to continental and transitional deposits, observed at the transition from A to B sequence, should correspond to the OIS 8.

E depositonal sequence, following this interpretation, should be related to a post-1.5, pre-1.8My biozone. Moving up into the succession, the following possible age constraint corresponds to the first pyroclastic layer reported by the borehole stratigraphy. Located at the bottom of C sequence, this volcanic layer could represents the onset of the Roccamonfina volcanic activity, dating back to 630 ky (Radicati di Brozolo et al., 1988; Giordano et al., 1995). Finally, the shift from marine to continental and transitional deposits (75m), recorded by the well stratigraphy and closing the stratigraphical succession, should be attributed to the emersion of the area caused by the OIS 8 related sea level lowstand (Santangelo, 2010). The author conducted a study finalized to the characterization of the superficial succession of the Campania Plain, dating and analysing an 80 m-long sediment core drilled in the Volturno Plain. The deepest part of the core, recorded a lagoonal environment correlated by the author, with the high sea level stand of OIS 7 (210-190 ka, Martinson et al., 1987). Following this interpretation at the bottom of the 75m recorded by CastelVolturno1 well, the erosional surface separating lagoonal and continental deposits, to a marine condition should have been caused by the OIS 8 related sea level lowstand.

6. Structural analysis

Here we present 5 of the 19 seismic reflection profiles interpreted in the Volturno Plain. The first section described corresponds to a WNW-ESE striking profile, identified as Volturno Plain 002 (Fig 6). The acoustic substratum seems to be affected by a major ESE dipping normal fault, controlling the deposition of E and D sequences, revealing a wedge like external form. Digitisations observed in the stratal reflections kinking against the above mentioned SE dipping normal fault and mirroring in this way an inversion in the polarity of the structural relief, start to appear from C sequence. After the deposition of the above lying B sequence, minor normal faulting individuates smaller scale graben and half graben structures, deforming both C and B sequences. The same wedging external geometries have been revealed by section Volturno Plain 003, a NNW-SSE oriented profile (Fig.7). Stratal reflections, mainly in D sequence, showed a diverging internal pattern and an increased thickness moving towards a SE dipping discontinuity. Castelvolturno 001 deep well, located on the Volturno river mouth, calibrates this seismic profile, revealing in this area the maximum thickness reached by the Pleistocene cover. Moving towards the northeastern side of the plain, seismic profile Volturno Plain 006 (Fig.8), NE-SW oriented, shows a step-like deformation affecting the acoustic substratum, as testified by SW dipping normal faults, downthrowing the individuated blocks and creating space for the infilling sequences C,B and A. A

similar step-like deformations have been revealed by seismic profiles Volturno Plain 004 and 005 showing SSE dipping normal faults affecting the acoustic substratum. These E-W trending faults define the wedging geometry observed for D sequence on Volturno Plain 005 profile (Fig.9). An acoustically invisible body lying above the before mentioned E-W trending faults, with a conical external shape has been revealed by this profile, enabling also the observation of interdigitations between stratal reflection belonging to depositional sequence C and the intrusive body internal layering. In seismic profile 004 (Fig.10) two oppositely dipping E-W striking normal faults, accompanied by an upward spreading system of deformations, individuate a downthrown block. The northernmost SSE dipping normal fault observed on this profile, individuated also in seismic section 005, seems to affect seismic line Volturno Plain 006, revealing a more articulated trending direction (fig.11).

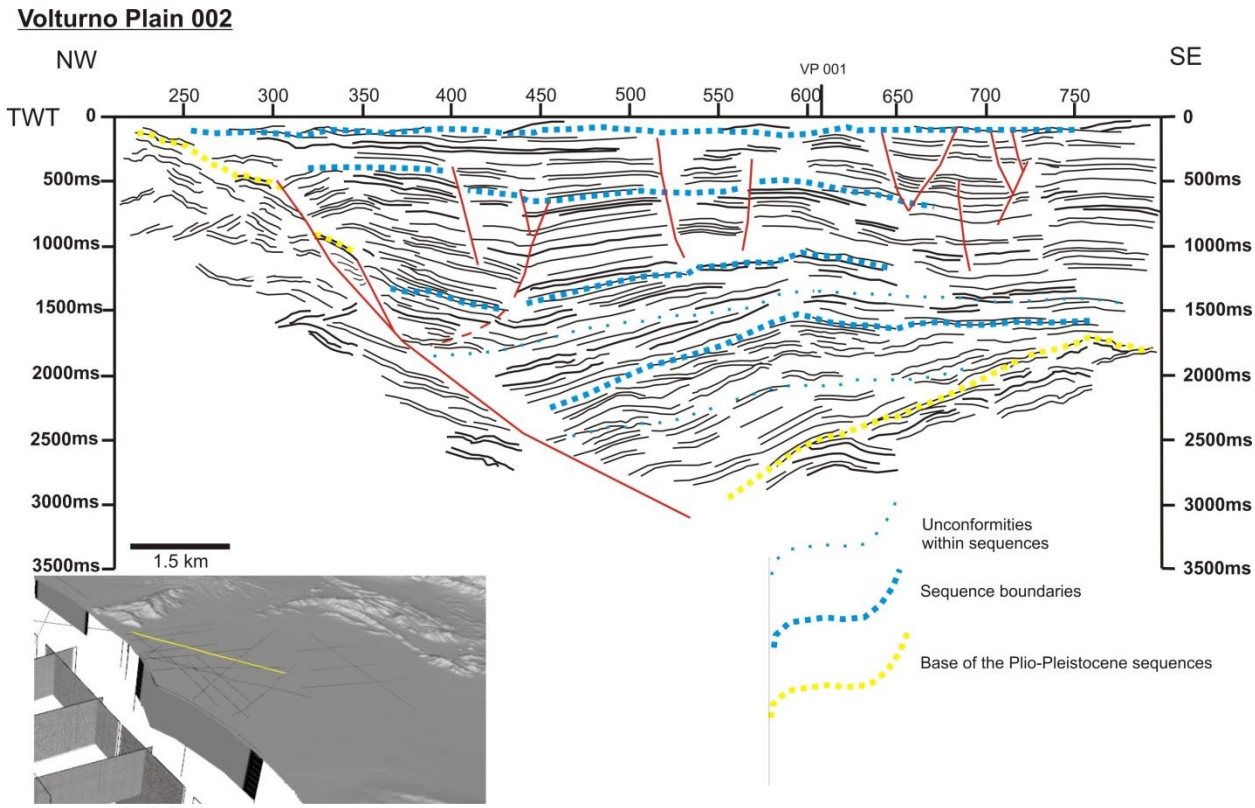

Figure 6: Presentation of Volturno Plain 002 seismic profile: a SE dipping normal fault deforms the acoustic substratum and seems to affect also E and D sequences, as revealed by their wedge like external form. Digitisations in the stratal reflections, kinking against the above mentioned SE dipping normal fault and mirroring in this way an inversion in the polarity of the structural relief, start to appear from C sequence. After the deposition of the above lying B sequence, minor normal faulting individuates smaller scale graben and half graben structures, deforming both C and B sequences.

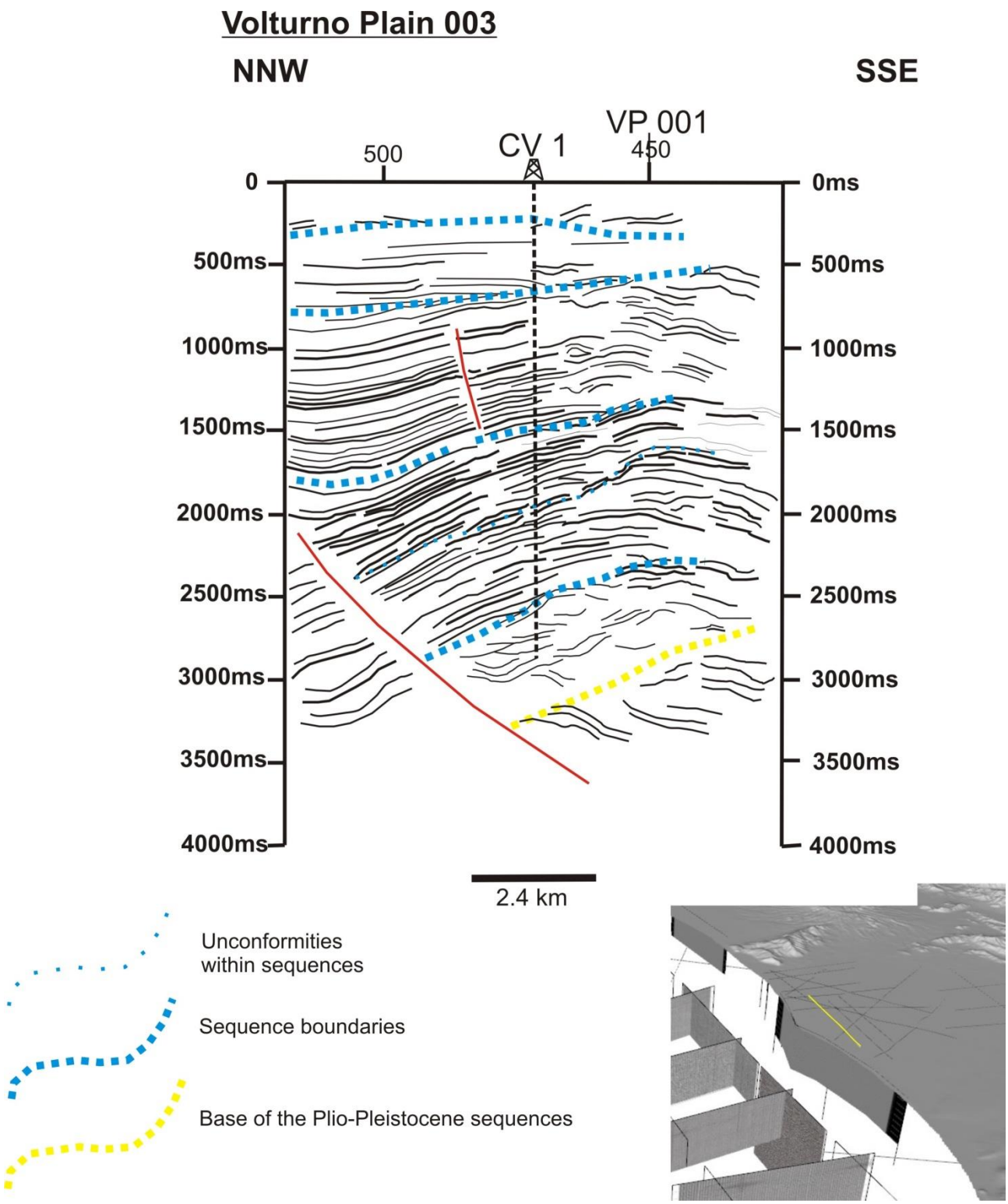

Figure 7: presentation of Volturno Plain 003 profile: a diverging internal pattern and an increased thickness moving towards a SE dipping discontinuity has been revealed by D sequence. Castelvolturno 001 deep well calibrates this seismic profile, revealing in this area the maximum thickness reached by the Pleistocene cover.

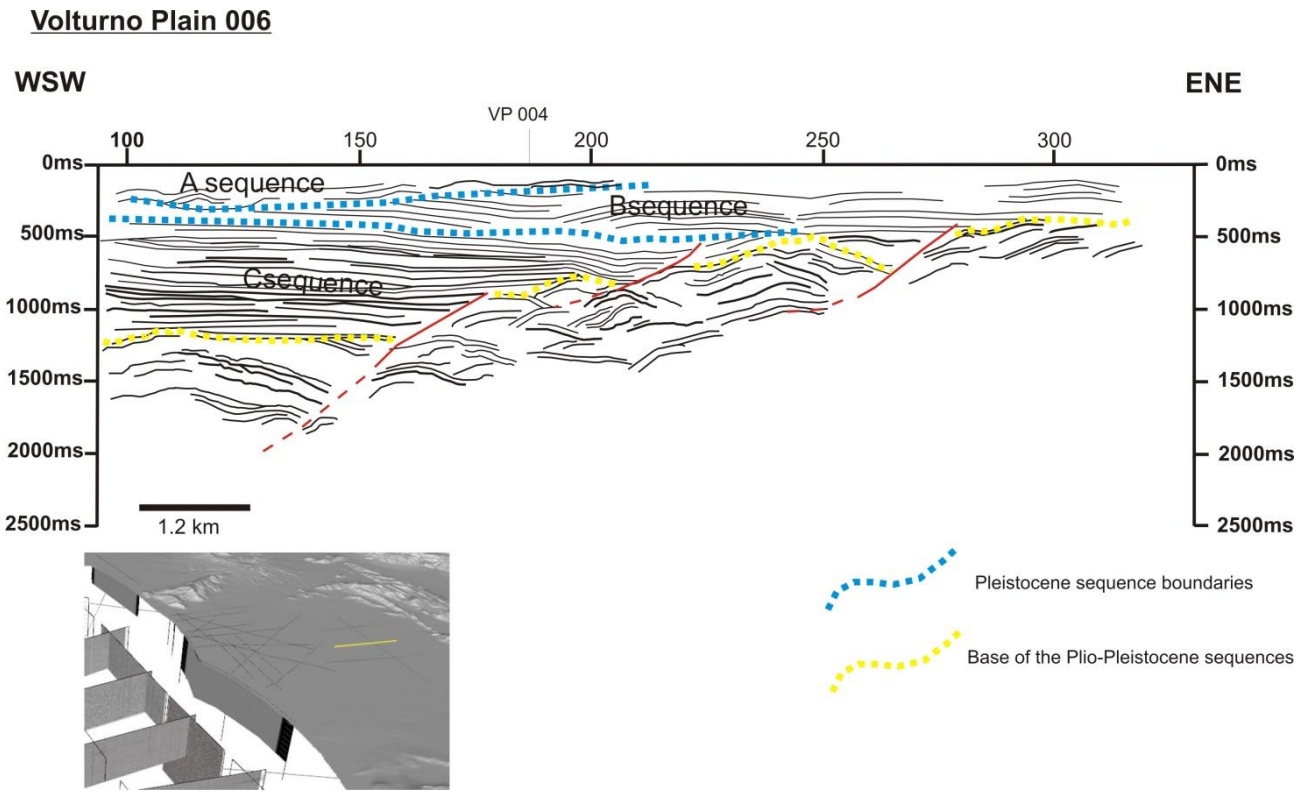

Figure 8: presentation of Volturno Plain 006 seismic profile: a step-like deformation seems to affect the acoustic substratum, as testified by the observed SW dipping normal faults, downthrowing the individuated blocks and creating space for the infilling sequences C, B and A.

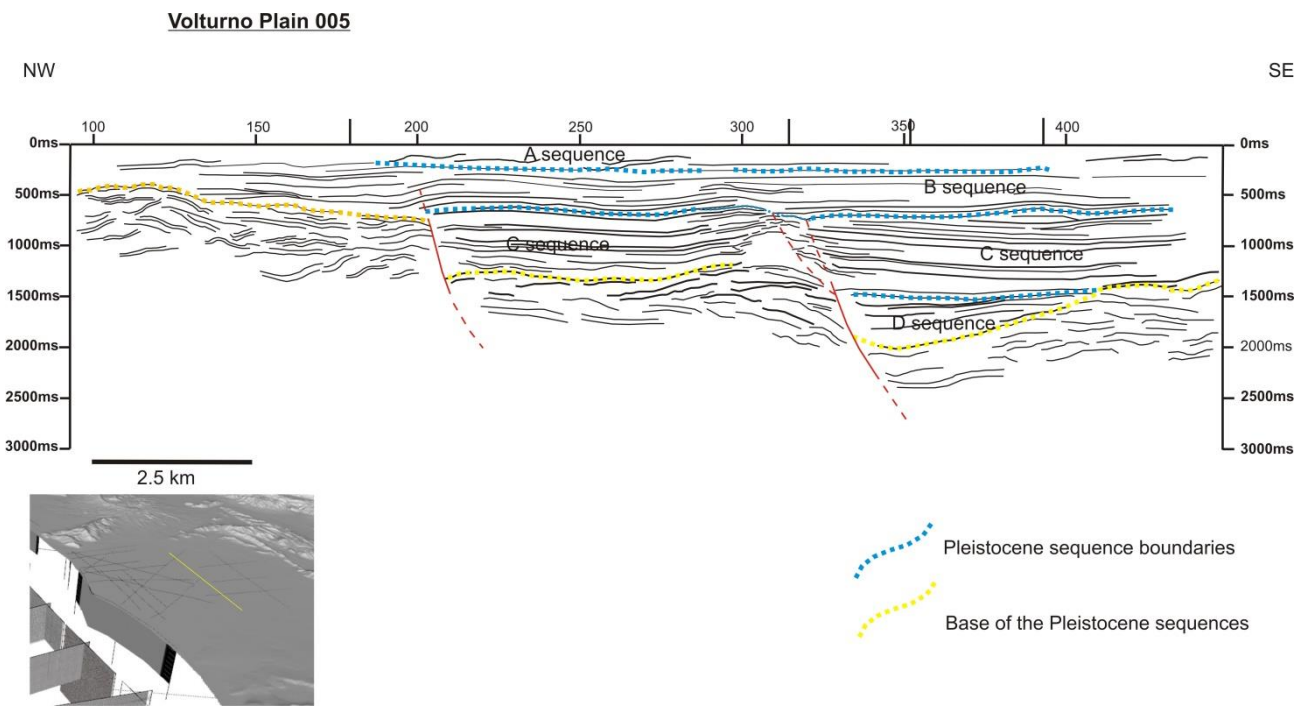

Figure 9: presentation of Volturno Plain 005 seismic profile: SSE dipping normal faults affect the acoustic substratum and define the wedging geometry observed for D sequence . An acoustically invisible body, with a conical external shape, has been here revealed. Interdigitations between stratal reflection belonging to depositional sequence C and the intrusive body internal layering have been here observed.

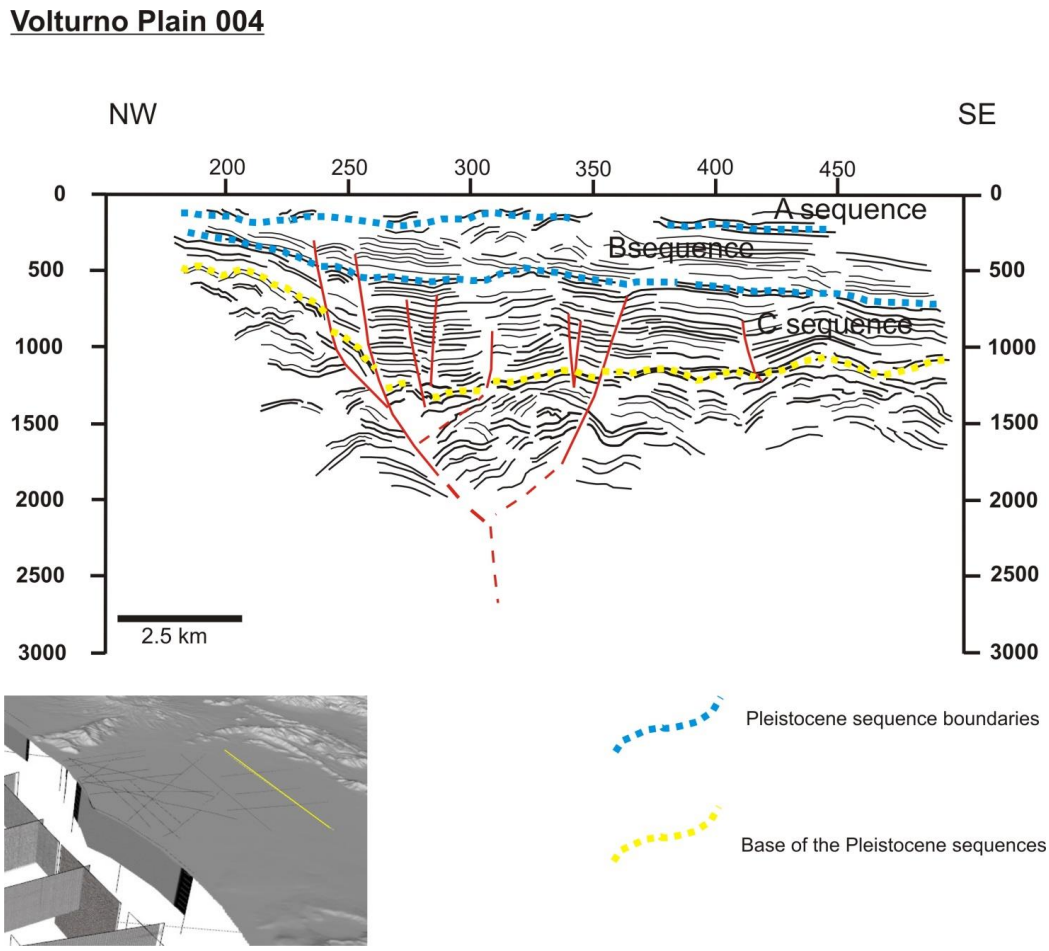

Figure 10: presentation of Voltuno Plain 004 profile:) two oppositely dipping normal faults, accompanied by an upward spreading system of subsidiary deformations, individuate a downthrown block. Deformations seem to affect the acoustic substratum, C and B sequences.

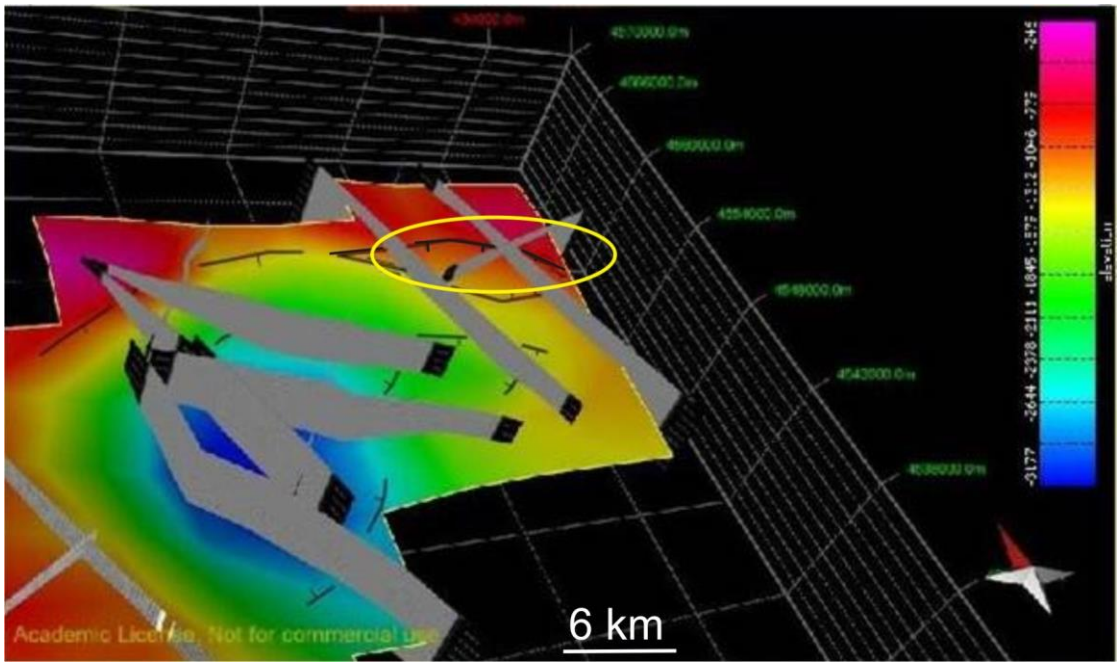

Figure 11: the northern SE dipping normal fault observed on profiles 004 and 005, has been traced also on 006 seismic sections, suggesting a roughly E-W trending direction.

6.1. *Timing of tectonic events*

The 3D modelling of the boundaries of each T-R cycle enabled the recognition of the structural lineaments responsible for the deformations observed in the depositional sequences. The timing of tectonic events has been revealed by morphobathymetric maps showing relative lows and highs, resulted by the modelling of the successive boundaries of the seismically detected sequences and by the external and internal configurations of the displayed sequences. *G horizon*, separating the Quaternary infillings from the acoustic deformed substratum, is an erosional surface predating the onset of the early Pleistocene marine transgression. It is a polygenic surface recording multiple tectonic events and represents the base of the progressive onlap of each succesive depositional sequence. Locally it corresponds to the lower boundary of the bottom E sequence whose maximum thickness is reached in the coastline sectors of the basin, with a maximum depocenter elongated in a NE-SW striking direction (Fig. 12).

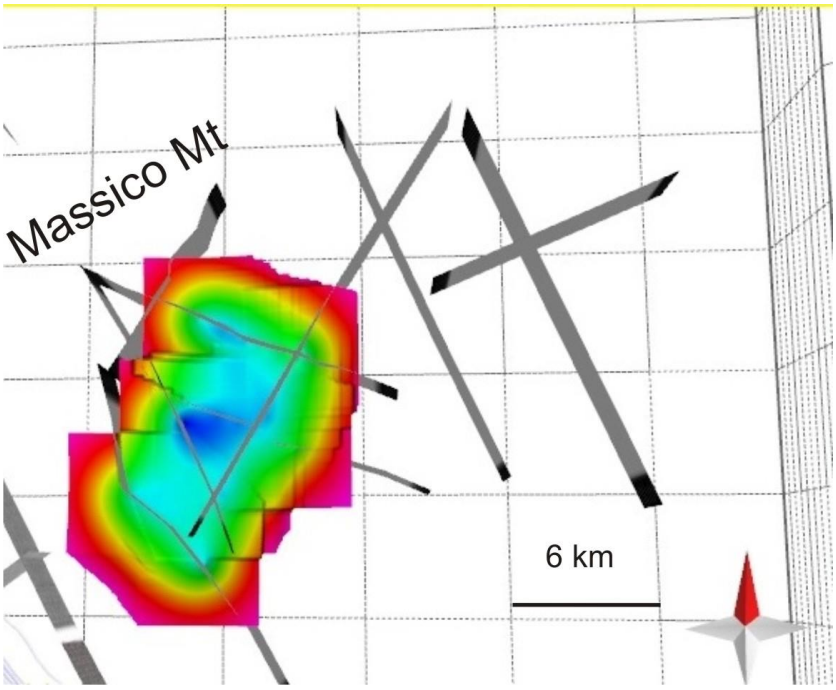

Figure 12: 3D modelling of the bottom E sequence whose deposition seems to have been controlled by a NE-SW striking discontinuity, as also observed on seismic section Volturno Plain 002.

The thickness of the sequence increase towards NW with a deposition controlled by a NE-SW normal fault bounding to the south the Massico Mt. The activity of this fault also affected the deposition of sequence D (Fig.13) showing diverging reflections against the master fault in its upper reflections and displaying a wedge like external form. With an early Calabrian age constraint resulted by the FCO of *Hyalinea balthica* in the upper part of the D sequence, the previous E

sequence should be dated back to a pre-Emilian chronostratigraphical substage, probably correlated to a Santernian chronostratigraphical stage. This interpretation attributes a normal component on the activity of the fault at least in early Pleistocene times. The geometry of the C sequence lower boundary reveal a more complex articulation.

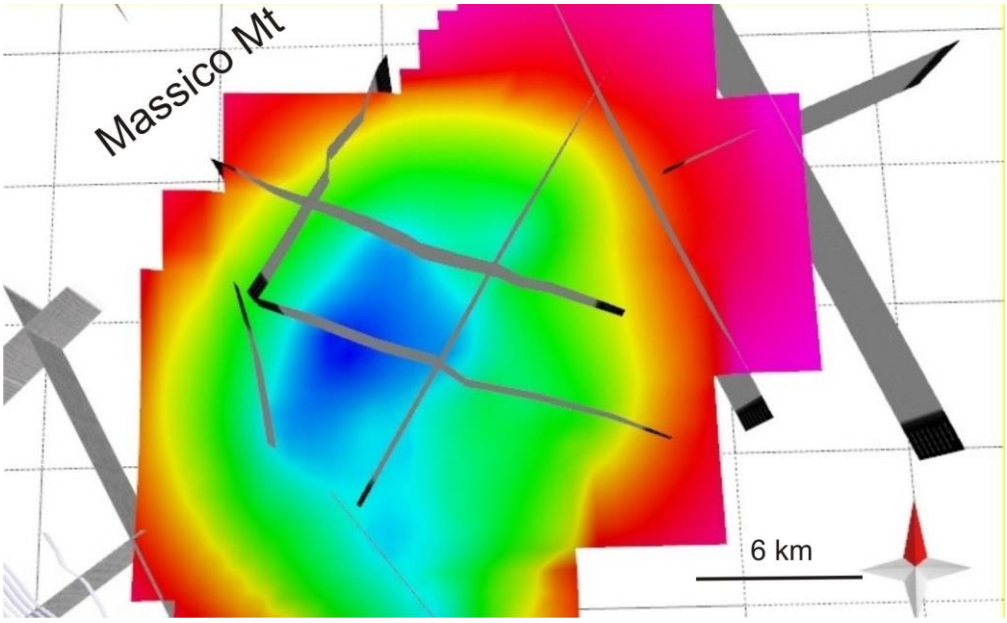

Figure 13: geometry of the B sequence lower boundary : as already observed for the modelling of the bottom of E sequence, the bottom of D depositional sequence displays a NE-SW trend, increasing in thickness toward NW.

The morphobathymetric low is always located in the same position with a NE-SW striking direction, but deformations, as observed in seismic profiles, start to migrate also in an inland direction (Fig.14).

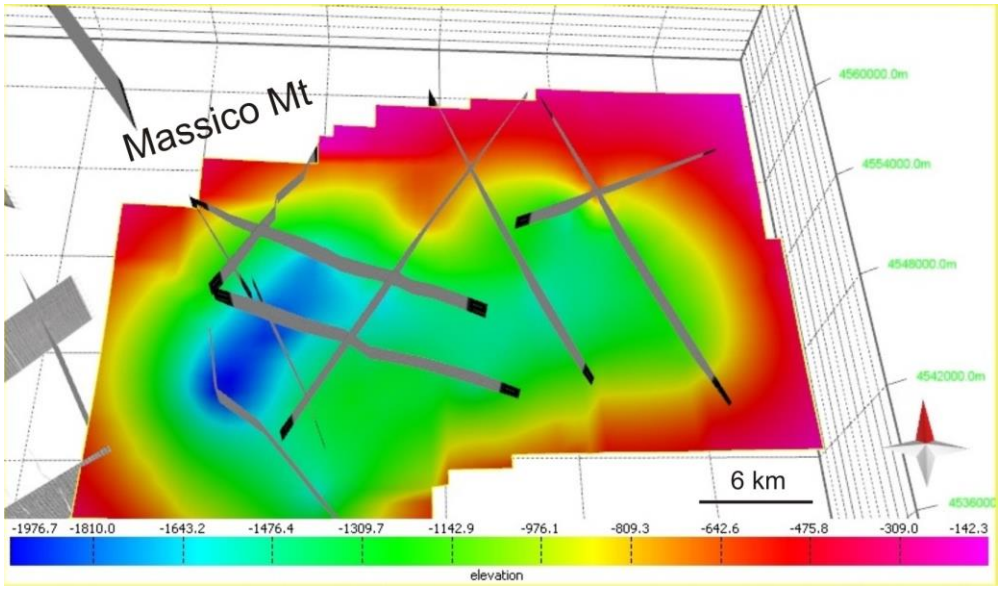

Figure 14: geometry of the C sequence lower boundary : deformations start to migrate in an inland direction with C sequence.

WNW-ESE normal to oblique faults locally create downthrown blocks and negative flower structures. Tectonic inversions start to occur with the deposition of C sequence where a new oblique component superimpose on NE-SW previous normal faults. In the upper stratal reflections of this sequence we observe kinks against the NE-SW master fault bounding the Mssico Mt to the South, with a structural relief mirroring in an opposite relief the low originated by the previous dip-slip component (Harding, 1985). Volcanic bodies have been seismically detected within this sequence. A pyroclastic layer recorded in Castelvolturno 1 deep well, interpreted here as the first evidence of the onset of the Roccamonfina volcanic activity, revealed for this sequence a middle Pleistocene age constraint. A volcanic body deforming the stratal reflections of this sequence has also been displayed. This interpretation seems to be in accordance with data from literature. An early-middle Pleistocene transtensional associated with a magmatic event has been recognized by previous authors (Caiazzo et al., 2006; Cinque et al., 1993). The lower boundary of the B sequence is less articulated and more uniform (Fig.15); it represents the base on which a deep middle-Pleistocene marine transgression occurred. Little kinks in the lower stratal reflections of B sequence against a NE-SW main fault, allowed us to infer that tectonic inversions influenced also the lower part of this depositional sequence. WNW-ESE en echelon basin sidewall faults arrays are particularly evident in the modelling of this sequence boundary (Fig.16).

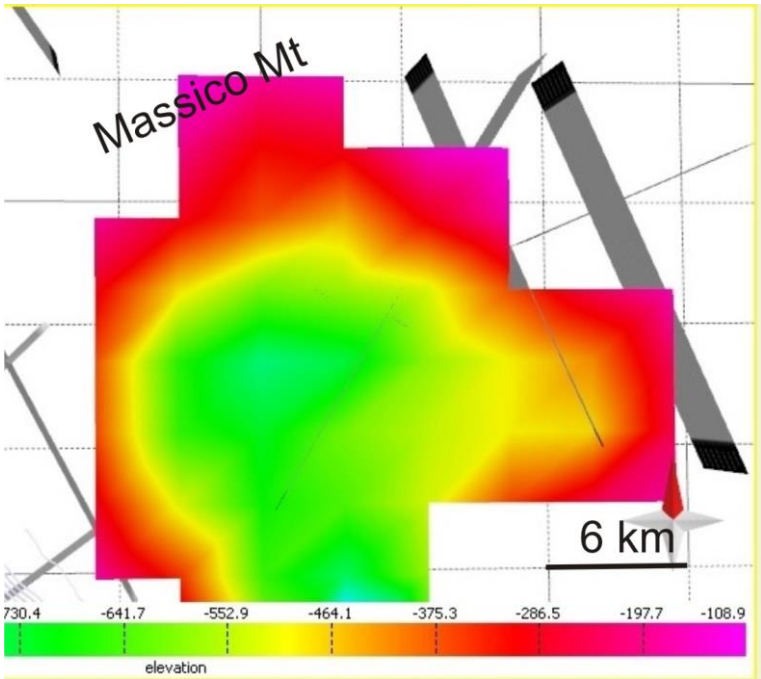

Figure 15: geometry of the B sequence lower boundary: it represents the base on which a deep middle-Pleistocene marine transgression occurred. Deformations related to WNW-ESE oriented basin sidewall faults result particularly evident in the modelling of this sequence boundary.

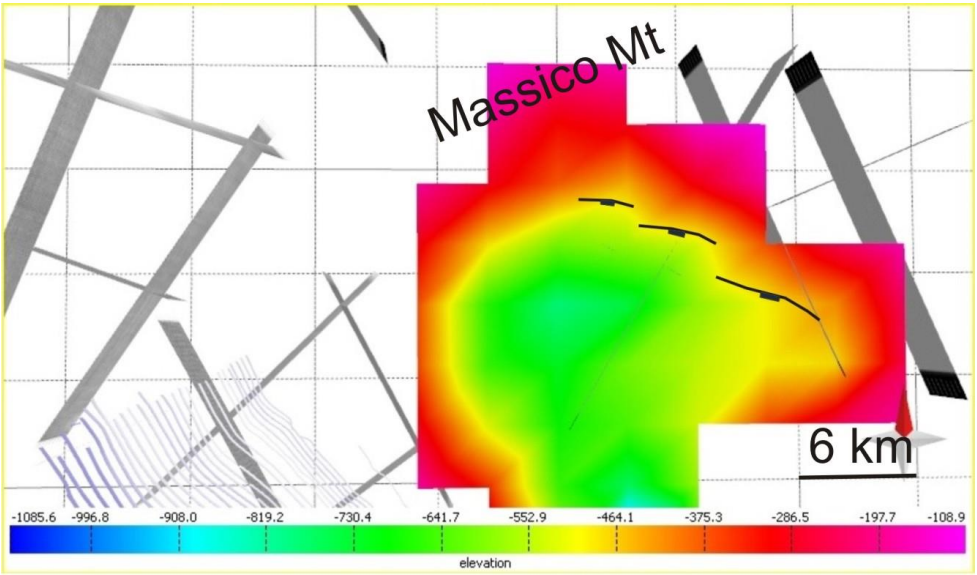

Figure 16: Evidence of basinal sidewall faults on the modelled lower boundary of B sequence.

6.2. Geometry of the basin

The 3D modeling of the base of the Quaternary infillings revealed an asymmetric rhombic shaped relative low with a single depocentre and basin margins characterized by an half-graben geometry. Mapping the distribution of structural features observed on seismic profiles we have reconstructed the direction of the main lineaments influencing the evolution of the basin. The main boundaries defining the basin geometry are NE-SW, WNW-ESE and NW-SE striking (Fig. 17).

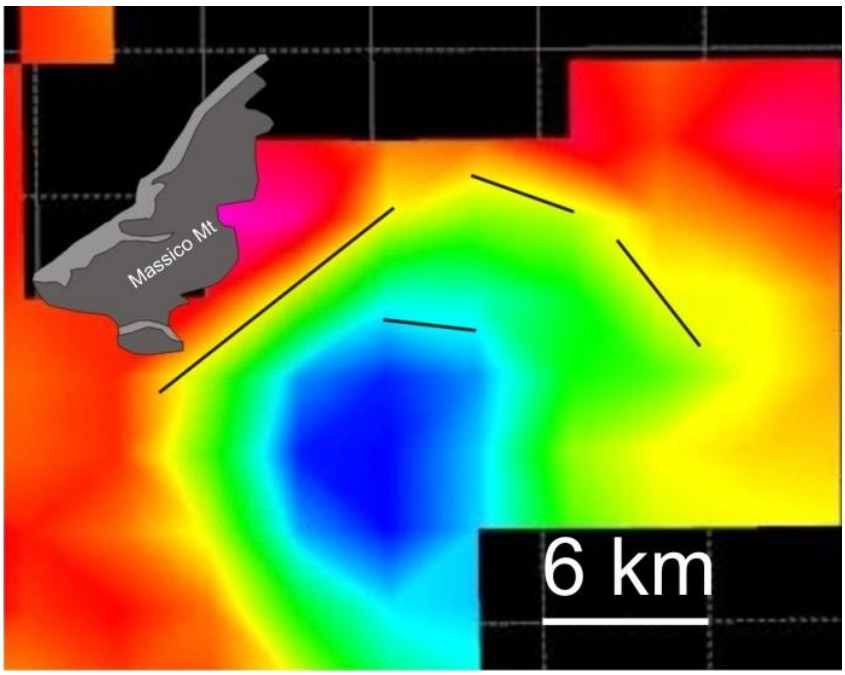

Figure 17: 3D modelling of the base of the Quaternary infillings revealing an asymmetric rhombic shaped relative low. The main discontinuities observed correspond to NE-SW, E-W and NW-SE planes.

Kinks and digitisations in Pleistocene reflections have been observed on NE-SW normal faults planes, indentifying inversions in the polarity of the structural relief (Harding, 1985) mainly recorded in C sequence. These striking planes recorded maximum throws of more than 3000 meters, individuating the depositional depocenter of the Volturno Plain. Minor WNW-ESE striking normal faults with maximum offsets of 1000 meters have been also displayed. Two major overstepping upward spreading WNW-ESE normal faults individuated, in section VP 004, a downthrown region. A splaying system of subsidiary faults with smaller scale offsets of the order of hundreds of meters, accompanied the deformation of the above defined structure. An acoustically invisible body with a conical external shape, has been observed above a WNW-ESE normal faults. Onlaps on its flanks and interdigitisation of marine deposits related to the third depositional sequence, with the low amplitude reflectors constituting the internal pattern of this acoustic body have been seismically observed. Finally, NW-SE trending normal faults dipping southwestward, deformed with a step-like geometry the base of the infillings sequences, affecting the upper part of the Quaternary sediments and apparently coinciding with the lateral tips of the above mentioned WNW-ESE normal faults.

6.3. Structural interpretation

NE-SW and WNW-ESE planes have been interpreted as antithetic and synthetic planes (Fig.18, a e b) of a main left-lateral NW-SE Principal Displacement Zone (PDZ), cropping out in the Monti di Caserta area (Bravi et al., 2006), bounding to the NE the Campana Plain and observed in the south in the Cilento region (Turco et al., 1990; Capotorti & Tozzi 1991; Catalano et al., 1993; Cinque et al., 1993; Ascione & Cinque, 1996; Saitto et al., 2002). PDZs are typically segmented and are constituted by segments, coinciding with synthetic Riedel R shears and antithetic conjugated R' Riedel shears, thus connected by oversteps. R' shears are generally oriented at high angle, typically at 75°, i.e. $90° - \left(\frac{\varphi}{2}\right)$, clockwise to a dextral and anticlockwise to a sinistral main fault plane. WNW-ESE to NW-SE normal faults coincided with basinal sidewall faults (Fig.19) terracing and defining the NE margin of the basin (Sugan et al., 2014). The synformal area observed in the overstepping region of WNW-ESE normal faults has produced an upward spreading splaying system of deformations interpreted as a negative flower structure. Positive structural inversions, representing opposite changes in the observed relief and possibly induced, in this case, by the superposition of a strike-slip motion on a dip-slip component (Harding, 1985), should represent the interpretation of reflections digitisations of upper Pleistocene sediments, kinking against a

major NE-SW normal to oblique fault. High subsidence rates affect basin associated to strike-slip tectonics. The Volturno basin show 3km of Quaternary deposits, resulting in a subsidence rate, once decompacted and corrected, with an average value of tectonic signature of 0,8 mm/yr. Values greater than 0.5 mm/yr are generally associated to strike-slip basins, thus our interpretation for the Volturno Plain coincides with a pullapart basin, formed in the stepover region of two NW-SE left-lateral faults, probably representing the northern tips of the Pollino-Cilento shear zone.

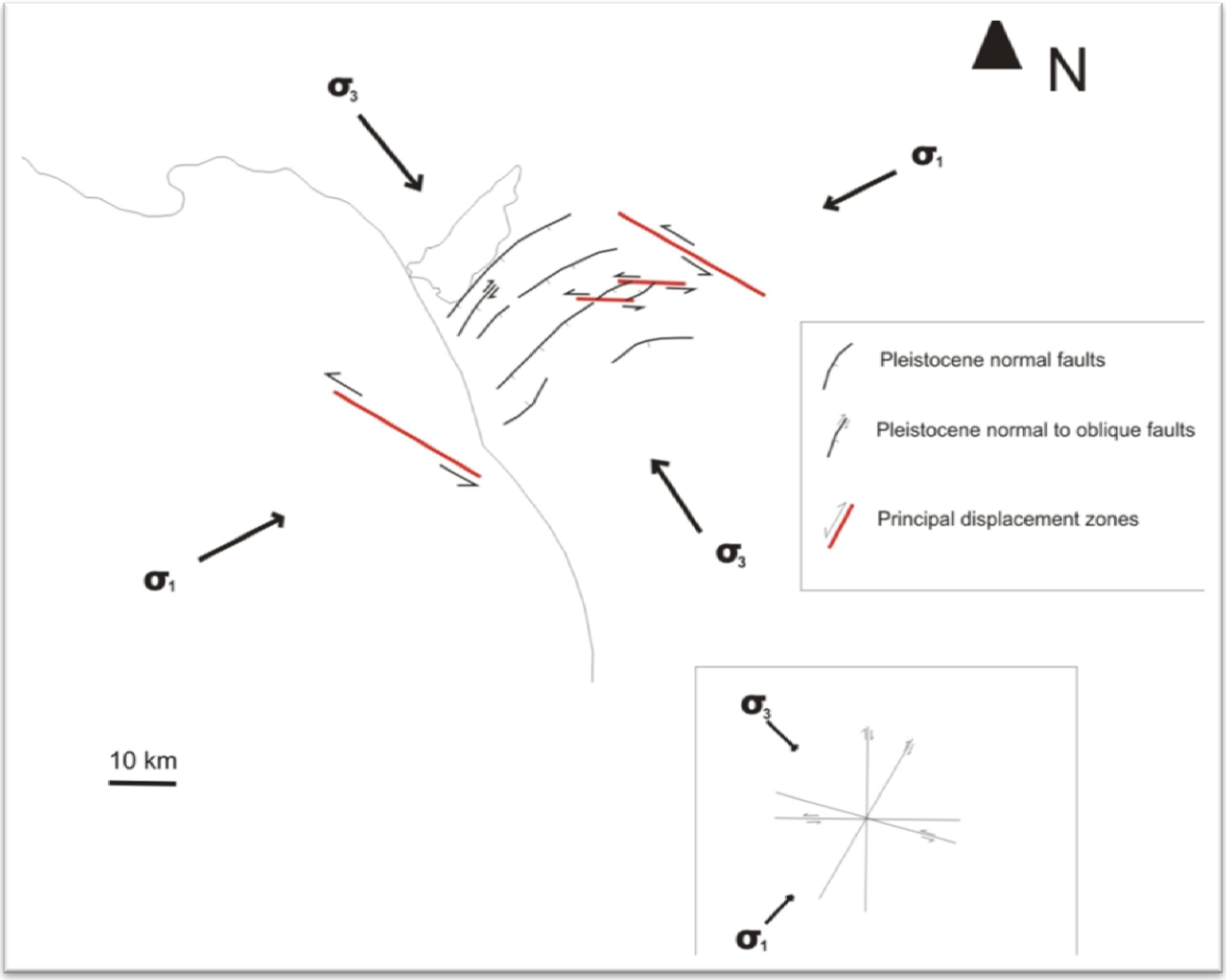

Figure 18: Synthetic structural map and stress field distribution. NE-SW and WNW-ESE planes have been interpreted as antithetic and synthetic planes (Fig.18, a e b) of a main left-lateral NW-SE Principal Displacement Zone (PDZ).

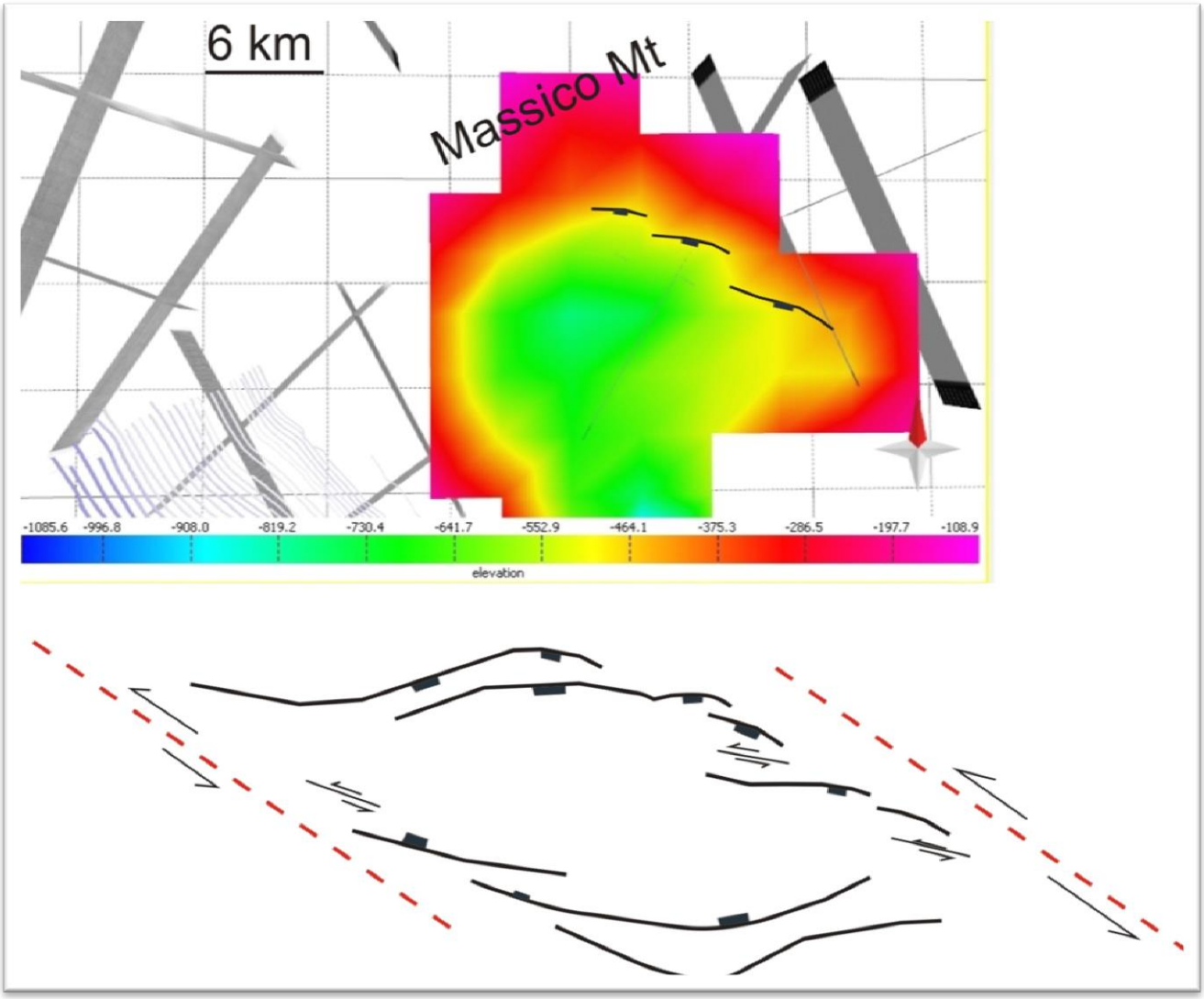

Figure 19: Evidence on the Volturno basin of en echelon basin sidewall faults and synthetic structural sketch, resulted from the kinematic reconstruction.

7. Subsidence curves and seismic interpretation

Observing the trendlines of both the cumulative and tectonic subsidence curves it is immediately visible that they are composed by two distinctive stages (Fig.20). the basin seems to subside very rapidly, slowing later on and then, in Middle Pleistocene, a renewed subsidence seems to occur. Strike-slip basins backstrip curves show features of both rift-type and foreland-type basins (Watts et al., 1982), thus they may be particularly difficult to discriminate by analysing tectonic subsidence curves (Allen& Allen, 2005). Seismic interpretation pointed out an initial dip slip motion followed by a subsequent strike slip component. The produced curves display two distinctive concave up segments. The second stage has an age constraint of 630 ky, observed in

the third of the five sequences seismically detected. Sequence C displayed one of the greatest thickness among the interpreted sequences and revealed tulip structures and positive structural inversions, deformations correlatable with a transtensional regime. Both The tectonic signature values for the two distinctive segments and the total average value for tectonic subsidence pointed out values greater than 0.5 mm/yr, which referring to the Allen & Allen (2005) classification could be correlated with strike-slip basins.

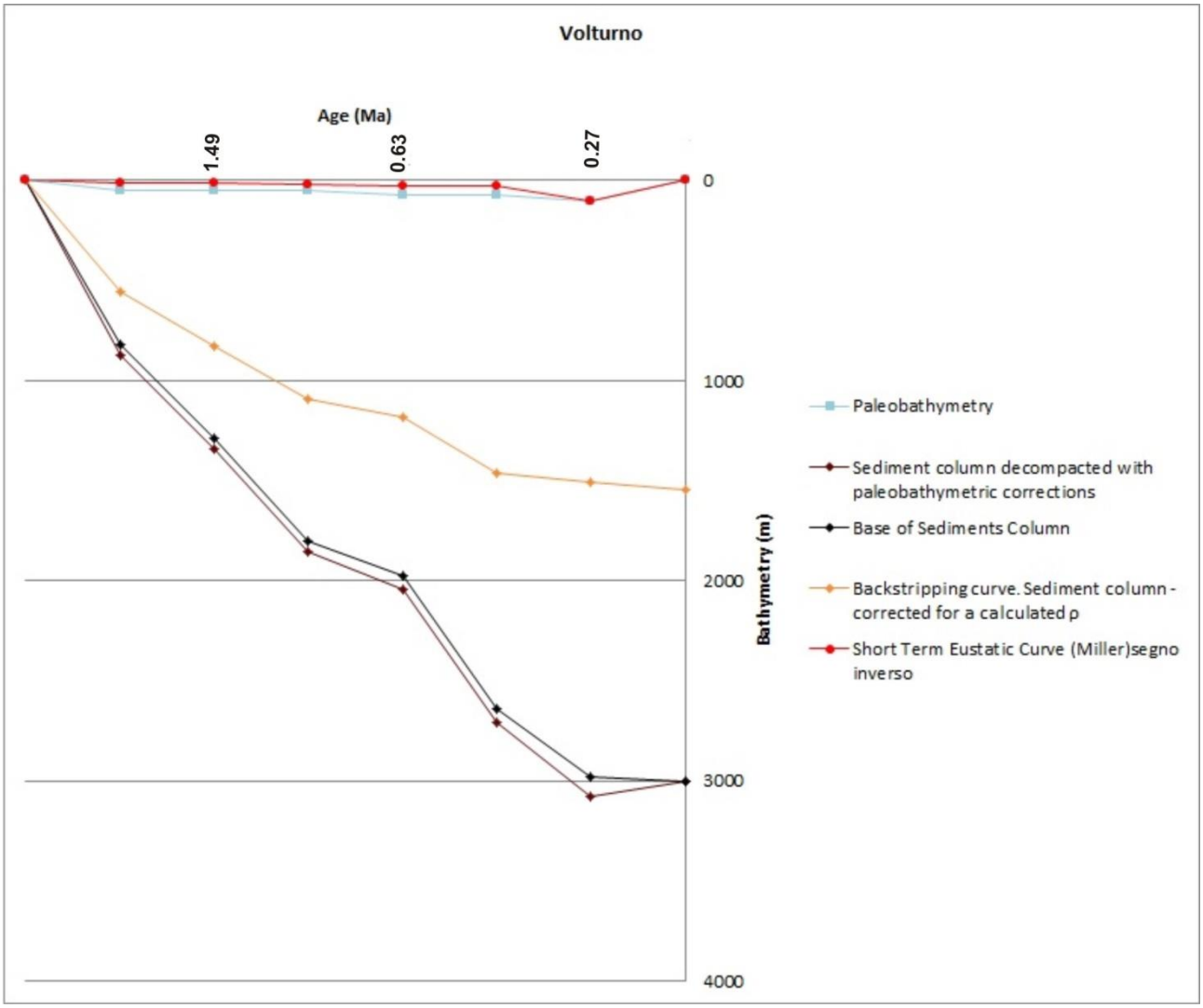

Figure 20: The produced curves display two distinctive concave up segments. The second stage has an age constraint of 630 ky, observed on sequence C, revealing in seismic profiles tulip structures and positive structural inversions, evidence of a transtensional regime.

8. Conclusions

Structural and stratigraphical observations, combined with a sequence boundaries modelling and calculation of tectonic signatures for the subsidence of the basin, enabled us to depict the Pleistocene tectono-sedimentary evolution of the plain. We have distinguished five depositional

sequences corresponding to distinctive transgressive-regressive cycles lying on top of an acoustic substratum probably coinciding, as suggested from literature (Brancaccio et al., 1991; Cinque et al., 1993; Caiazzo et al., 2006;¸Santangelo, 2010), with a Meso-Cenozoic carbonatic and siliclastic succession. The observation of major structural discontinuities on seismic profiles and a mapping procedure on the analysed grid, first enabled to display the structural pattern of deformations affecting the basin. The external geometry of the interpreted sequences and their internal stratal pattern revealed the period of activity of such faults and the superposition of distinctive vertical and lateral movements. A strong dip-slip component on major NE-SW normal faults seems to control the deposition of E and D bottom sequences, constrained to an early Pleistocene by the FCO of *Hyalinea balthica* in the upper part of D sequence. Starting from C sequence, deformations start to migrate in an inland direction. A pyroclastic layer recorded in Castelvolturno 1 deep well, interpreted here as the first evidence of the onset of the Roccamonfina volcanic activity, revealed for this sequence a middle Pleistocene age constraint. Negative flower geometries observed in the overstepping region of WNW-ESE normal to oblique faults, igneous intrusions and kinkings on NE-SW striking faults, reflecting an opposite structural relief among such planes, have been observed within this sequence. This interpretation seems to be in accordance with data from literature suggesting the onset of an early-middle Pleistocene transtensional event in the area (Caiazzo et al., 2006; Cinque et al., 1993). Kinkings and digitisations on NE-SW normal to oblique faults have been displayed in the lower stratal reflections of B sequence, enabling us to infer that tectonic inversions influenced also the lower part of this depositional sequence, bounded at its top by the erosional surface created by the MIS 8 related sea level low stand. NE-SW and WNW-ESE planes, controlling the geometry of the basin, have been interpreted as antithetic and synthetic planes of a main left-lateral NW-SE Principal Displacement Zone (PDZ), cropping out in the Monti di Caserta area (Bravi et al., 2006), bounding to the NE the Campana Plain and observed in the south in the Cilento region (Turco et al., 1990; Capotorti & Tozzi 1991; Catalano et al., 1993; Cinque et al., 1993; Ascione & Cinque, 1996; Saitto et al., 2002). The 3D modeling of the base of the Quaternary infillings revealed an asymmetric rhombic shaped relative low with a single depocentre and basin margins with half-graben geometries. This configuration has been interpreted as an intermediate stage in the continuum model of pull-apart evolution proposed by Mann (1983). Bruno et al. (2000) proposed a similar interpretation for the formation of Volturno Basin, suggesting that the depression should have been referred to a pull-apart basin or, alternatively to a graben structure, originated by the action of WNW-ESE normal faults. Thus, the Volturno basin, showing 3km of

Quaternary deposits, resulting in a subsidence rate, once decompacted and corrected, with an average value of tectonic signature of 0,8 mm/yr, has been interpreted as a pullapart basin formed in the stepover region of two NW-SE left-lateral faults. High tectonic subsidence rates affect basins associated to strike-slip tectonics, associated to values greater than 0.5 mm/yr (Allen&Allen, 2005).

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Chapter 4

Late Quaternary to Holocene evolution of the northern Campania continental shelf (central, Italy)

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Abstract

A set of high resolution seismic reflection profiles has been acquired in collaboration with the IAMC-CNR (Naples) immediately offshore the Volturno river mouth. Chirp sub-bottom sonar investigations, performed along the continental shelf, enabled the recognition of two main reflectors representing the top of the Holocene sediments and the Last Glacial Maximum (LGM) erosional surface. Morphobathymetric maps were reconstructed by the interpolation of seismically detected horizons. The morphology of the LGM revealed an antithetic oblique synclinal accommodation zone, defined by an interbasinal relative high with a NE-SW trending direction, bounded by two outward facing sets of normal faults. The observed sets of faults, cutting the seismically imaged transgressive and highstand units with very small offsets, have revealed a NNW-SSE and an ENE-WSW trending direction. The interpretation of Chirp profiles has also enabled the recognition of degassing features, displayed as vertically stacked amplitude anomalies, distributed along an ESE-WNW trending direction and affecting the seismically imaged transgressive and highstand units. Sparker profiles revealed a deeper laterally extensive acoustic turbidity front, with the same striking direction. The orientation of this front is similar to the one observed for a detected volcanic intrusion, leading us to hypothesize that intrusions may have followed an E-W trend, correlatable with the main direction of normal to oblique faults active during Quaternary times.

1. Introduction

Seal by-pass systems are defined as “seismically resolvable geological features embedded within sealing sequences that promote cross-stratal fluid migration and allow fluids to bypass the pore network” (Cartwright et al, 2007). A variety of structures may occur in zones of high fluid pressure

which can be resolved, following the classification proposed by Cartwright et al. (2007), in i) fault related, ii) intrusion related and iii) pipe related. The most common seismic expressions of fluid escape features are pockmarks and pipes structures: sub-circular depressions and subvertical conduits produced by the hydraulic fracturing in conditions of high pore fluid pressure. The overpressure of clay rich gas saturated sequence may also lead to the formation of mud volcanoes, an excellent mechanism to dehydrate the overburden sequences (Cartwright et al., 2007). Different triggering factors may lead to the overpressure of subsurface gasses: 1) a strong sedimentation rate producing a rapid burial, 2) tectonic compression defining traps and preferential migration pathways, 3) storage and generation of methane in sealing sequences (Judd and Hovland, 2007). The presence of gas in shallow water has been reported by several authors for modern continental shelves (Duran et al., 2007, Mazumdar et al., 2009; Chun et al., 2012). A muddy organic-rich supply represent an important condition to promote the generation of biogenic methane (Fleischer et al., 2001), which start to occur as free gas in sediments when its concentrations exceed the methane solubility (Schubel, 1974; Abegg and Anderson, 1997). Hydrothermal fluids should also promote such kind of structures, producing columnar zones of disturbed reflections. The area is located offshore the Campania and Latium coasts where Pleistocene volcanic structures have been observed along the Pontine Archipelago and displayed as magnetic anomalies offshore the Volturno river-mouth (De Alteriis et al., 2002;2006; Aiello et al., 2011). The origin of fluid venting structures in this area should be possibly attributed either to hydrothermal fluids or to overpressure of clay and organic rich sequences. Our dataset is composed by Chirp and Sparker profiles covering the Campania continental shelf. We have observed pockmarks, pipes and mounds with their relative conduits. The different details of investigation, offered by Sparker profiles, enabled the observation of wide zones of acoustic turbidity with distinct lateral flanks and irregular top fronts. The description of the structures observed and a mapping procedure should suggest their origin and facilitate their definition following Cartwright classification.

2. Geologic framework

Several studies have been performed on high resolution seismic profiles in order to define the Middle-Late Pleistocene stratal architecture and growth patterns of the Western Mediterranean margins (Alonso et al., 1990; Farrán and Maldonado, 1990; Tesson et al., 1990; Ercilla et al., 1994; Chiocci, 1994; Torres, 1995; Fraccascia et al., 2013; Ridente et al., 2012; Chiocci, 2000; Chiocci et

al., 1997; Chiocci & Orlando, 1996; Lobo et al., 2004). The Western Mediterranean margins could be considered as mainly controlled by a siliciclastic sedimentation and by a growth pattern characterized by vertically and laterally stacked progradational and aggradational units (Chiocci et al., 1997). The investigated area is located in northern Campania shelf, offshore the Volturno coastal plain (Fig.1).

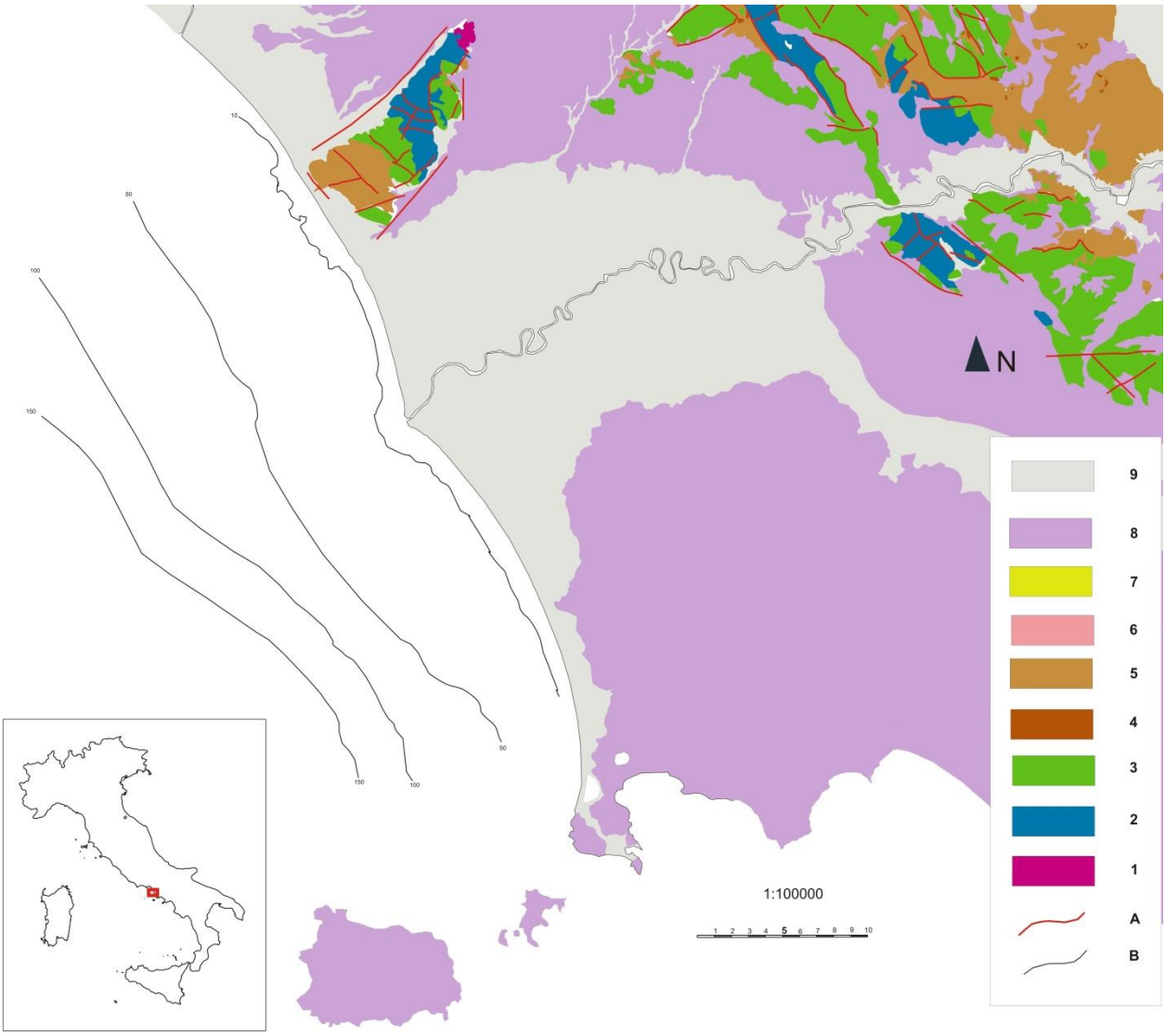

Figure 1: :Structural sketch map of central-southern Apennines. study area corresponding to the continental shelf. Legend: 9) Pleistocene-Holocene alluvial deposits; 8) Quaternary volcanic deposits; 7) Early Pleistocene conglomeratic deposits; 6) Upper Messinian gypsum-bearing clays; 5) Late Tortonian siliciclastic foredeep deposits; 4) Langhian-Serravalian *Calcari a Briozoi e Litotamni* Fm; 3) Cretaceous shallow water limestones; 2) Jurassic shallow water limestones and dolomites; Triassic dolomites and limestones; A) undifferentiated faults; B) isobaths.

The late Quaternary succession along this sector of the margin is characterized by prograding clinostratified deposits, truncated by the youngest Wurm unconformity, recording multiple events, from the subaerial exposure of the shelf to the successive Versilian sea level rise (Aiello et al., 1978; Chiocci, 2000). Overlying the Wurm unconformity, sediments recording the latest sea level

rise, occurred from 18 ky BP to 5 ky, and the present highstand conditions, described transgressive and highstand deposits constituting a sedimentary wedge decreasing in thickness towards the shelf edge (Chappell and Shackleton, 1986; Hunt and Tucker, 1992; Amore et al. 1996; Coppa et al., 1996; Buccheri et al., 2002; D'Argenio et al. 2004; Iorio et al., 2014). Below the erosional unconformity, the middle-Late architecture of the margin is considered to be formed mainly during periods of falling sea-level and lowstands. Considering the last 550 ky, the sea has been falling for the 65% of time (Chiocci, 2000). This strongly asymmetric sea-level curve indicates how the Middle-Late Pleistocene glacio-eustatic fluctuations have been affected by slow and gradual sea-level falling stages and by short-lived rise and highstand stages (Williams et al., 1988). The Middle-Late Pleistocene glacio-eustatic fluctuations were characterized by high frequency (20-100ky) and high amplitude, ranging from +10m to- 120m (Chiocci et al., 1997). The fluctuations occurred in the same depth range, leading in this way to the erosion, during a sea level fall of the deposits related to a previous cycle. The total subsidence enabled the preservation of deposits, acting as a key factor to drive and unravel the growth of the margin (Chiocci, 2000). Since early Pleistocene the Campanian margin has been affected by an extensional tectonic regime resulting in NE-trending normal faults, SE dipping, defining asymmetrical half grabens (Moussat et al., 1986; Sartori, 1990; Hyppolite et al, 1994; Cinque et al., 1993; Caiazzo et al., 2006). The activity of these faults, with a vertical slip rate reaching also values of 4.3 mm/yr (Milia and Torrente, 2003), shaped the present day morphology of the coast defining subsiding coastal plains and uplifiting rocky promontories. Pery-tirrhenian grabens experienced intense subsidence rates during this tectonic event in which also transtensive left-lateral NW-SE faults were active (Caiazzo et al., 2006). Early–Middle Pleistocene horizontal offsets were recorded on NW–SE left-lateral strike-slip faults in the Cilento region (Cinque et al., 1993) and in the Sorrento area (Capotorti & Tozzi, 1991; Caiazzo et al., 2006). The activity of both normal and oblique faults ceased in late Quaternary with the onset of a tectonic event with a NE-SW stretching direction locally reactivating pre-existing structural planes (Caiazzo et al., 2006). NW-SE normal faults with a dip slip displacements of a few tens of meters were recognized in the Campana (Romano et al., 1994) and in the Sele Plains (Amato et al., 2011). NW-SE faults controlled the sedimentation of the 40 ky Campanian ignimbrite and affected the 12ky transgressive unit in the offshore of Naples Gulf (Milia and Torrente, 2003).

3. Methods and dataset

Different details of investigation on the continental margin, immediately offshore the Volturno river mouth, enabled some structural observations and the recognition of sequences with their distinctive relative stratal patterns for Late Pleistocene to Holocene deposits. A detailed description of the external and internal configurations of seismic units, imaged with different resolution and penetration parameters will follow, in order to contextualize their meaning in a more comprehensive regional stratigraphic and structural framework. The interpreted grid is composed by 60 Chirp sub-bottom profiles, with a vertical penetration of 50 meters below bottom sea level and by 3 Sparker profiles, covering the first 300 meters of the continental shelf (Fig.2).

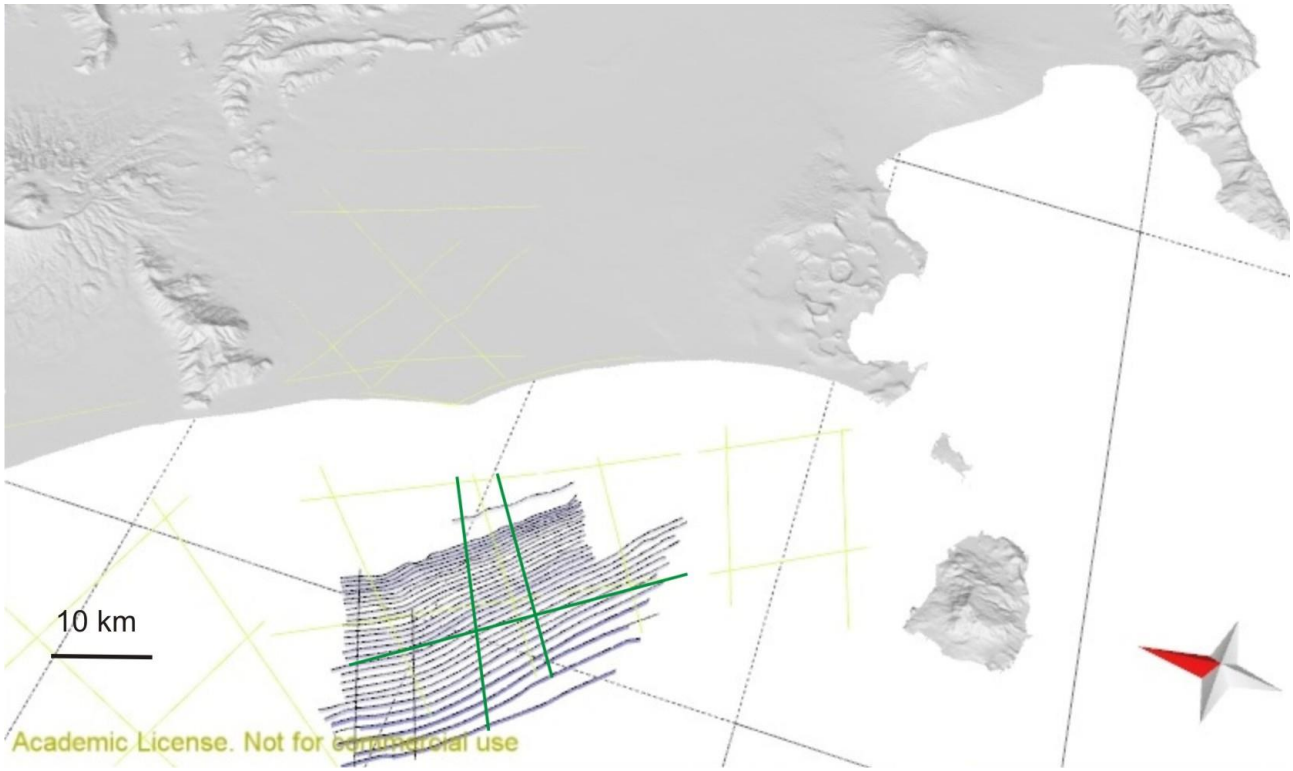

Figure 2: Interpreted seismic high resolution grid. In green we have represented the location of Sparker profiles. In black 60 high resolution Chirp sub-bottom profiles.

A 7 meters long core (C5) has been recovered on the outer shelf (Fig.3), representing the only tool in the constraining of the more superficial sequences. Stratigraphic and magnetic susceptibility analysis were performed on C5 core by the IAMC-CNR laboratory. For deeper Sparker profiles, data from literature on glacio-eustasy driven processes for the Late Quaternary outbuilding of the margin and geometrical analogies with other Sparker profiles, interpreted by previous authors along the Latium and Campania continental shelf, have provided a guide in their interpretation.

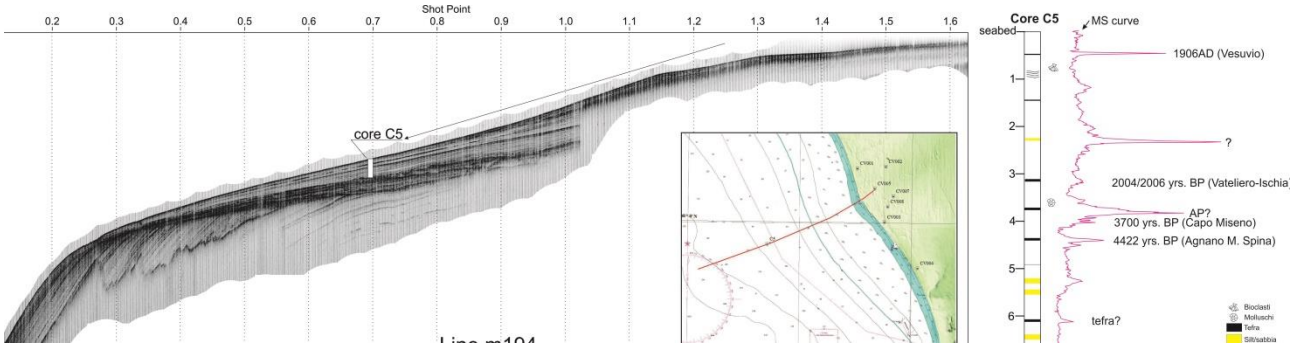

Figure 3: Location of C5 core (7m), calibrating the more superficial sequences.

4. Chirp profiles

4.1. Acoustic units

Three main horizons have been observed on Chirp profiles: H1, H2, H3 (Fig.4). The deepest one, H1, has an highly irregular trend and is characterized by a strong impedance contrast marking the transition to a region, beneath it, in which the signal is not always penetrating.

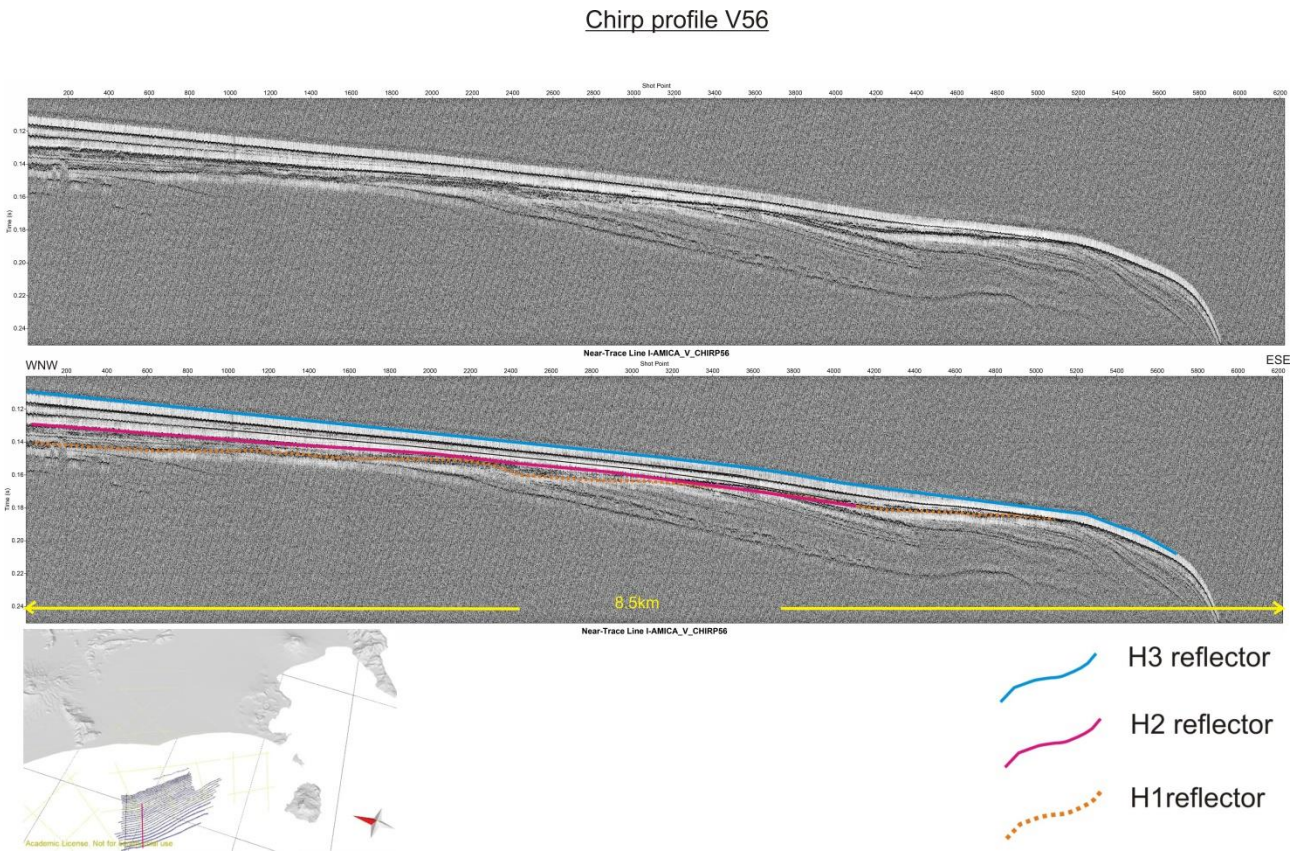

Figure 4: Description of acoustic features: three main horizons have been observed on Chirp profiles: H1, H2, H3. H1 has an irregular trend and mark the transition to a region, beneath it, in which the signal is not always penetrating. The above unit (Unit1), with a thickness increasing in a landward direction, is characterized by high amplitude sometimes patchy and wavy reflectors. Above H2 horizon, Unit2 reveals a seismically transparent body and clear downlap terminations on H2 reflector. Its thickness decrease towards the shelf break describing an external wedge shaped configuration.

When visible medium to low amplitude, prograding and sub-parallel oblique reflections, have been displayed below H1 reflector, revealing toplap terminations beneath it. The above unit (Unit1) is characterized by high amplitude sometimes patchy and wavy reflectors, lying on the H1 horizon. A wedge shaped external configuration has been in some cases detected, with a thickness increasing in a landward direction and revealing a sedimentation controlled, in some cases, by normal faulting (Fig.5).

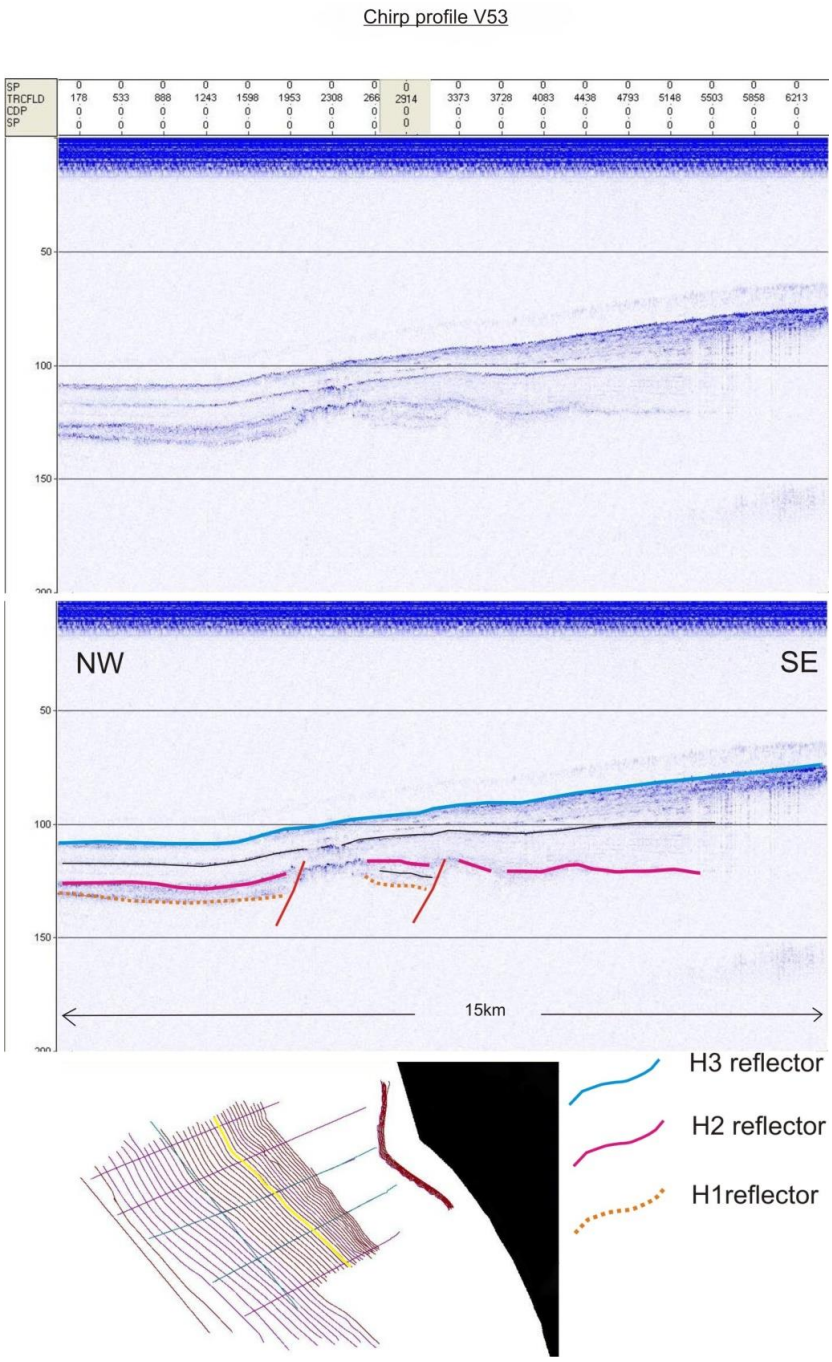

Figure 5: Chirp sub-bottom profile V53 revealed a wedge shaped external configuration for Unit 1, with a thickness increasing towards a normal fault.

Medium to high amplitude reflections constitute this acoustic unit, reaching a thickness of more than 10 ms. Its upper boundary is characterized by H2 horizon, above which we observe a seismically transparent body (Unit2), characterized by an aggrading stacking pattern and by onlap and downlap terminations. Its thickness decrease towards the shelf break describing an external wedge shaped configuration. This unit displays cylindrical reflection anomalies, constituted by a series of vertically stacked depression affecting the unit until the seabed, representing the H3 reflector. Small scale offset faults, with an almost seismically non resolvable throw, affect this acoustic unit.

4.2. Calibration

Stratigraphic and magnetic susceptibility analysis were perfomed on C5 core by the IAMC-CNR laboratory. This 7 m long core, drilled in the immediate offshore of the Volturno river mouth, recorded a Late Quaternary to Holocene succession and calibrated the observed wedging seismic units. Coarser grained deposits, with more frequent sandy intercalations, characterize the first two meters at the base of the C5 core (Fig.3). Moving upward, a dominantly pelitic succession characterize the following 5 meters sampled. Records of the last Phlaegrean Fields major eruption at 15 ky BP (Neapolitan Yellow Tuff, NYT; Deino et al. 1994), have been observed at the base of the core, calibrating in this way the latest sea level rise, occurred from 18 ky BP to 5 ky, and the present highstand conditions, describing the transgressive and highstand deposits constituting the observed sedimentary wedge. Wavy and patchy high amplitude reflectors, constituting Unit1, should correspond to high-energy deposits related to transgressive intervals (Lobo et al.,2004), while low amplitude reflections of the above lying Unit2, have been interpreted as the response of an highstand muddy sequence

5. Sparker profiles

5.1. Acoustic units

A grid of three Sparker profiles (Fig.6), NE and NW trending, with a vertical resolution of about 10 meters, has been acquired in collaboration with the CNR-IAMC research group, on board of R/V Urania vessel. Eight acoustic units have been recognized on these sections (Fig.7). Bottom to top, the first seismic unit detected corresponds to an invisible acoustic body (V1 Unit). Onlaps

terminations against its flanks and differential compaction above its top have been observed on the above seismic unit V2 (Fig.8).

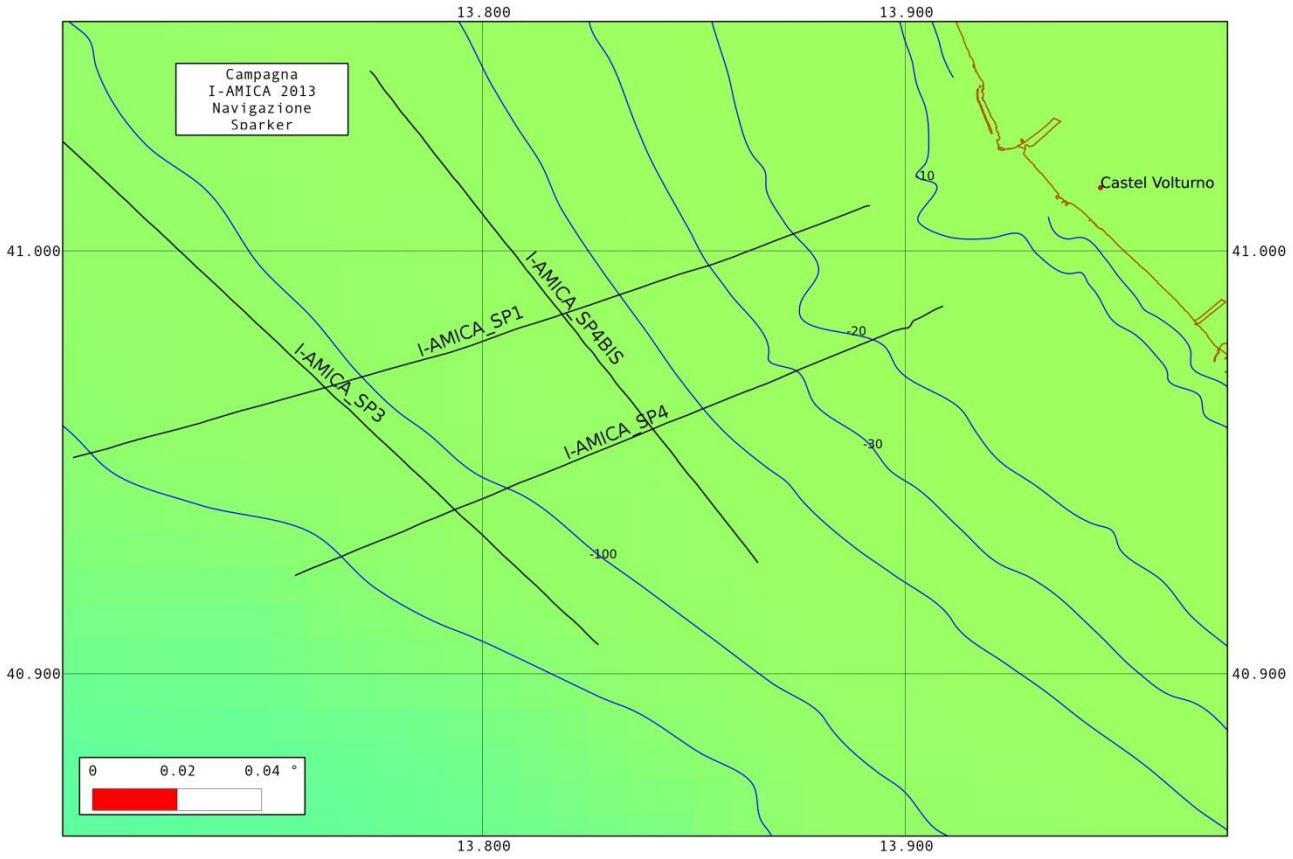

Figure 6: Location of SP1, SP3 and SP4 Sparker profiles.

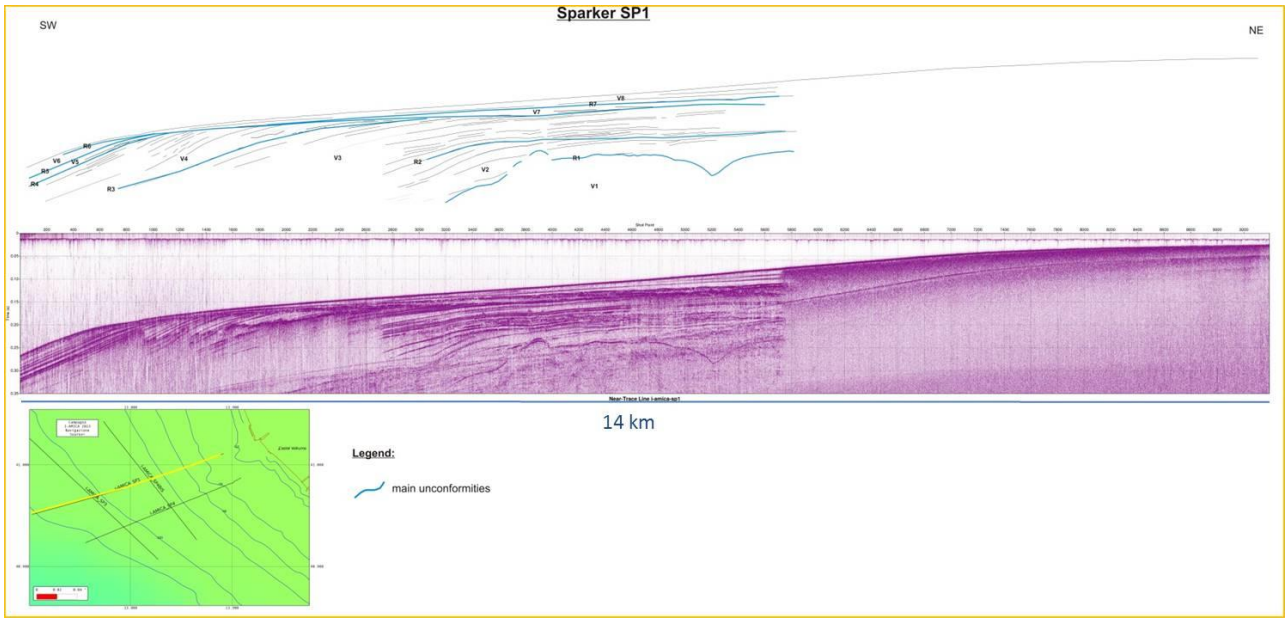

Figure 7: Presentation of acoustic units observed on Sparker profiles (here SP1 section has been represented): a total of eight acoustic units have been recognized.

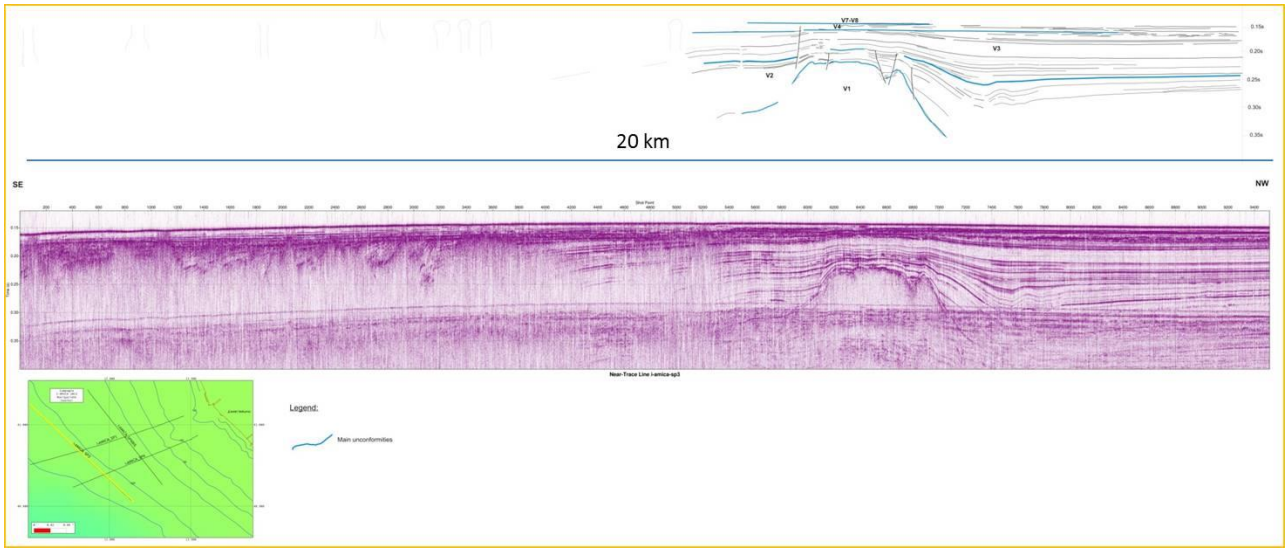

Figure 8: Presentation of SP3 Sparker profiles and Evidence of deformations affecting mostly seismic unit V2: onlaps terminations against V1 unit and differential compaction above the observed structure have been observed.

Its medium to low amplitude reflections are characterized by an oblique tangential internal configuration. This unit seems to be deformed and displays downlap terminations on R1 reflectors, coinciding with the top of the acoustically invisible body. V2 seismic unit revealed an aggrading prograding migration of the offlap breaks and upper toplap terminations against a reflector (R2), constituting a major erosional unconformity gently dipping in a seaward direction. Above it V3 seismic unit displayed a tabular external configuration and a stratified aggradational-

progradational internal growth pattern, revealing onlap terminations on R2 erosional unconformity. Above it a sigmoidal seismic unit V4 revealed downlap terminations on a major R3 reflector. The migration of offlap break indicates aggradational-progradational processes, with a decrease in transparency moving upsection, as observed also for V2 and V3 seismic Units. Across a generally concordant R4 reflector, we observe the transition from offlaps observed for acoustic unit V4 passing laterally to oblique parallel prograding clinostratifications (V5 acoustic Unit). Above R5 reflector, bounding at the top V5 acoustic unit, we observe onlap terminations of the upslope thinning unit characterizing seismic unit V6. A flat and gently seaward deeping reflector (R6), as already pointed out, cuts along the observed profiles almost all the imaged units. This erosional horizon produces toplap terminations on the mostly laterally stacked V3, V4,V5, and V6 seismic units. Wavy and high amplitude reflectors lie above it and describe a lenticular body increasing in thickness in a landward direction and with an undulating upper boundary (V7 acoustic unit). On this irregular acoustic reflector (R7,) downlap terminations of a wedging acoustic body (V8), characterized by low amplitude reflections, have been displayed.

5.2. Interpretation

Lacking a clear datum to calibrate our seismic sections, geometrical and seismic facies analogies with other Sparker profiles interpreted on the Latium margin enabled a preliminary interpretation. Observations on clinoform geometry and analysis of the internal motif and external configurations displayed by each individual sequence, provided a tool to recognize cycles of relative changes in sea level. Following the criteria proposed by Ridente et al., (2012): 1) seaward converging oblique tangential clinoforms have been referred to highstand sea level conditions, 2) oblique parallel distal foresets seemed to be representative of falling stage phases and 3) units thinning towards the shelf-edge, with seaward diverging clinoforms, have been attributed to low stand sea level conditions. Bottom to top, seismic unit V1 has been interpreted as an intruded igneous body correlated with the E-W trending volcanic structure reported by De Alteriis et al. (2006) in that area. On the basis of its internal prograding oblique tangential configuration and as suggested by its aggrading-prograding growth pattern, we have interpreted the above sealing sequence V2 as an Highstand System Tract (HST). The unit seems to be deformed by the intruded body, emplaced about 0.7 My ago (De Alteriis et al., 2006). As testified by the upper V2 toplap terminations, an erosional nature has been recognized for R2 reflector, revealing the occurrence of a major sea level fall. The above lying tabular V3 unit, revealed in the same way coastal aggradation processes.

Moving upward, a strong decrease in transparency has been observed for its upper reflections, testifying a coarsening upward trend (Chiocci, 2000). Its internal configuration and the observed trend suggested its interpretation as an HST. Clear downlap terminations on the below lying and above described HST, revealed the evidence of time lapses, probably induced by another dramatic sea level fall. R3 reflector has been thus interpreted as a subaerial erosion surface later reworked by the subsequent sea level rise. Above it, the aggrading prograding internal pattern revealed by seismic Unit V4 lead to identify it as an HST. The subsequent falling stage phase has been recorded by the oblique parallel clinostratified deposits constituting the FSST, corresponding in this case to V5 seismic unit. Above it, the wedge shaped V6 seismic unit, in our interpretation should correspond to a Lowstand System Tract (LST). The R6 erosional surface, producing toplaps on the previously laterally stacked seismic units should represent the ravinement surface, reworking the previous R5 erosional surface, above which lies the V7 seismic unit, interpreted as a Transgressive System Tract (TST), recording the Versilian marine transgression. Closing the observed succession the V8 seismic unit has been interpreted as a record of the actual sea level highstand.

5.2.1. Age constraints

Chiocci (2000) interpreted a large number of seismic high resolution profiles on the Latium margin, pointing out major Late Pleistocene key horizons, consisting in erosional surfaces developed during glacio-eustatic lowstands. An analogy in the stacking pattern and on seismic facies between a Sparker profile interpreted by Chiocci (2000) offshore Civitavecchia and our Sparker profile SP1 has been recognized. The author recognized two main erosional surfaces (U1 and U2 surfaces), correlated with the most extremes glacioeustatic sea level falls, corresponding to MIS 16 and MIS12 (600 ky and 450 ky respectively). Such dramatic events should have been recorded also in the southern sectors of the margin. A preliminary correlation with the R2 and R3 erosional surfaces, evidencing major time lapses, has been here hypothesized (Fig.9).

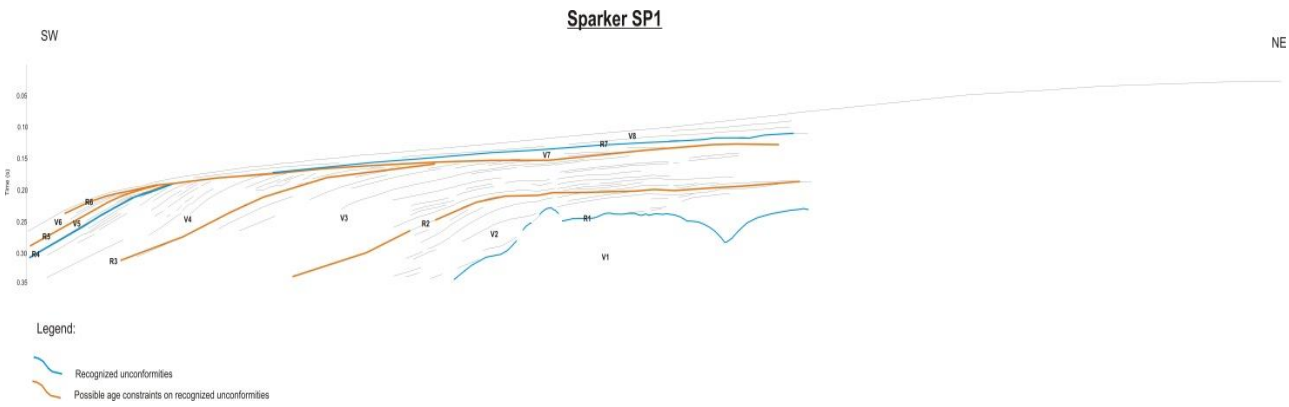

Figure 9: preliminary correlation of R2 and R3 erosional surfaces with MIS 16 and MIS12. R5 and R6 reflectors should correspond to the lower sequence boundary of the latest Late Quaternary-Holocene sequence, later reworked by the successive Versilian sea level rise.

The described clinostratified Late Quaternary deposits building out the margin, following the interpretation of the author, are cutted by the youngest last glacial Wurm erosional surface, recording the last eustatic lowstand and the successive sea level rise (Aiello et al., 1978; Chiocci, 2000). A correlation with the seismically detected R5 and R6 erosional surfaces should be pointed out, representing the lower sequence boundary of the latest Late Quaternary-Holocene sequence, later reworked by the successive sea level rise. The Middle Quaternary to Holocene succession of the margin has been preliminary revealed by the interpretation of Sparker profiles, pointing out the presence of four 4th order depositional sequences. The absence of a clear and precise calibration for Sparker profiles represents a big obstacle in the interpretation and allow just to propose working and preliminary hypothesis.

6. Structural pattern

6.1. Structures revealed by Chirp profiles

Structural features have been individuated and mapped from the observation of Chirp sub bottom profiles covering the first 0,15 seconds of the Campania continental shelf. With an average velocity of 1500 m/s the maximum depth observed correspond to 112 meters, thus the seismically detected structural pattern involves the Late Quaternary to Holocene highstand and transgressive units. Normal faults cutting the transgressive and highstand units with very small offsets (less than 10 meters) have been displayed by acoustic profiles. A 3D modelling of the LGM erosional surface has been elaborated (Fig.10) and the resulted surface revealed a relative high, bounded by two sets of outward facing faults. In the northern side of the interpreted grid NW dipping normal

listric faults formed a downthrown region in an half-graben geometry, with a tilted block configuration (Fig.11). In the southeastern side of the grid ENE-WSW trending, SE dipping normal faults define a relative morphological low (Fig.12). An interbasinal relative high, with a NE-SW trending direction, defined by two outward facing normal faults, separates these two topographical lows. Isolated randomly oriented faults affecting only the Holocene mud-rich highstand units have been also observed.

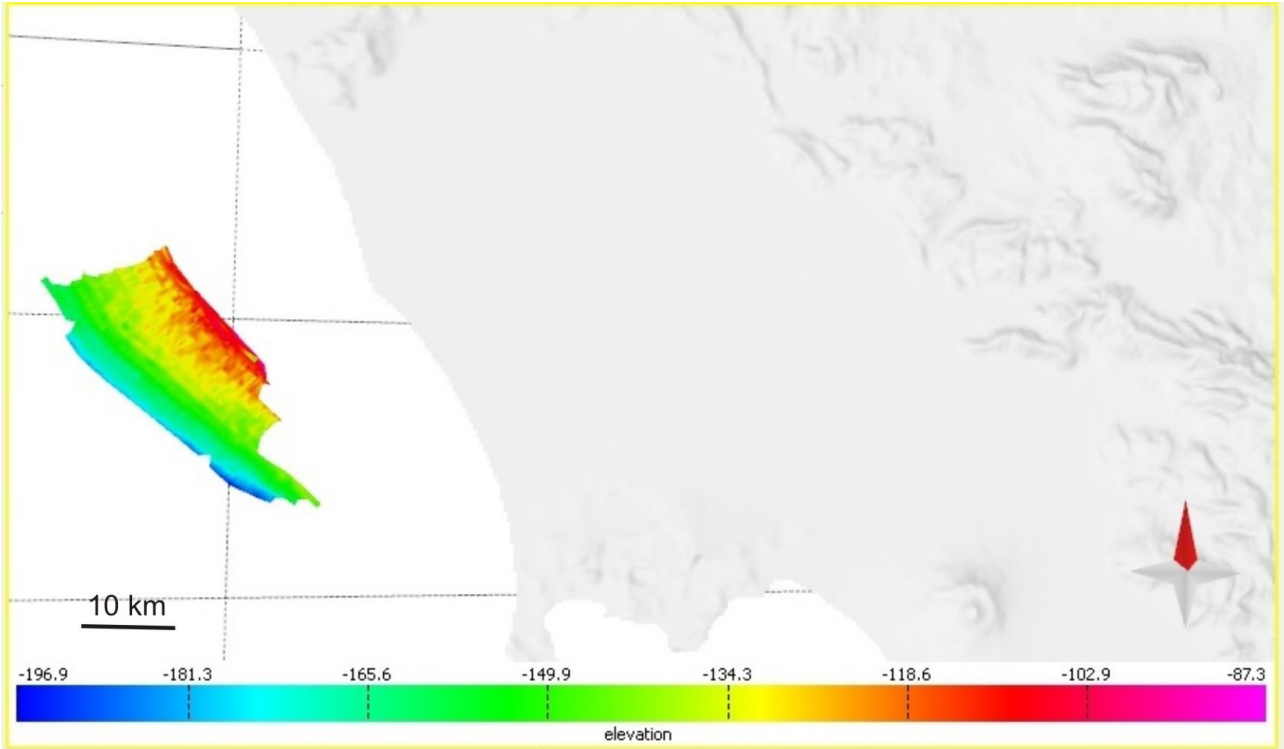

Figure 10: 3D modelling of the last glacial maximum erosional surface (H1 reflector).

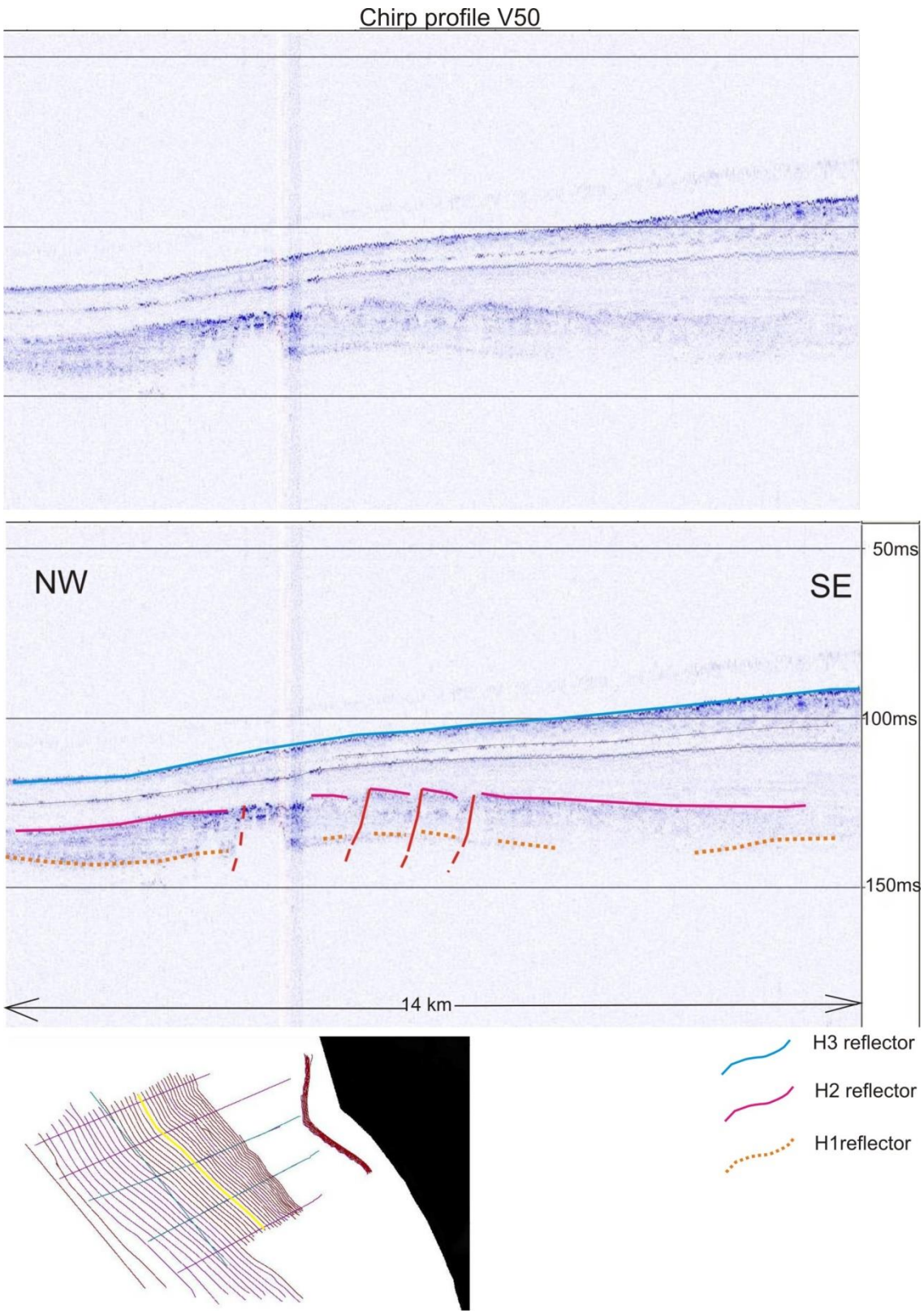

Figure 11: NW dipping normal listric faults on V50 profile, forming a downthrown region in an half-graben geometry, with a tilted block configuration.

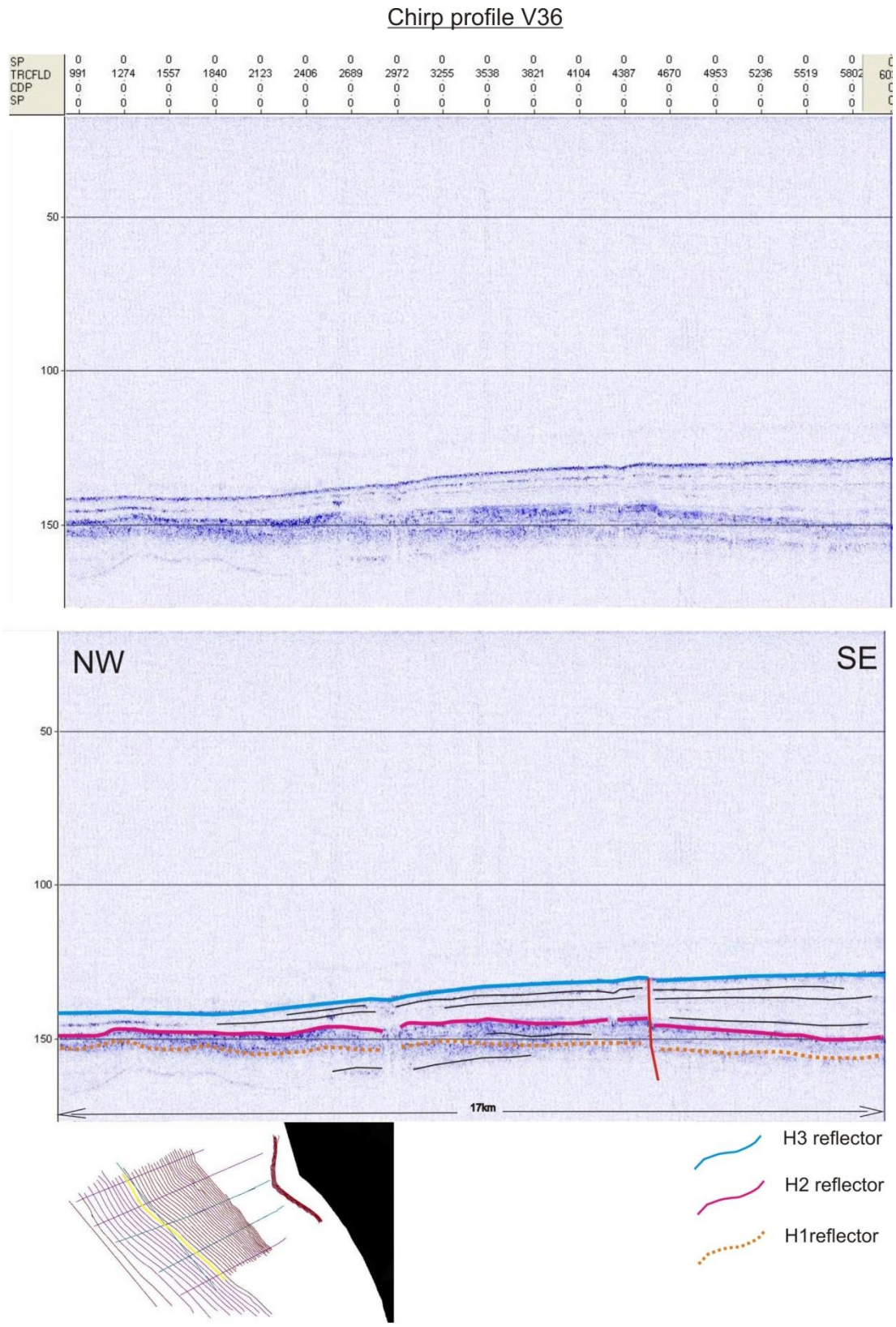

Figure 12: SE dipping normal fault revealed by Chirp profile V36. V stacked amplitude anomalies, affecting H1, H2 and H3 reflectors, have also been observed on this section.

6.1.1. Structural interpretation

Extended domains are usually segmented in fault systems whose terminations and geometrical transitions have been extensively studied in the past (Gibbs, 1984; Bosworth, 1985; Rosendahl, 1987; Larsen, 1988; Faulds et al., 1990; Crone and Haller, 1991; De Polo et al., 1991; Peacock and Sanderson, 1994; Rowland and Sibson, 2001; Gawthorpe and Hurst, 1993; Trudgill and Cartwright, 1994). Fault linkages, in this typically asymmetrical segmentation, (Anderson, 1977; Brown et al., 1980) are generally ascribed to two main families of structures responsible for displacement transfer, known as accommodation and transfer zones (Gibbs, 1984). Accomodation zones correspond to areas in which soft and distributed deformation occur at the overlapping fault terminations (Rosendahl, 1987; Morley et al. 1990; Faulds et al., 1990; Faulds and Varga, 1998; Rowland and Sibson, 2001). Hard-linkage processes, in response to an increased displacement (Peacock & Sanderson, 1991), should be invoked for the formation of transfer zones, defined as areas of discrete deformations, with a very strong strike-slip component (Gibbs, 1984; Lister et al., 1986; Walsh and Watterson, 1991; McClay et al., 1998; Gawthorpe and Hurst, 1993). The observed Late Quaternary to Holocene deformations revealed a structural setting constituted by two opposite facing set of faults (Fig.13), separated by a relative topographic high, located in the overstepping region.

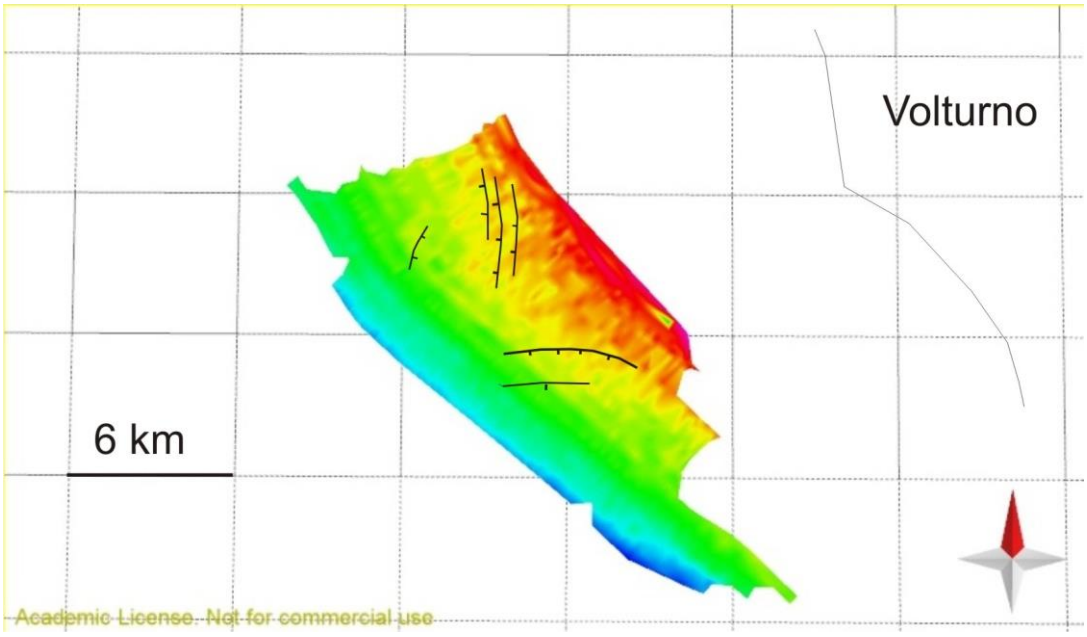

Figure 13: The observed Late Quaternary to Holocene deformations revealed a structural setting constituted by two opposite facing set of faults (Fig.13), separated by a relative topographic high, located in the overstepping region.

No strike-slip component have been seismically detected and the accommodation zone seems to have a slightly oblique orientation with respect to the NE-SW extension trending direction, revealed by the main NNW-SSE trending set of faults. Faulds and Varga (1998) proposed a general classification for accommodation zones, in which the antithetical ones have been furtherly subdivided on the basis of the inward or outward facing of faults and on the orientation of the zone of transfer with respect to the regional σ3. Following this classification the structure observed seems to be an antithetic oblique synclinal accommodation zone (fig.14).

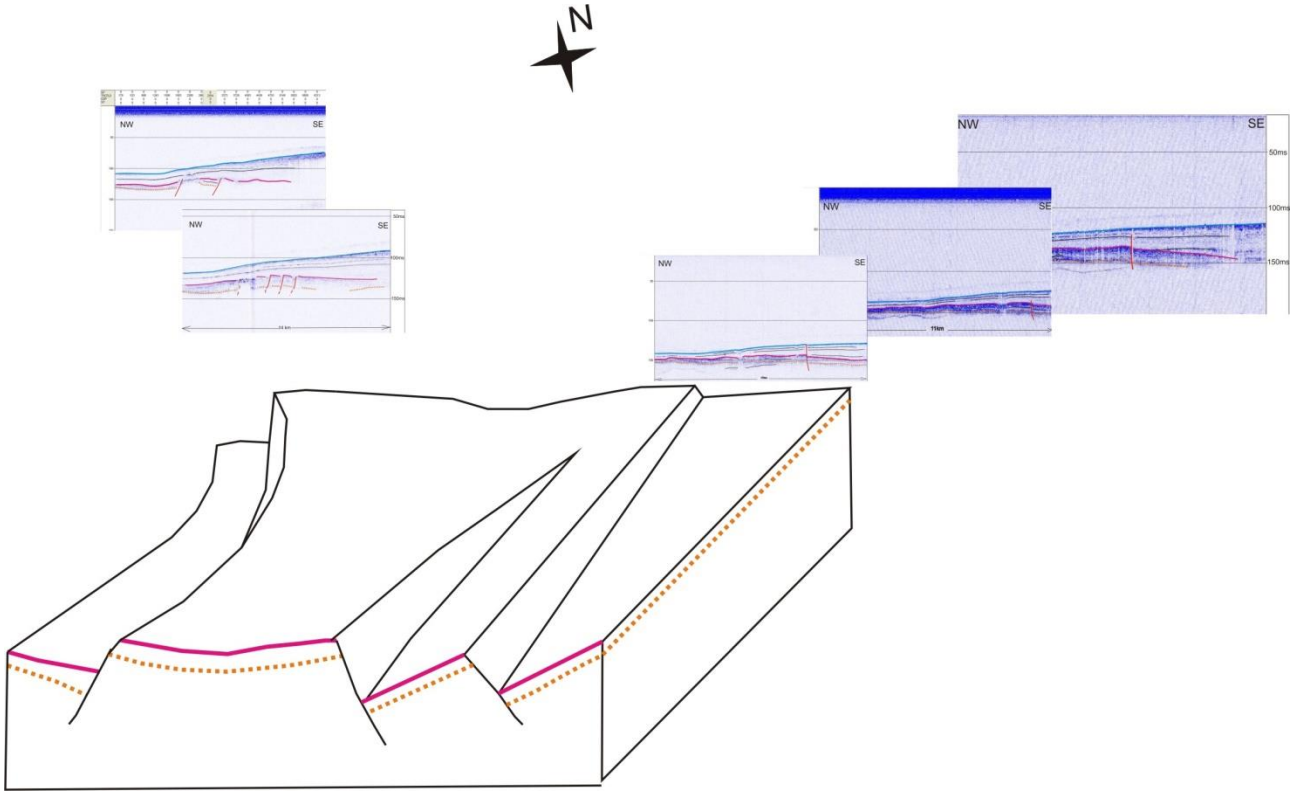

Figure 14: The detected structure, analysing its geometrical feature, should correspond to an antithetic oblique synclinal accommodation zone, following Faulds and Varga (1998) classification.

6.2. Structures revealed by Sparker profiles

A coverage of 3 Sparker profiles enabled some structural observations for the first 300 meters of the northern Campania continental shelf. An E-W trending acoustic invisible body, corresponding to acoustic unit V1, has been seismically detected. Onlaps against its flanks and a draping morphology over its top with stratal reflections revealing different thickness, suggested differential compaction above the seismical invisible structure. Deformation on the above lying sequence and an acoustic invisible response, testify in our opinion, the presence of a growing and intruding volcanic structure. The occurrence of volcanic intrusions offshore the Volturno river mouth has been proposed and documented by previous authors (Bruno et al., 2000; De Alteriis et

al., 2002;2006; Aiello et al., 2011), carrying out seismic and magnetic prospecting in this area. An E-W elongated and flat topped structure giving an intense magnetic anomaly (De Alteriis et al., 2006), has been recognized by this author, interpreting the detected body as a volcanic edifice and constraining the emplacing of the edifice in middle Pleistocene.

7. Description of venting structures

Vertically stacked depressions, conduits, sediment mobilization processes and intruded acoustic transparent bodies have been observed on Chirp high resolution profiles. A mapping procedure on the seabed, corresponding to the Chirp detected H3 reflector (Fig.15), modelled throughout the seismic grid, enabled structural and stratigraphical observations.

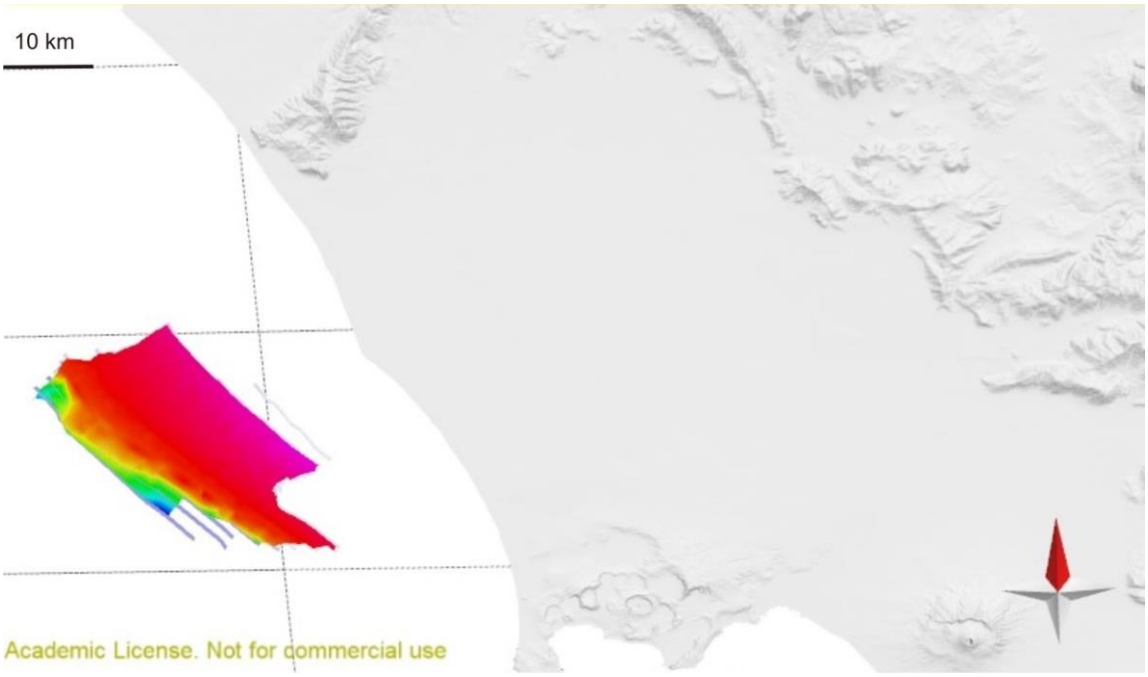

Figure 15: Bathymetry : H3 modelled surface.

Two classes of seabed craters have been detected by the observation of an high resolution bathymetric map elaborated at CNR-IAMC of Naples (unpublished data): sub-circular-elliptical and elongated depressions. Most of the sub-circular craters displayed by Chirp sub-bottom profiles seem to have smaller dimensions and to be aligned in a NE-SW trending direction. The elongated ones, displaying a bigger diameter, seem to be aligned on a NW-SE direction (Fig.16). These vertical stacked V-shaped depression mostly occur in zones where the muddy highstand unit reach nearby its maximum thickness. Chirp profiles enabled also the observation of mound chaotic deposits with sub-vertical low amplitude anomalies and convex up distorted reflections (Fig.17).

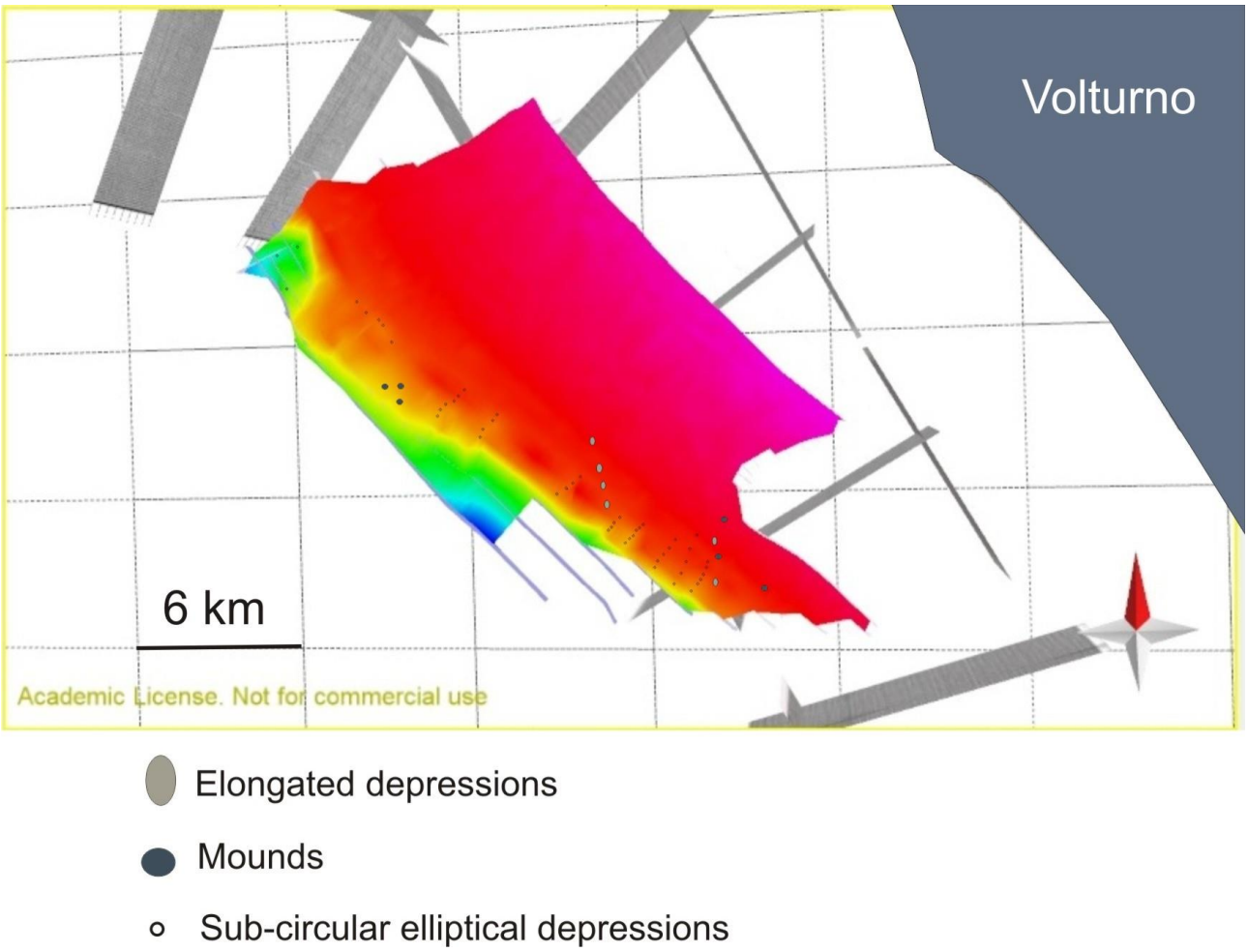

Figure 16: sub-circular-elliptical and elongated depressions. Most of the sub-circular craters displayed by Chirp sub-bottom profiles seem to have smaller dimensions and to be aligned in a NE-SW trending direction. The elongated ones, displaying a bigger diameter, seem to be aligned on a NW-SE direction.

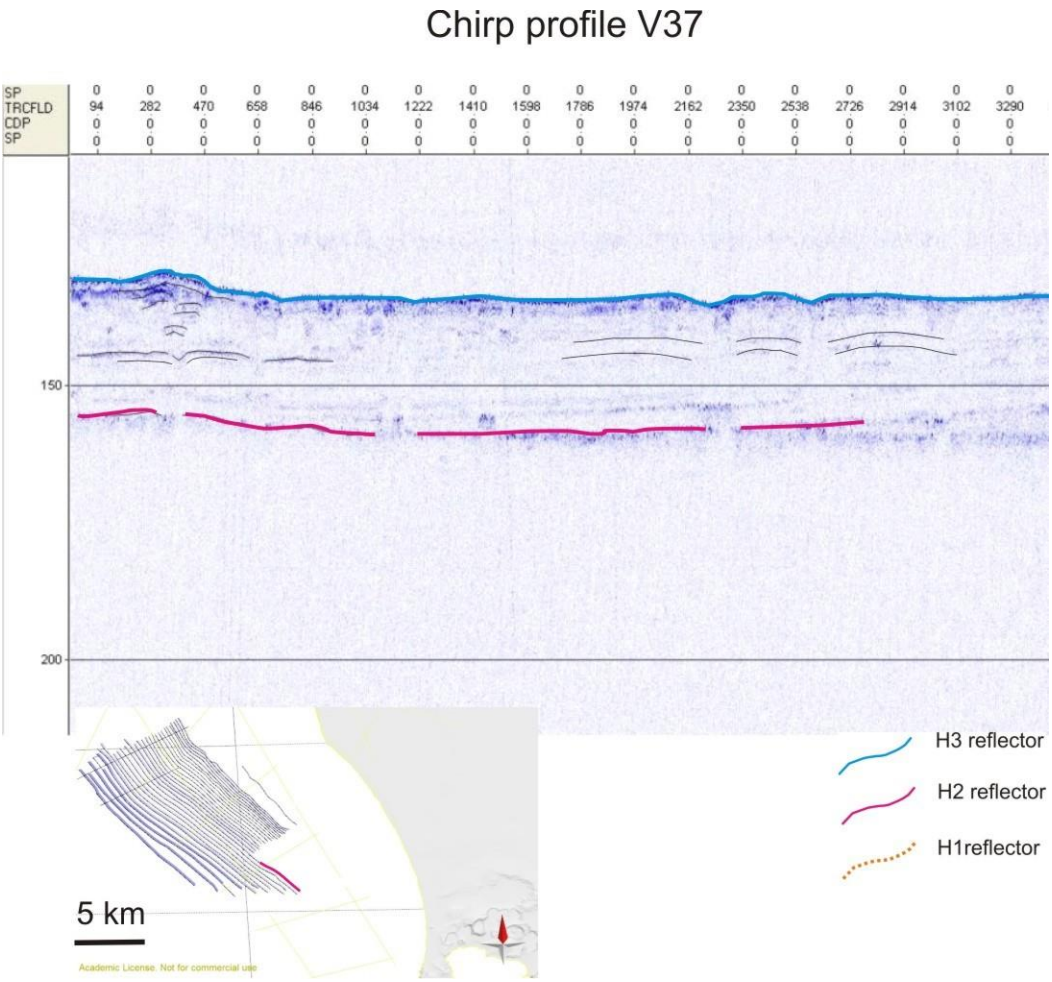

Figure 17: Chirp profile V37: a strike section showing mound chaotic deposits with sub-vertical low amplitude anomalies (in the left side) and convex up distorted reflections, interpreted as vertically stacked pockmarks (on the right side).

Sparker profiles located in the same area enabled the observation of deeper seismic units, displaying zones of acoustic turbidity with distinct lateral fronts and irregular and diffuse top fronts (Fig.18). Vertical anomalies in the reflections have been observed with Chirp profiles in the first 50 m of the sedimentary succession while in a more deep domain, laterally extensive pocket of low amplitude anomalies have been observed on Sparker profiles (Fig 19). The seismic expression of these features is an acoustic blanking marked at the top by high amplitude disrupted reflectors (Fig.20). These zones seem to occur at a certain subsurface depth, ranging from 140 to 200 meters and are located in most cases below the more superficial vertically stacked anomalies have been observed on Chirp sub-bottom profiles. A mapping procedure for craters and depressions and a comparison of it with the acoustic blanking zones revealed by Sparker profiles, suggested that the majority of them occurred above these laterally extensive zones of acoustic anomalies or in their immediate vicinities (Fig.21). The bulk of these manifestations seems to occur at the edge of the continental shelf with a NW-SE striking direction. A distinct lateral flank

interrupts the acoustic turbidity in an inland direction while moving offshore the flank seem to parallel the slope morphology with a less sharp lateral front. Their top front is irregular and diffuse with a saw tooth profile occurring in the prograding Late Quaternary sequences.

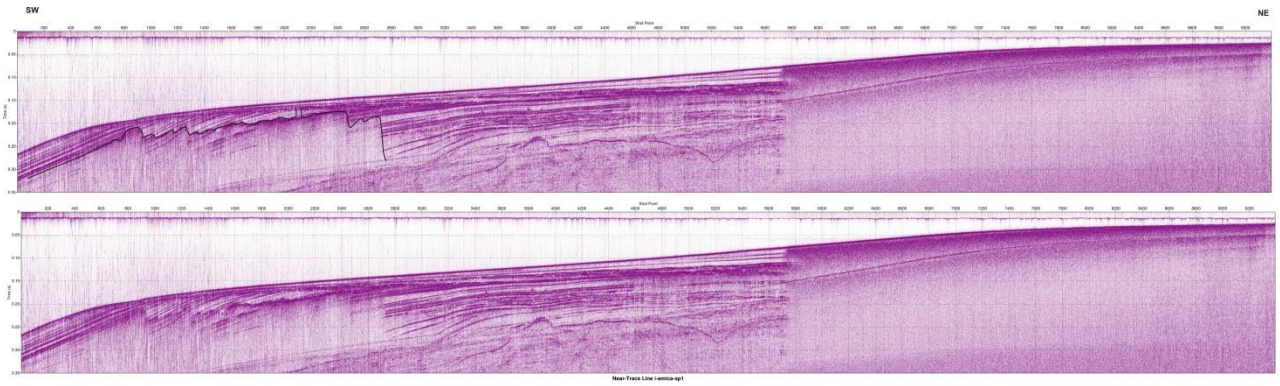

Figure 18: Sparker profile SP1: in black we have traced zones of acoustic turbidity with distinct lateral fronts and irregular and diffuse top fronts profiles.

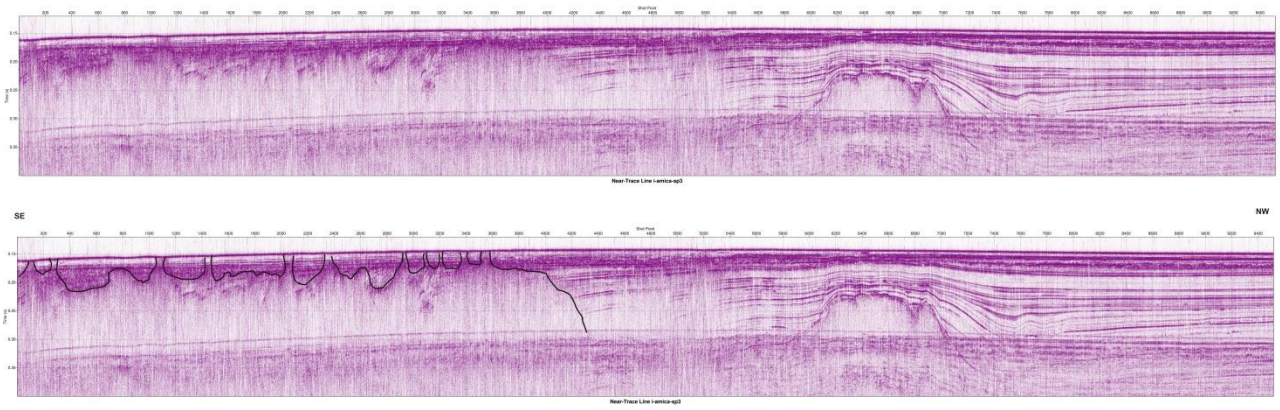

Figure 19: Sparker profile SP3: laterally extensive pocket of low amplitude anomalies, traced in black.

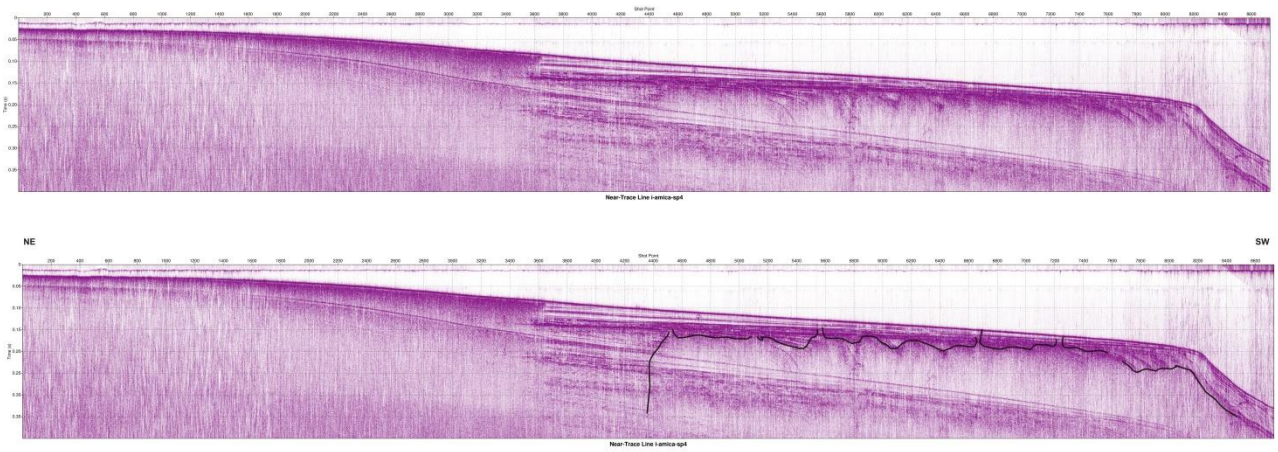

Figure 20: Sparker profile SP4: irregular top front with a sawtooth profile and distinct lateral fronts, traced in black.

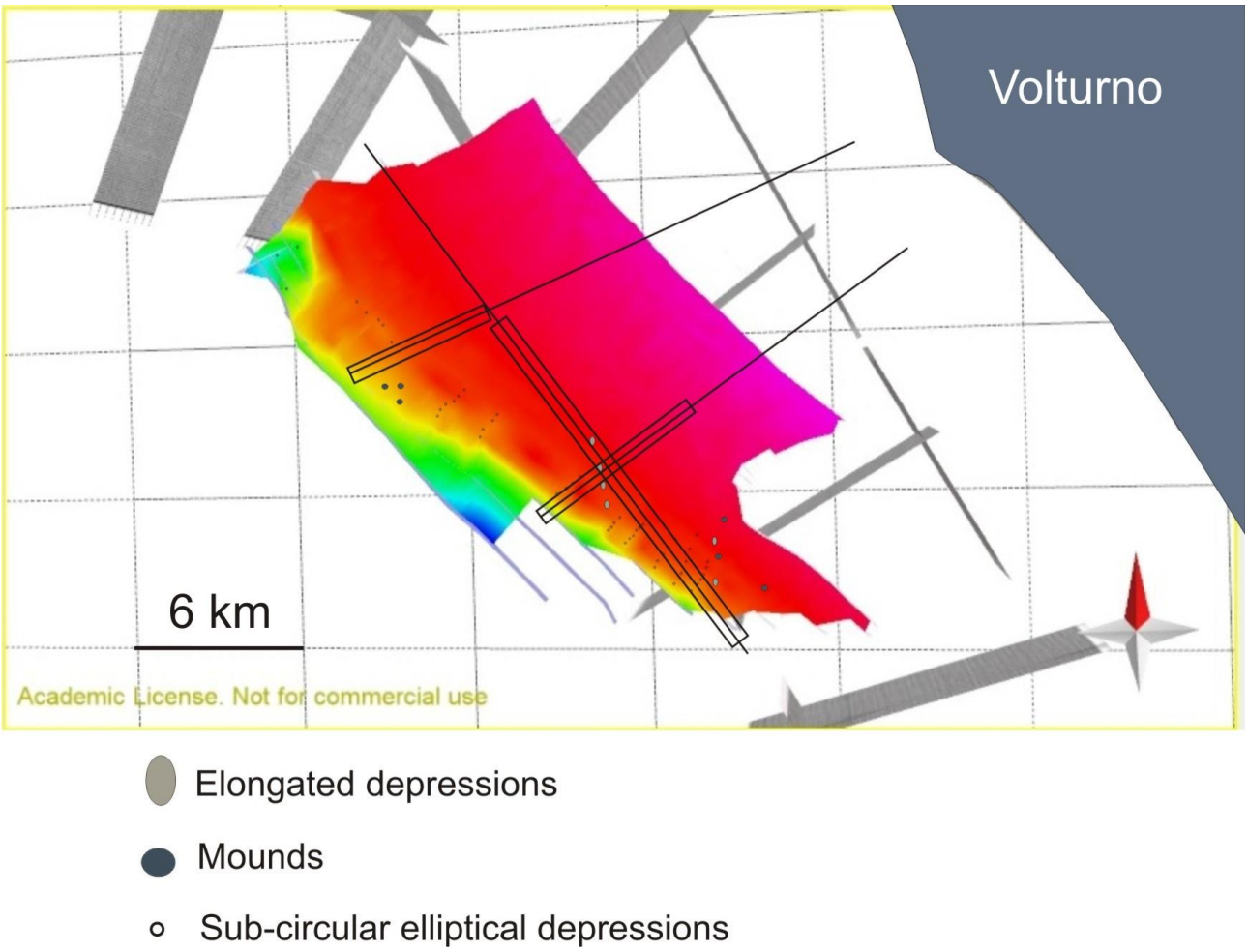

Figure 21: modelled seabed (TWT surface) and location of pockmarks, observed on Chirp profiles and mapping of laterally extensive zones of acoustic turbidity observed on Sparker profiles (in black we have traced SP1, SP3 and SP4 Sparker profiles).

7.1. Interpretation of fluid escape structures

Andresen (2012) proposed a classification based on the geometric pattern of fluid venting structures in order to define their origin. The structures observed could be related to 1) focused vertical fluid flow, 2) sediment remobilization processes and 3) laterally extensive fluid flow. The seismically detected V-shaped depression could be interpreted as collapse structures induced by the hydraulic fracture and fluid driven erosion in conditions of high pore fluid pressure. These fluid venting structures, induced by focused vertical fluid flow, are very good timing indicators since they constrain the expulsion process to the reflection on which they occur (Judd and Hovland, 2007). Mounds on the seabed linked to deep vertically stacked low amplitude anomalies could be interpreted as diapiric structures due to sediment remobilization processes, like mud volcanoes. Laterally extensive fronts of acoustic turbidity could be correlated to fluids or free gas accumulation zones, occurring in certain stratigraphic intervals or at certain depths. Gas front morphologies have been explained in literature as pressure and bottom water temperature

related (Chun et al., 2012) or by sedimentary facies association and permeability related (Martínez-Carreño and García-Gil, 2013). The low penetration of the interpreted profiles does not allow the definition of the origin of these venting structures, preventing the individuation of a stratigraphic source for these fluids or gasses. Pockmarks and pipes in Chirp sub bottom profiles have been detected in zones where the thickness of the muddy Holocene highstand units almost reached its maximum thickness, suggesting a direct link between sedimentary loading and over-pressure. Mud-volcanoes are considered to be a very good tool in dewatering over-pressured mud-rich sequences (Cartwright et al., 2007). Pockmarks and overpressure are also closely linked as they are considered to be the first stage in the evolution of a mud volcano. Over-pressure of organic and clay rich sedimentary sequences could be a logical assumption to explain such features. Free-gas in shallow environments have been recorded in many continental shelves all over the world (Fleischer et al., 2001; Chun et al., 2012; Martínez-Carreño and García-Gil, 2013). Biogenic methane should be produced in deltaic areas where clay-rich sequences are supported with a constant apport of organic matter. Nevertheless, the presence of igneous intrusions have been directly observed and also reported by previous authors (Bruno et al., 2000; De Alteriis et al., 2002;2006; Aiello et al., 2011). Vertical and lateral expressions of fluid flow may also have an hydrothermal origin. The presence of thermal fluids could also have an effect in decreasing methane solubility allowing the formation of gas bubbles and fluid venting structures (Chun et al., 2012). These superficial venting structures, occurring in the first 50 meters of the sedimentary succession, seem to be related to the laterally extensive acoustic turbidity pockets, defining a WNW-ESE domain for these manifestations. More coarse-grained sediments, in comparison with the Holocene highstand units, constitute the prograding sequences composing the margin. Such sediments could host the fluids providing good conditions for their lateral migration (Martínez-Carreño and García-Gil, 2013).

7.2. Pipe, fault or intrusion related structures?

Identified pockmarks, occurring along an WNW-ESE trending domain, display an array distribution and seem to be mostly aligned on an NE-SW trending direction, matching the submarine channels crossing the shelf and the slope area. Buried palaeo channels have a coarser grained lithology if compared to the muddy sequences which represent the bulk of the margin, constituting in this way a preferred migration pathway (Haskell et al., 1997; Gay et al., 2006a,b; Pilcher and Argent, 2007). The fluid escape structures are mostly confined to the slope area probably indicating

slumping processes reducing lithostatic pressure of fluid or gas saturated stratigraphic intervals (Foland et al., 1999; McNeill et al., 1998; Sultan et al., 2004; Pilcher and Argent, 2007). Another observed distribution for aligned pockmarks is a NW-SE trending direction, matching the striking of normal fault planes affecting the Late Quaternary Holocene sequences. These NW-SE features board the outer shelf in the immediate vicinity of the slope, suggesting also instability processes of the outer-shelf/slope area. The key factor to understand the origin of such structures, detected on Chirp profiles, comes from the observation and interpretation of Sparker profiles. The superficial venting structures are located above a main acoustic turbidity zone detected by the observation of more deep Sparker profiles (Fig.22).

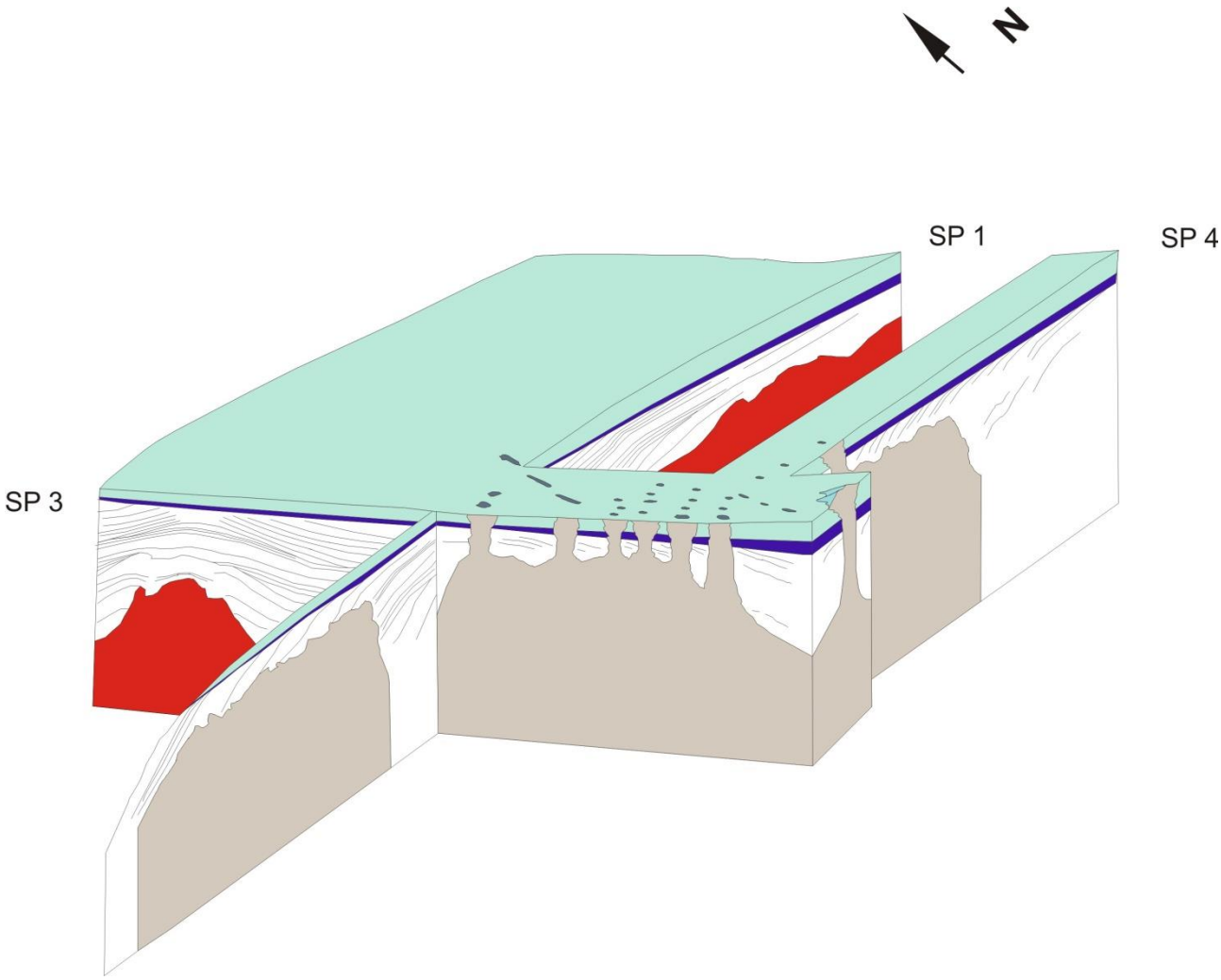

Figure 22: The superficial venting structures (pockmarks field) are located above a main acoustic turbidity zone, detected by the observation of more deep Sparker profiles. In red we have represented the intruded igneous body and in grey the fluid/gas pocket, revealing a similar roughly E-W trending direction. In pale blue we have represented the highstand unit and in dark blue the transgressive unit.

Vertical funnel shaped and downward tapering anomalies, interpreted as conduits and pipes, located immediately below the main detected pockmark field, come from a deeper fluid/gas pocket and have been individuated in the southeastern area of the interpreted grid. The main trending direction of this front is similar to the one observed for the detected volcanic intrusion, also if its location seems to be shifted southward. This observation could suggest that volcanic intrusions may have followed an E-W trend, correlatable with the main direction of normal to oblique faults active during Quaternary times. below this laterally extensive gas pocket another E-W volcanic intrusion should have triggered these fluid venting structures. The following assumption should be in this way that these fluid escape features are intrusion related structures. Igneous intrusions produce on the hosting sedimentary sequences thermal effects and cause the expulsion of great volumes of pore-waters (Grapes etal. 1973; Einsele 1982; Krynauw et al., 1988).

8. Conclusions

The Late Quaternary-Holocene evolution of the northern Campania continental shelf was affected by igneous intrusions, degassing features and minor faulting. Deformations, mainly observed on Chirp high resolution seismic profiles, defined a structure characterized by two opposite facing set of faults, separated by a relative topographic high located in the overstepping region. Outward facing NW-SE normal listric faults and ENE-WSW oppositely dipping normal faults identified a structural horst, cutting the transgressive Late Quaternary to Holocene units. This interbasinal ridge, displayed as a belt at the overlapping fault systems terminations, described a roughly NE-SW oriented zone, accommodating the deformations. Following the definition proposed by Faulds and Varga (1998), identifying accommodation zones as structures, in regions of overlaps between separated systems of faults, accommodating deformations and using as a guide the geometrical classification proposed by the author for such zones, we interpreted the observed deformational pattern as the result of an antithetic oblique synclinal accommodation zone. Systems of NNW-SSE and ENE-WSW faults defining the structure, should correspond to fault planes reactivated in a different kinematic context, as revealed by their trending direction, matching the orientation of the most important discontinuities controlling the Tertiary to Quaternary evolution of the area (Moussat et al., 1986; Hyppolite et al., 1994; Giordano et al., 1995; Ferranti et al., 1996; Ascione and Cinque, 1996; Cinque et al. 2000; Caiazzo et al., 2006). Major Late Quaternary to Holocene NW-SE normal faults with quite modest displacements have been reported by several authors (Hyppolite et al., 1994; Milia, 1999; Cinque et al., 2000; Milia & Torrente, 2003; Caiazzo et al.,

2006;). A NE trending extension direction has been revealed by the distribution of deformations, coinciding with an already recognized (Hyppolite et al.,1994; Caiazzo et al., 2006) extensional regime characterized by a NE–SW trending σ3 axis. The interpretation of Chirp profiles enabled the recognition of degassing features, displayed as vertically stacked amplitude anomalies affecting the Trasgressive and highstand units observed on high resolution seismic sections. Pockmarks, conduits and mounds, distributed along an ESE-WNW trending direction, have been interpreted as the superficial response of a deeper laterally extensive acoustic turbidity front with the same striking direction. Sparker profiles enabled the observation of this laterally extensive fluids and gas pocket revealing distinct lateral fronts and an irregular top one, displaying conduits and pipes affecting the Late Quaternary to Holocene units. The main trending direction of this front is similar to the one observed for the detected volcanic intrusion, resulting in an E-W trending flat topped edifice seismically invisible, deforming the above lying sealing sequence which displays pinch out terminations against its flanks. This observation could suggest that the observed fluid escape features are intrusion related structures. Igneous intrusions trigger thermal effects on the hosting sedimentary sequences and produce the expulsion of pore-waters volumes (Grapes etal. 1973; Einsele 1982; Krynauw et a[. 1988). Volcanic intrusions may have followed an E-W trend, correlatable with the main direction of normal to oblique faults active during Quaternary times.

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