Meso-Cenozoic seismic stratigraphy and the tectonic setting of the Gulf of Trieste (northern Adriatic)

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Abstract

The Friuli Plain-Gulf of Trieste area is the foreland of both the East/West Alpine and North-West/South-East External Dinaric chains; it presents a flexure in correspondence of the Mesozoic carbonate Friuli Platform. The geological setting is quite well known on land, on the contrary it is poorly investigated offshore. In June 2005, 150 km of multichannel seismic and gravity profiles have been acquired by R/V OGS Explora in the Gulf of Trieste together with 37 km of multichannel seismic profiles from the inner to the external part of the Grado and Marano Lagoon. Seismo-stratigraphic analysis provides new insights into the Mesozoic carbonate Friuli Platform geological setting, in particular: a) the NW-SE orientation of the shelf margin; b) the presence, at the Friuli Platform margin, of carbonate highs of about 500 m and 350 m below sea level in the Gulf of Trieste, as a consequence of the southward shallowing trend of the shelf margin; c) the flexuring and gentle folding of the overall Friuli Platform that reaches depths of more than 1200 metres at the front of the Karst. The seismic profiles do not show evidence of reverse faults with significant vertical throw in the carbonate sequence, but it can be inferred that the Karst coastal front, up to 2-3 km offshore, constitutes the accommodation zone of the Dinaric thrust system with about 1400 m of vertical displacement. Moreover, in the Gulf of Trieste, a compressional tectonic structure with Dinaric orientation is linked to the NW-SE thrusts and folds of the Tinjan Structure present on land, where the Flysch crops out. The Friuli Platform flexure is testified also by indicative Bouguer gravity anomalies, with positive values in correspondence of the carbonate highs, and negative values at the Dinaric thrusts front.

Keywords: Gulf of Trieste, Friuli Platform, Dinaric structures, Seismic stratigraphy, Bouguer gravity anomalies.

Introduction

Within the scientific community, the knowledge of the geological setting and the Meso-Cenozoic evolution of the Friuli Plain comes from geophysical data based mainly on exploration multichannel seismics (Amato *et al.*, 1977; Pieri and Groppi 1981; Cati *et al.*, 1987*a*, *b*; Casero *et al.*, 1990; Fantoni *et al.*, 2002, 2003; Nicolich *et al.*, 2004), and wells drilled by ENI (AGIP, 1972, 1977, 1994). On the contrary, the deep geological features in the Gulf of Trieste are still poorly known, due to paucity of published seismic data, except for the CROP M-18 seismic profile for deep crustal investigation (Fantoni *et al.*, 2002, 2003; Scrocca *et al.*, 2003; Nicolich *et al.*, 2004; Finetti and Del Ben, 2005).

Of particular interest, in the Gulf of Trieste, are the settings of the Mesozoic carbonate platform, the overlying Flysch sequence, and the presence of Dinaric structures, the latter two being well known on land. The presence of Dinaric features in the offshore area is still hypothesized on the basis of the surrounding onshore geology rather than of geophysical data, for example the NW-SE Palmanova Line which was thought to cross the eastern part of the Gulf of Trieste (Cavallin *et al.*, 1978; Carulli *et al.*, 1980; Carobene *et al.*, 1981) (Fig. 1).

The Direzione Centrale Ambiente e Lavori Pubblici – Servizio Geologico of the Regione Autonoma Friuli Venezia Giulia commissioned a study to evaluate the geothermal resources present at the shelf margin of the carbonate platform in the northernmost part of the Gulf of Trieste. The study involved the Dipartimento di Ingegneria Civile e Ambientale (DICA), as project leader, the Dipartimento di Scienze Geologiche, Ambientali e Marine (DiSGAM) of University of Trieste and the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS). Within this project, OGS acquired about 150 km of multichannel seismic profiles in the Gulf of Trieste and 37 km of multichannel high-resolution seismic profiles in the Lagoon of Grado and Marano (Fig. 1). The aim of the seismic survey

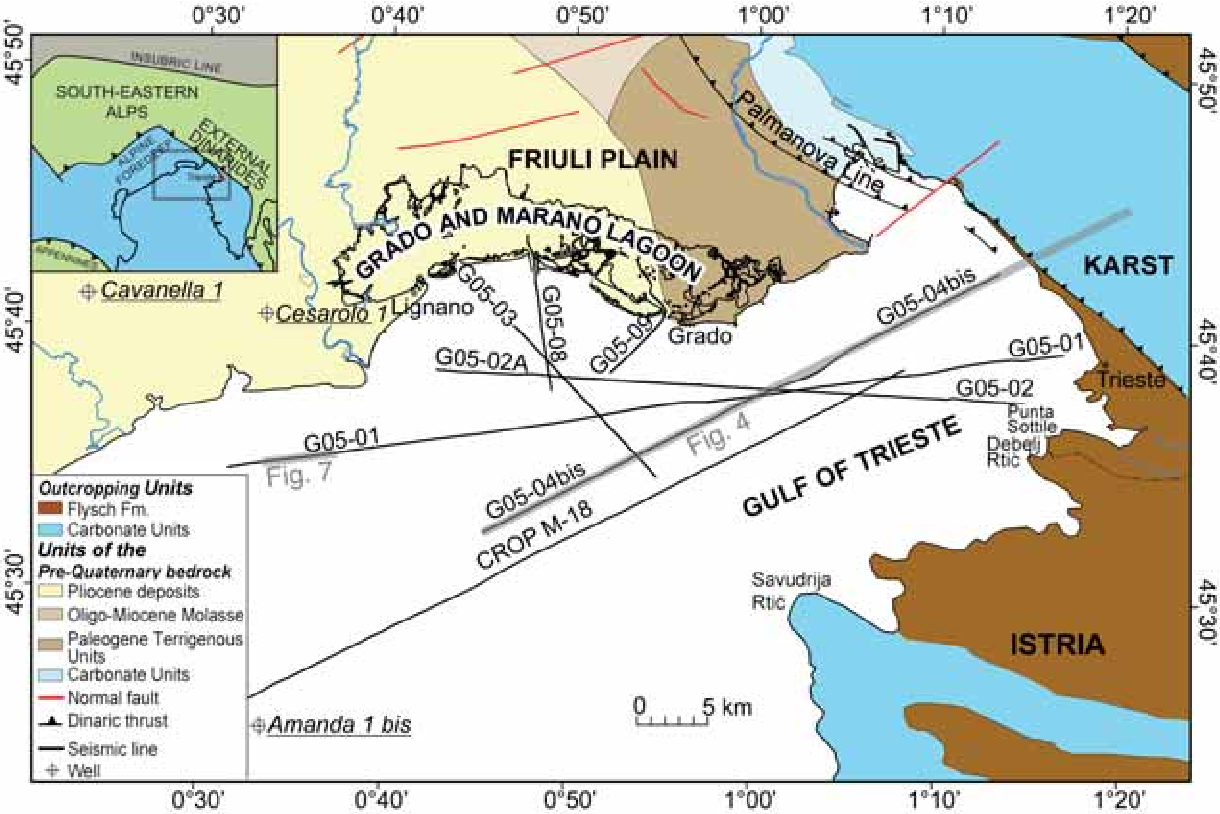

Fig. 1 - Position map of the multichannel seismic lines acquired by OGS Explora. Outcropping units and units of pre-Quaternary bedrock from Nicolich et al. (2004).

was the identification of the top of the carbonates and the relative highs located at the shelf margin where the geothermal resources should be located. Analysing the dataset, some new insights in the Cenozoic stratigraphy and tectonic evolution of the Gulf of Trieste were determined.

Geological setting

The *Dolomia Principale* wide carbonate platform of Upper Triassic age, during the Early Jurassic, as a consequence of the extensional phase, was differentiated in a series of paleogeographic units as the Friuli Platform, the Belluno Basin (Cati *et al.*, 1987b) and the Adriatic Carbonate Platform (Tišljar *et al.*, 1998) (Fig. 2).

The carbonate Friuli Platform developed during the Middle Jurassic-Lower Cretaceous; the subsidence of the area induced the continuation of shallow-water conditions, providing 1200-1500 m of aggradational deposits above the surrounding basin (Fantoni *et al.*, 2002, 2003; Picotti *et al.*, 2003). This evolution is displayed in the Cesarolo 1 well log that recovered 2660 m of Jurassic limestones, mainly from lagoon (*Calcari Grigi* and *Cellina Limestone)* and reef facies (*Ellipsactinie Limestone)*, 833 m of Cretaceous limestone, the bioclastic shelf margin *San Donà Limestone* and the well stratified lagoonal *Cellina Limestone*. The Cavanella 1 well recovered the stratified *Monte Cavallo Limestone* (Cenomanian-Campanian) of shelf margin facies, stratigraphically overlying the *Cellina Limestone* (Fig. 3). The paleoshelf margin of the Friuli Platform, at present, is approximately located between the Friuli and Venetian plains, and is characterised by NW-SE and NE-SW sawtooth trends (Cati *et al.*, 1987b; Nicolich *et al.*, 2004).

In the basin area, westward of the Friuli Platform, deep-sea carbonate facies of the Belluno Basin were deposited in the Jurassic-Cretaceous (Cati *et al.*, 1987b; Casero *et al.*, 1990), and overlain by the marly limestone *Scaglia Alpina (or Scaglia) (*Aptian-Early Eocene) which indicates the beginning of terrigenous sedimentation. Suc-

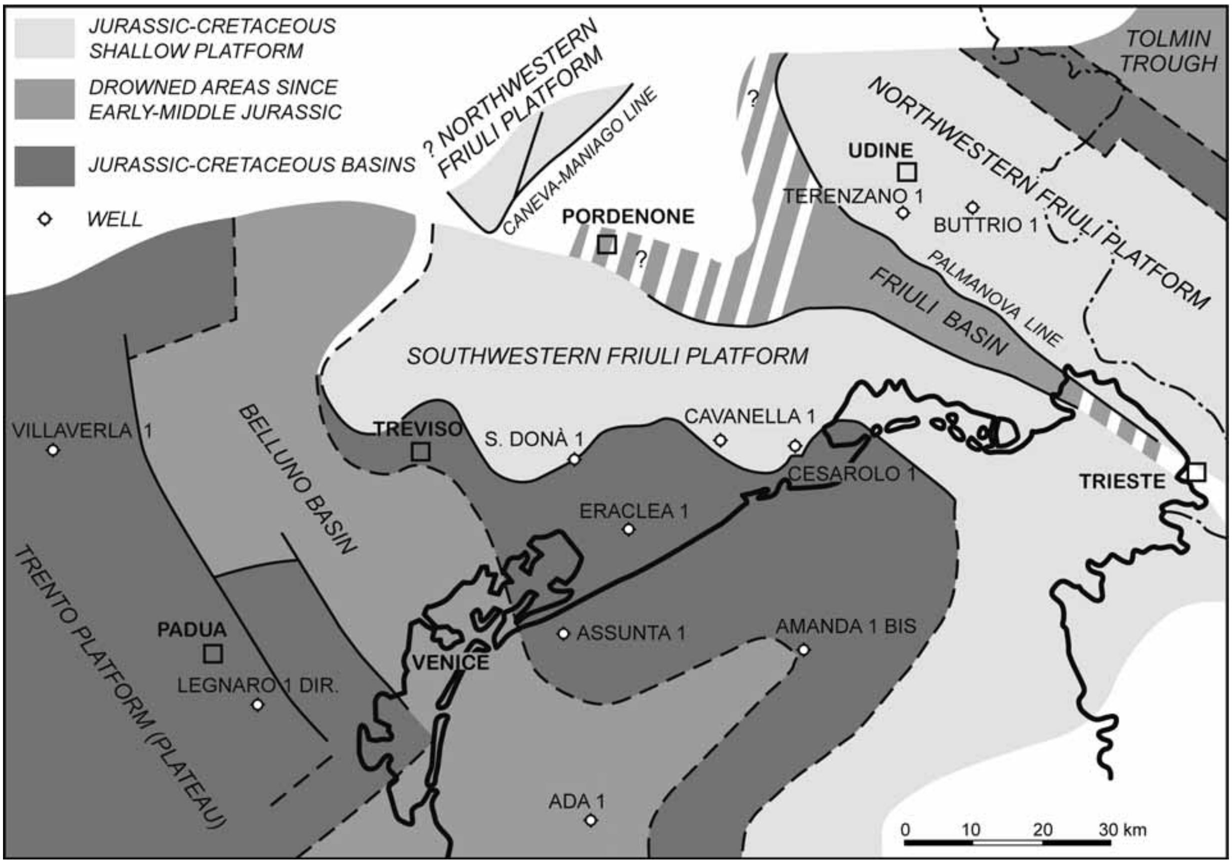

Fig. 2 - Present day position of the carbonate units during the Jurassic and Cretaceous in the Northern Adriatic Area (modified after Cati et al., 1987b).

cessively, the *Gallare Marls* filled the basin in the Eocene, as documented by the Amanda 1 bis well (Fig. 3).

The Adriatic Carbonate Platform developed from Middle Jurassic to Eocene, extending with a NW-SE trend for 700 km (Tišljar *et al.*, 1998). The present Istria Peninsula, representing the northern part of the Adriatic Carbonate Platform, is constituted by shallow-water carbonates distinguished in four megasequences of different ages (Bathonian – Early Kimmeridgian; Late Tithonian – Late Aptian; Late Albian – Early Campanian and Paleocene – Eocene) that have experienced subaerial conditions (Velić *et al.*, 2000; Velić *et al.*, 2002, Vlahović *et al.*, 2005).

Both in the Friuli and the Adriatic Carbonate Platform, the occurrence of intra-platform basins was hypothesized: the Friuli Basin, with a Dinaric elongation, subdividing the Friuli Platform in North-Eastern and South-Western parts (Fig. 2) on the basis of seismic profiles (Cati *et al.*, 1987b; Casero *et al.* 1990); the Epiadriatic Basin, separating the Adriatic and Dinaric Platforms, now buried below the Karst Dinaric thrusts (Herak 1986, 1987, 1991, 1993; Cati *et al.*, 1987b; Vlahović *et al.* 2002). Recently, this hypothesis has been challenged as no basin and shelf margin facies have been found in outcrops or recovered from wells (Buser 1987; Velić *et al.*, 1989, Gušić and Jelaska, 1993; Grandić *et al.*, 1997; Pamič *et al.*, 1998: Vlahović *et al.*, 2002; Placer, 2002; Tari, 2002).

Consequent to the geodynamic events of the Dinaric (Late Cretaceous-Paleogene) and Alpine (Oligocene-Miocene) compressional phases, two foredeeps developed, deforming the Mesozoic carbonate platform: the Dinaric foredeep, in the eastern area filled by the turbidites of the Flysch (Eocene) formation, and the Alpine foredeep, in the north-western, filled by the continental to coastal deposit of the Molassa (Late Miocene).

During the Messinian, a complex interplay between the marine regression and the compressional event induced the subaerial exposure of the

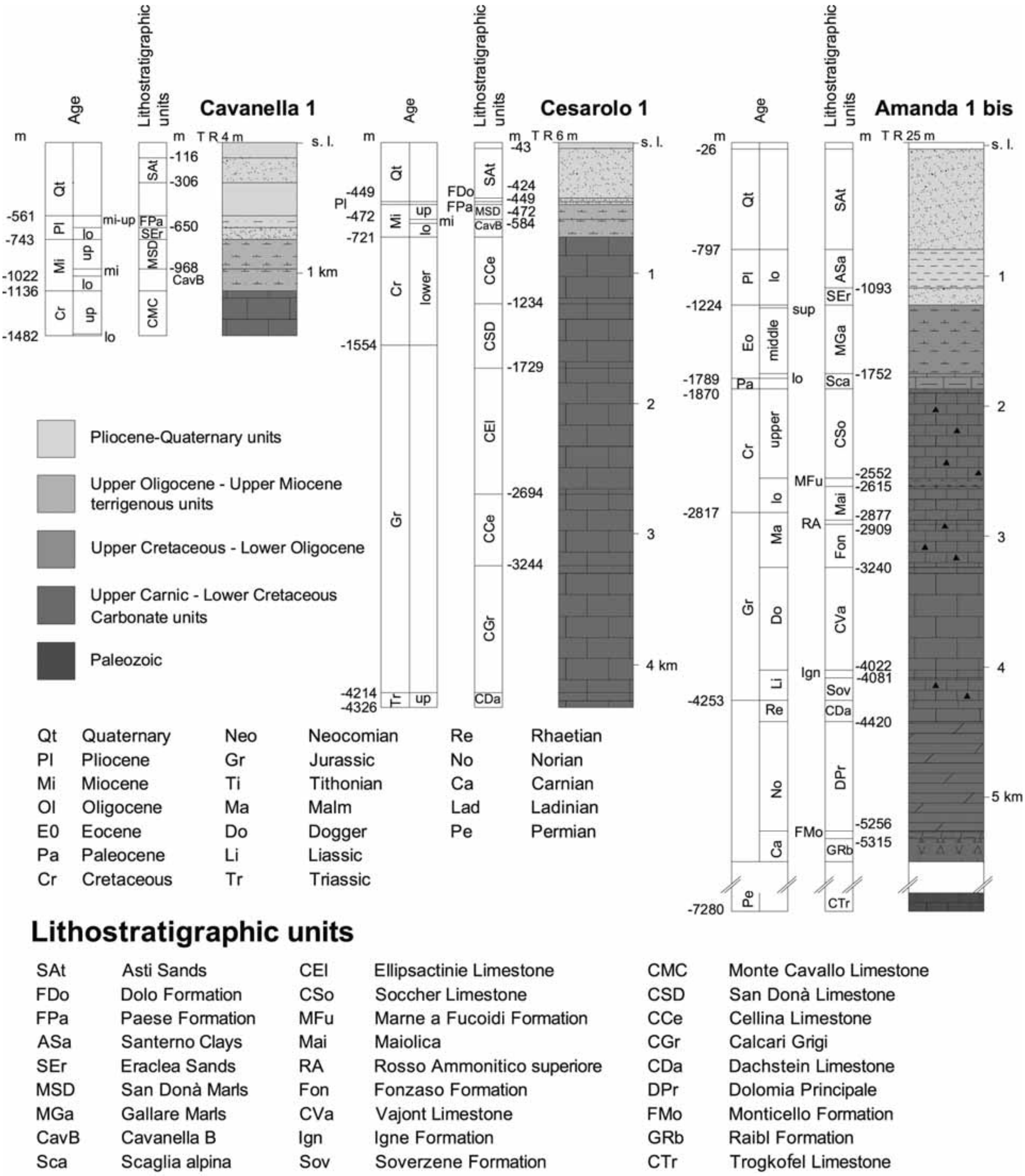

Fig. 3 - Stratigraphy of the wells Cavanella 1, Cesarolo 1, and Amanda 1bis (Nicolich et al., 2004 modified after AGIP, 1972 and 1977). See Figs. 1 and 2 for location.

northern Adriatic favouring the erosional processes of the area (Fantoni *et al.*, 2002), while the Veneto and western Friuli areas became the foredeep of the Alpine chain, characterised by fluvial conglomerate and fan-delta to lacustrine sedimentation (Dondi and D'Andrea, 1986), with a framework of rivers roughly corresponding to the present (Massari *et al.*, 1974). In the postevaporitic Messinian the delta systems shifted several tens of kilometers southward, down to offshore Ravenna, and were fed by the fluvial incision systems bringing sediment from the Alps (Fantoni *et al.*, 2002). The Messinian was followed by the marine transgression with deposition of Pliocene marine sediments (Fantoni *et al.*, 2002).

The tectonic flexure induced by the building of the south-vergent belt of the eastern Southern Alps, provided the tilting of the Friuli Platform; at present, in the Grado – Lignano coastal area, the carbonate platform rises to about 800 m below sea-level (b.s.l.), and down to over 3500 m b.s.l., towards the NNW, at the front of the Alpine thrusts (Nicolich *et al.*, 2004). The CROP M-18 seismic profile reveals that offshore, in the central part of the Gulf of Trieste, the carbonate platform is dipping eastward and covered by the Flysch sequence (Fantoni *et al.*, 2003; Scrocca *et al.*, 2003).

Dinaric features are present on land in the Karst anticline, in Istria as the Buzet thrust (Placer *et al.*, 2004) and in the Friuli Plain with buried thrusts, such as the Palmanova Line, which is thought to continue offshore (Cavallin *et al.*, 1978; Carulli *et al.*, 1980; Carobene *et al.*, 1981) as the Trieste-Golfo di Panzano Fault (Zanferrari *et al.*, 1982). Del Ben *et al.* (1991) considered the Palmanova fault and the Karst frontal thrust to be the same structure, named the Trieste Fault, being the result of a transpressive deformation with a consistent dextral strike-slip component, generated in Middle-Alpine orogeny (Paleogene) and reactivated during the Neo-Alpine phase.

Data used

The multichannel seismic (MCS) dataset consists of 150 km of profiles acquired by R/V OGS Explora in the Gulf of Trieste in June 2005 (Table 1), and by 37 km of profiles acquired across the Lagoon of Grado and Marano in May 2005 (Table 2).

The closest exploration wells, Cavanella 1 and Cesarolo 1 on land, and Amanda 1 bis offshore (AGIP 1972, 1977 and 1994) (Fig. 3), together with published oil exploration seismic profiles (Amato et. al. 1977; Casero *et al.*, 1990) and the deep crustal seismic profile CROP M-18 (Scrocca *et al.*, 2003; Fantoni *et al.*, 2003; Finetti and Del Ben, 2005), were used for calibrating the seismic horizons.

SEISMIC SOURCE	
Number and type	2 x G.I. Gun Sodera
Total volume	710 in^3
Pressure	140 bar
Depth	3 m
CABLE	
Streamer length	600 m
Number of channels	48
Intertrace	12,5 m
Depth	3 m
RECORDING	
Record length	2 s
Sampling interval	0.5 ms
High cut filter	4.7 kHz – 12 dB/Octave
Low cut filter	3Hz – 6 dB/Octave

Table 1 – Acquisition parameters of the multichannnel seismic survey with R/V OGS Explora in the Gulf of Trieste.

The Bouguer gravity anomaly has been calculated for the Gulf of Trieste and the surrounding Italian coastal area using the OGS gravity dataset, consisting of 3833 stations. The offshore gravity dataset consisted of 1656 measurements acquired during seismic surveys in June 2005, with a Bodenseewerk KSS 31 gravimeter placed at the center of gravity of the R/V OGS Explora, and 32 measurements acquired by AGIP using a sea-floor gravimeter. These data have been merged with on land gravity data consisting of 2145 stations, with density of about 1 station / km^2, acquired by AGIP, OGS and the University of Trieste (Zanolla *et al.*, 2006).

The Bouguer gravimetric anomalies have been calculated with 2.67 kg/m^3 density reduction and topographic correction distance up to 167 km from the station. The map was created using the Mercator projection and the Roma40 datum.

SEISMIC SOURCE	
Number and Type	1 x Par Bolt Air Gun 1200 DH
Total volume	80 in^3
Pressure	120 bar
Depth	1.5 m
CABLE	
Streamer length	120 m
Number of channels	24
Intertrace	5 m
Depth	0.5 m
RECORDING	
Record length	1 s
Sampling interval	0.25 ms
High cut filter	Anti alias (default)
Low cut filter	3Hz – 6 dB/Octave

Table 2 – Acquisition parameters of the multichannnel seismic survey from the inner to external Grado and Marano Lagoon.

Seismic interpretation

Based on the interpreted seismic horizons the main seismo-stratigraphic sequences and unconformities were defined (Figs. 4-7):

Carbonate sequence

This sequence shows different acoustic facies according to the various depositional paleoenvironments:

a) in the eastern part, the horizon is well defined and continuous, with high amplitude and low frequency, being at the top of several parallel horizons with the same acoustic characteristics. The top of the limestone has the maximum depth on the eastern side, with ~800 ms b.s.l., corresponding to ~1100 m converted using the seismic interval velocities of the overlying formations, and rises gradually westward to the margin of the platform with a gentle undulated morphology.

b) the horizon at the margin of the platform is less continuous with lower amplitude and higher frequency than in the eastern part and with an irregular morphology (Figs. 4 and 6). The shelf margin is less than 450 ms (TWT) deep, corresponding to 350 m, hence constituting a high of the carbonate platform. From the stratigraphy of the Cesarolo 1 and Cavanella 1 wells, located on land at the platform margin, above the limestones lies the terrigenous-carbonatic platform deposit of the Cavanella (Chattian – Langhian) (Fig. 3). In the seismic profiles, the Cavanella with about 100 ms (TWT) of thickness, is overlain by marine Pliocene sediments. A high impedance contrast between the two produces a highly reflective horizon at the top of the Cavanella and internal multiples below it. Moreover, the Cavanella is underlain by platform deposits, which give rise to a low acoustic impedance contrast due to the similar carbonatic nature of the two. Hence, the reflector of the top of the Mesozoic carbonate is not easy to identify, as it is characterised by low amplitude, is discontinous and often hidden by the internal multiples.

In the talus, from 400 to 1000 ms depth, there are oblique horizons with high frequency and faintly continuous reflections, representing the progradation of sediment coming from the shelf margin, usually consisting of debris and coarse carbonate turbidites in the upper talus and fine carbonate turbidites in the lower talus.

c) to the west, in the deep basin, the seismic sequence has low frequency and often is discontinuous, nevertheless the characteristic signature allows the trend of the top of the carbonatic sequence to be identified.

The Isobath Map of the Top of the Carbonates has been produced for the Gulf of Trieste and merged with the one existing on land by Nicolich *et al.* (2004) (Fig. 9). The depth of the carbonates has been calculated by the conversion of the seismic profiles from two-way travel times to depth, using a velocity field obtained by integrating mean and interval velocities of every formation from the surface down to the top of the Carbonates. The mean and interval velocities were derived from well information and from the CROP M-18 seismic profile.

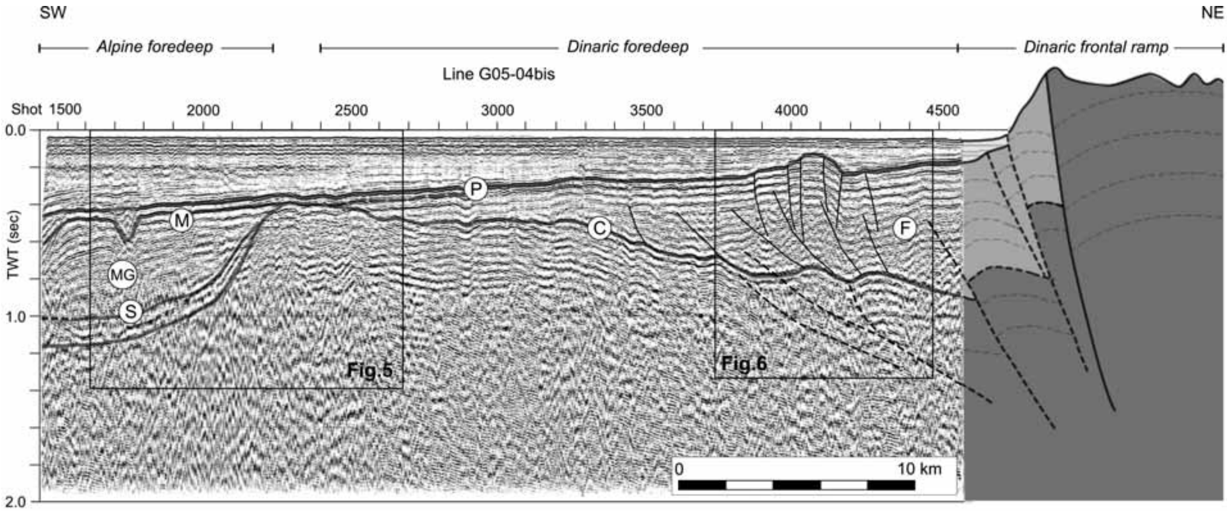

Fig. 4 - Multichannel seismic profile G05-4bis across the buried Friuli Platform and the overlying terrigenous sequence. The carbonate shelf margin represents the highest area of the platform, subdvided in: a) a south-westward basinal area (Fig. 5) with the deep sea carbonate "C" overlain by the Scaglia alpine "S" onlapping the talus; above the Gallare Marls "MG" are eroded by the Messinian marine regression "M"; b) the north-eastwards flexured carbonate platform (Fig. 6) overlain by the Flysch terrigenous sequence "F" representing the foredeep of the dinaric thrusts, gently folded by compressional tectonics. A compressional feature with inverse fault deforms the Flysch sequence. The Lower Pliocene marine deposits drape the Messinian erosional surface in the western part, while an erosional episode due to the Pliocene marine regression affected the overall area as the final Pliocene-Pleistocene marine transgressional phase. The Pliocene unconformity is represented by "P" on seismic profile. Onland geological section modified after Carulli, 2006.

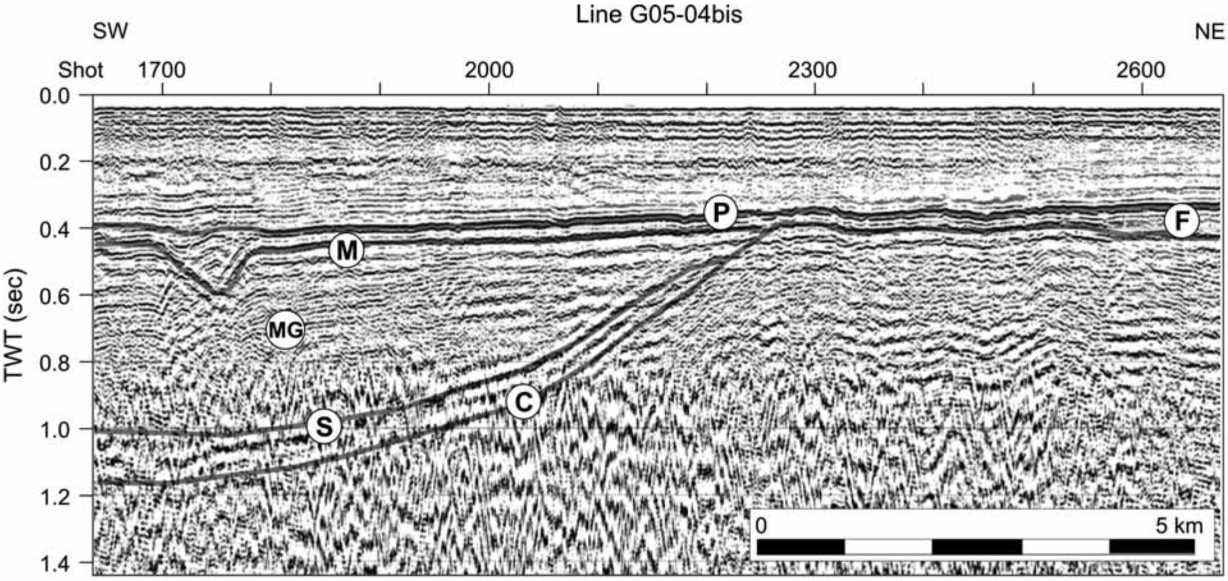

Fig. 5 – Multichannel seismic profile G05-04bis across the western margin of the Friuli Platform. According to the stratigraphy of Cesarolo 1 and Amanda 1 bis wells (Fig. 3), carbonate lithologies "C" could be constituted by the Cretaceous Soccher Limestone in the basinal area, and by the Cellina Limestone in the shelf. The Paleocene Scaglia alpina "S" onlaps the slope and is overlain by the Eocene Gallare Marls "MG" eroded during the subaerial exposure of the Messinian marine regression "M", and above the Pliocene-Pleistocene marine sediments with the Pliocene unconformity "P".

Scaglia Alpina

Scaglia Alpina (or *Scaglia*) (Aptian-Early Eocene) overlies the deep-sea carbonate in the basin and onlaps the lower talus. It is characterised by a low frequency horizon in the talus, and less distinct horizon toward the basin. The maximum thickness, on seismic data, is about 200 ms (TWT) in the talus.

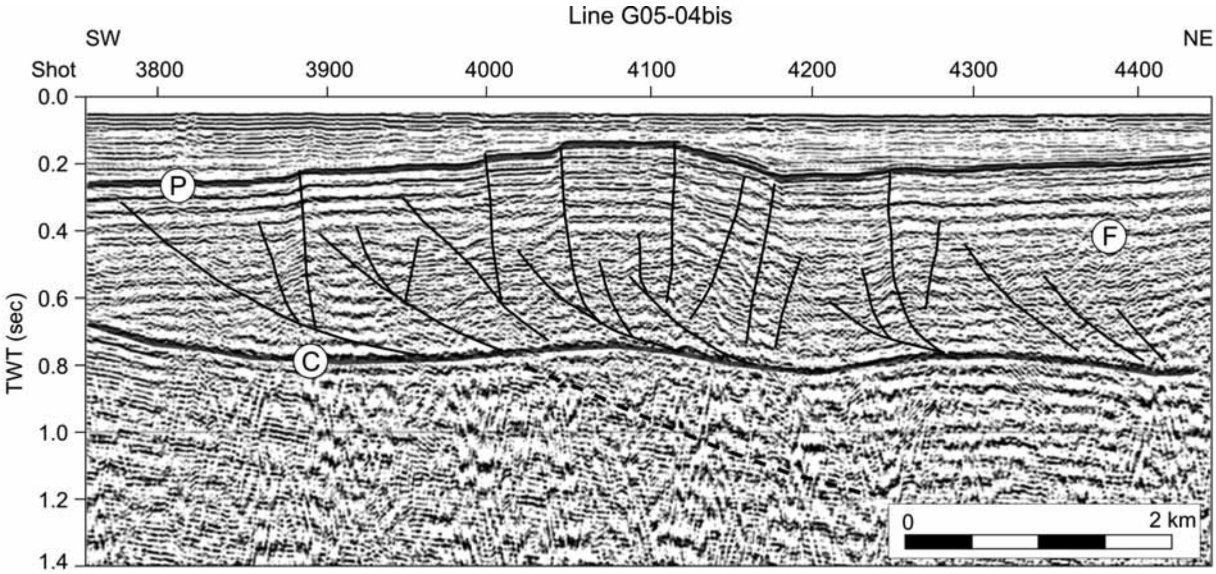

Fig. 6 – Multichannel seismic profile G05-04bis across the tectonic deformation of the Flysch sequence "F". Inverse fault strands have NE and SW dip at the western and eastern side of the structure, respectively. The structure has a Dinaric trend (Fig. 9). The underlying carbonate units "C" exhibits a gentle folding that could be due to compressional tectonics, as seen all along the flexured carbonate platform (Fig. 5).

Flysch

The Eocene *Flysch* terrigenous sediment is present above the carbonate platform. Two different seismic responses can be distinguished within the Flysch: the lower part, characterised by low frequency discontinuous horizons and the upper part, where the horizons are well stratified and continuous. The entire sequence onlaps the underlying carbonate, with an overall wedge shape geometry; its maximum thickness is of 700 ms (about 1000 m) to the east, tapering westward and pinching out in correspondence of the shelf margin carbonate high. Tectonic deformation produced folding and faulting of the sequence, in particular in the deeper part. Moreover, a tectonic feature, about 3 km wide and with a NW-SE orientation, is characterized by reverse faults on both sides, with strands disrupting the top of the Flysch with up to 30 m of vertical throw (Figs. 5 and 6).

Gallare Marls

The *Gallare Marls* (Middle-Late Eocene) are deposited above the *Scaglia Alpina* and onlap the platform slope. The sequence shows a deepening trend westward with a thickness up to 800 ms (TWT) (corresponding to about 1500 m) with low frequency in the lower part, and higher frequency and more continuity in the upper part.

Messinian erosion surface

Westward of the carbonate platform margin, an erosion surface is present at the top of the *Gallare Marls*. The erosion surface has clear seismic characteristics, represented by a high amplitude and continuous horizon. Moreover, it has typical erosive features and morphologies such as channels, up to 3000-4000 m wide and 250 m deep (Figs. 4, 5 and 7). The huge channels observed in the seismic profiles indicate a drainage system developed during the subaerial exposure induced by the Messinian marine regression, which in the Northern Adriatic area caused the southward shifting of the delta systems (Fantoni *et al.*, 2002).

Pliocene deposits and erosion surface

The unconformity is characterised by erosion of the underlying sediment and by onlap of the overlying sediments. The nature of the underlying sediments changes at the different locations; a) Pliocene marine sediments that were deposited in the western part during the marine transgression after the Messinian regression; b) Eocene *Flysch* terrigenous sediments in the eastern part.

The onlapping sediments above the Pliocene erosion surface are characterised by high frequency, variable amplitude, parallel and discontinuous horizons. The sequence has the maximum thickness of 600 ms (TWT) to the West,

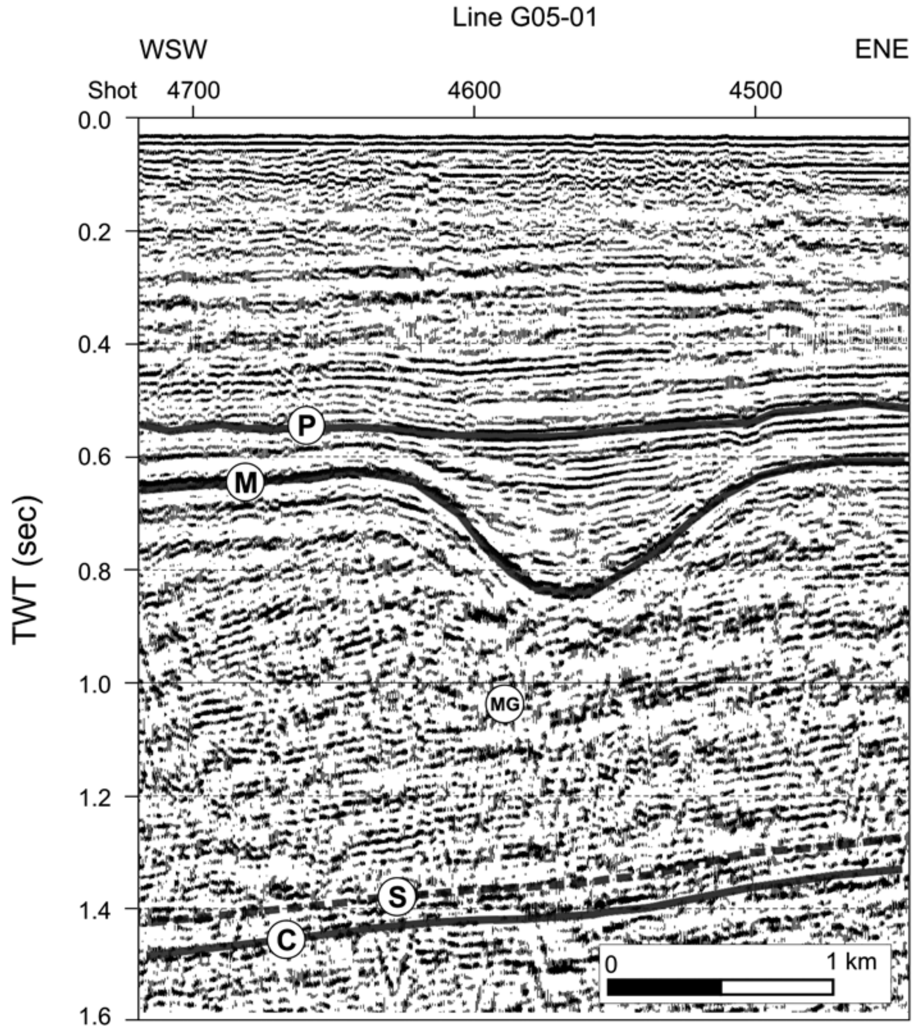

Fig. 7 – Multichannel seismic profile G05-01 with a fluvial channel eroded in the Gallare Marls "MG" (Eocene) during the subaerial exposure of the Messinian marine regression "M". The fluvial channel is more than 1 km wide and about 250 m deep (see Fig. 1 for location). Carbonate lithologies "C" are overlain by the Paleocene Scaglia alpina "S". Above, the Pliocene-Pleistocene marine sediments with the Pliocene unconformity "P".

whilst it reaches its minimum of 100-200 ms to the East. It reflects the depth of the Pliocene unconformity, deeper westward and shallower eastward. The Amanda 1 bis well, recovered 427 m of *Eraclea Sands* and *Santerno Clays* (Early Pliocene), followed by 771 m of *Asti Sands* (Pleistocene), while in the Cesarolo 1 well the same Pleistocene formations have a thickness of 381 m overlying the *Dolo* (Pleistocene) and *Paese* (Pliocene) *Formations*; they consist of sand and clay, with a thickness of 25 and 23 m, respectively (Fig. 3).

Discussion

The carbonate platform in the Gulf of Trieste belongs to the Friuli Platform, buried below the Veneto and Friuli Plains. It is tilted with a maximum depth to the East in front of the coastal area, and a minimum depth to the West at the shelf margin.

The Isobath Map of the Top of the Carbonates shows, at the shelf margin, a shallowing trend from NW to SE: starting from the Cesarolo High, about 800 m deep, it reaches depths of less than

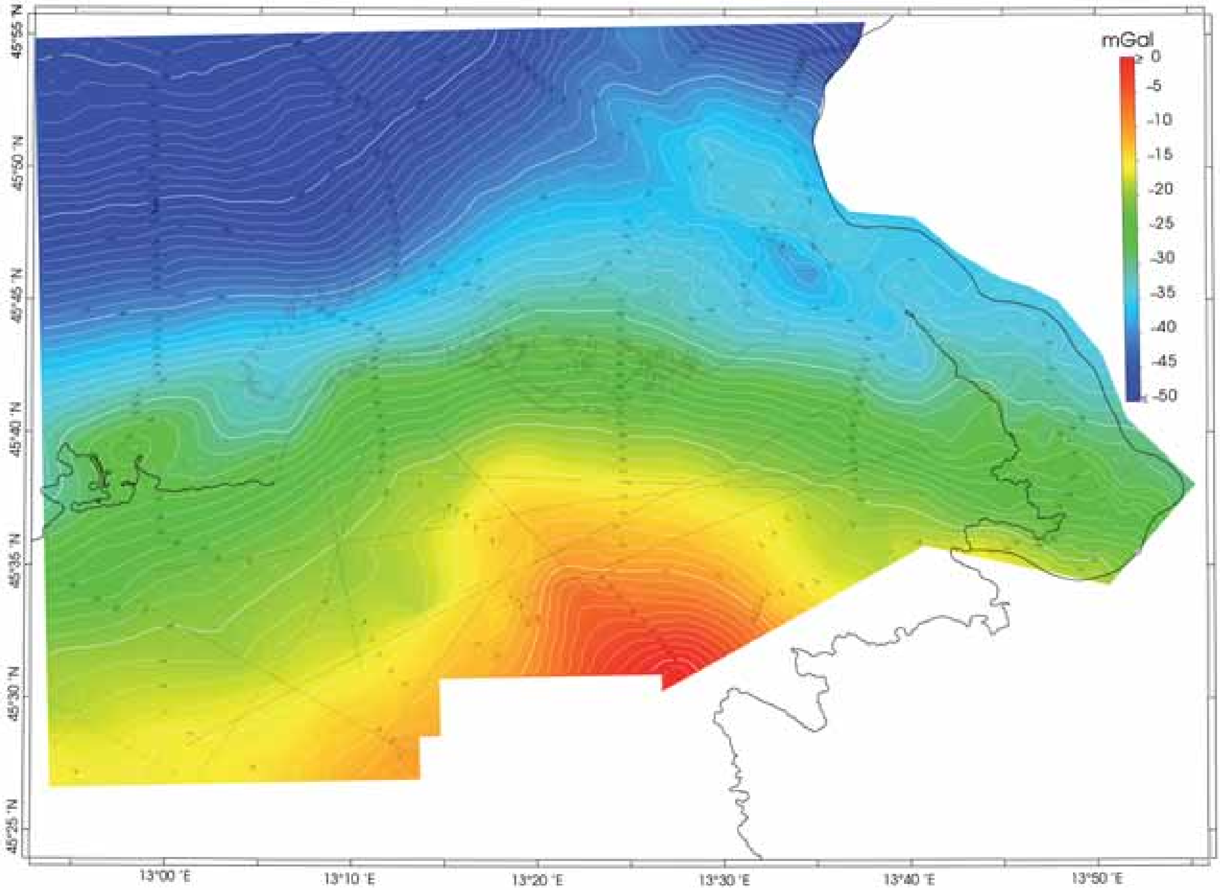

Fig. 8 – Bouguer gravimetric anomalies map, calculated with 2.67 kg/m^3. On land and offshore black dots indicate the measurement stations. The gravimetric high anomaly offshore (in red) is relative to the carbonate highs at the shelf margin of the platform that, from 800 metres deep below the coastal area, rises up southward to outcrop at Savudrija Rtič in Istria. Datum Roma40 and Mercator projection. Negative Bouguer anomalies to the North and to the East are relative to the flexuring of the carbonates with maximum depth at the front of the Alpine to the North and External Dinarides to the East.

500 m in the northern Gulf of Trieste. In the same map it is clearly visible a positive structure, elongated parallel to the shelf margin. Further South-East, in the central part of the Gulf, the top of the carbonates rises up reaching depth of 350 m. The trend suggests the presence of an NW-SE feature that connects the Cesarolo High to the Savudrija Rt (Croatia) limestones outcrops (Fig. 9).

The stratigraphic information of the Cesarolo 1 and Cavanella 1 wells, both located at the shelf margin of the Friuli Platform, indicates the presence of Lower Cretaceous *Cellina Limestone* and Upper Cretaceous *Monte Cavallo Limestone*, respectively (Fig. 3). The carbonate outcrops in the north-western part of Istria (Croatia) consist of an Upper Albian–Lower Campanian megasequence (Velić *et al.*, 2000, 2002; Vlahović *et al.*, 2005). Hence, it can be inferred that the Friuli Platform margin in the Gulf of Trieste consists of similar shallow-water carbonate lithologies of Cretaceous age (Fig. 9).

The shelf margin is oriented approximately NW-SE, with minor indentations in the orthogonal direction (NE-SW) (Fig. 9). This NW-SE trend, in agreement with that suggested by Cati *et al.* (1987b), represents one of the saw-toothed NW-SE and NE-SW trends present on land. The minor indentations in the central part of the gulf, with NW-SE and NE-SW trends, indicate that the carbonate margin extends southward and is probably linked to the Savudrjia High, as suggested by the shape of the carbonate isobaths that mimic the Savudrija Rt profile.

The carbonate shelf margin highs distinguish two areas with different depositional history from the Paleocene to the Miocene. In the eastern part,

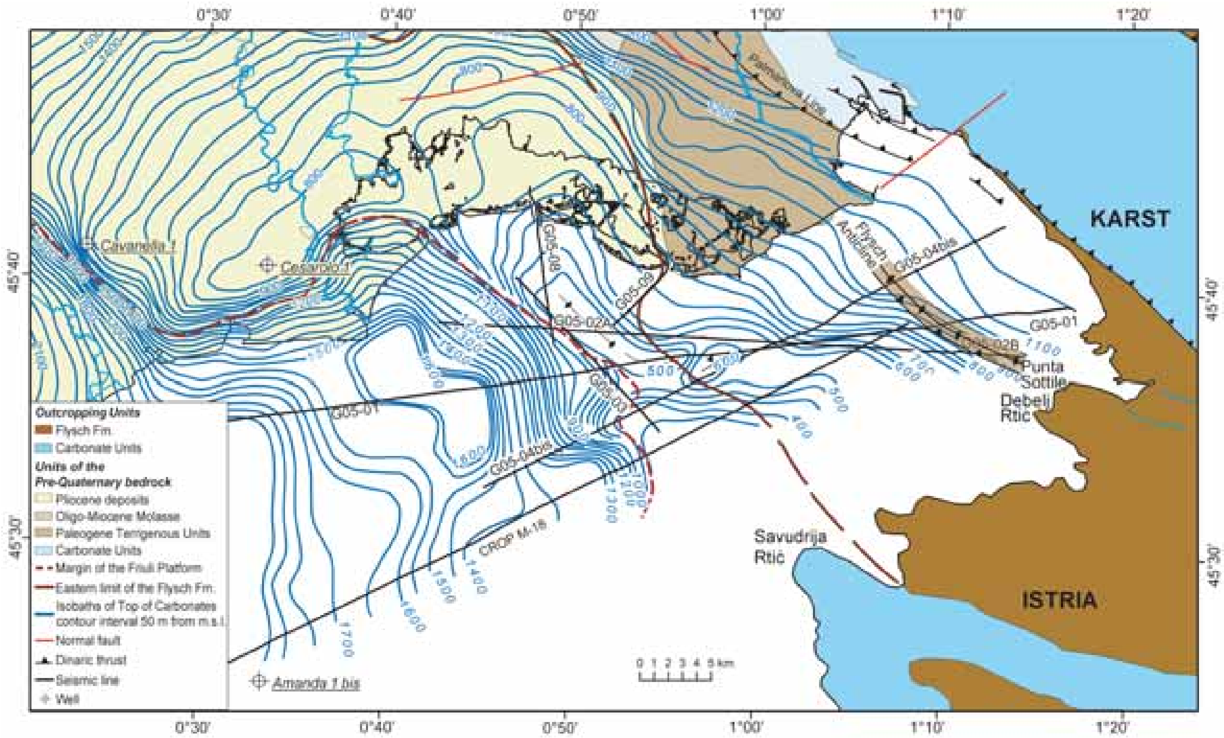

Fig. 9 – Top carbonate isobath map: the higher features are located at the shelf margin, at a depth of 800 m on land (Cesarolo High), 500 m offshore south of the Grado and Marano Lagoon, and rising up to 350 m southward in the central part of the Gulf of Trieste and linking up to the outcropping limestones at Savudrjia Rt in Istria (Croatia). The carbonates are flexured due to the Dinaric compressional tectonic, deepening down to 1200 m eastward at the coast (Fig. 4). The overlying Flysch sequence onlaps the flexured carbonate platform, and the offshore limit of distribution (brown line in the figure) is well correlated to the offshore limit in Istria. The Flysch sequence is deformed by compressional tectonic features having a dinaric trend (Figs. 4, 6) and aligned with Punta Sottile – Debelj Rt, the peninsula of Istria where the Flysch crops out.

above the limestone the Flysch filled the foredeep during the Dinaric orogenic phase. The Flysch thickness decreases westward, as it can be seen on seismic profiles as a pinch-out towards the carbonate shelf margin high. At the same time in the western part, beyond the platform margin, the deep-water facies of the *Scaglia Alpina* (Paleocene-Early Eocene) and successively the *Gallare Marls* (Middle and Late Eocene) were deposited. The Messinian unconformity (Late Miocene) is preserved only in the western part with evidences of erosion and the development of drainage systems. The eastern part, where the Flysch is present, according to Dondi and D'Andrea (1986), and Massari *et al.* (1986), was in subaerial conditions from the Messinian to the Upper Pliocene. Hence, the surface between the Flysch and the overlying onlapping Pliocene-Pleistocene sediments merges the Messinian and Pliocene unconformities. The resolution of the seismic profiles does not provide evidence of the lateral passage between the Flysch and the Pliocene deposits, which should occur approximately above the highs of the carbonate shelf margin.

In the Eastern sector of the Friuli Platform shelf margin, the tectonic activity produced deformation characterised by folds and faults, both in the carbonate and Flysch sequences. Folds in the carbonate range from several hundreds of metres to 2-3 km wide and up to about 100 m high. Folds in the Flysch sequence, in particular in the lower part, are not concordant with the underlying carbonate folds, instead they are narrower and related to thrusts (Fig. 6).

A main tectonic feature, with thrusts and backthrusts having SW and SE dip in the westward and the eastward side respectively, crosses the Gulf of Trieste with NW-SE orientation (Figs. 6 and 8). It has the same orientation and direction of the thrusts and folds of the Tinjan Structure present in the Debelj Rtič, the peninsula of Istria where the Flysch crops out (Placer, 2005) (Fig. 9).

Hence, it can be inferred that the offshore compressional structure is the continuation of the onland thrusts and folds. The overall features provide a deformational setting characterised by the Dinaric compressive regime that produced folding and low-angle faulting of the carbonate sequence and thrusts in the Flysch sequence, with the top of the underlying carbonate acting mainly as a detachment surface. The faults were active also in the Pliocene, as some strands have produced up to 30 m of vertical throw of the Pliocene unconformity. Recent tectonic activity cannot be excluded, even if the mainly unconsolidated Plio-Quaternary sediments and the seismic resolution of the profiles do not provide evidence of such deformation.

Eastward of the Flysch anticline, the Palmanova line was thought to continue (Carulli *et al.*, 1980, Zanferrari *et al.*, 1982) based on several metre high morphological series of escarpments in the flysch, approximately parallel to the coast, detected in high-resolution seismic profiles (Mosetti and Morelli, 1968) and from seismic refraction profiles (Finetti, 1967). No evidence of thrust faults with significant vertical throw disrupting the carbonate are present in the seismic profiles, instead, less than 2 km from the coast, the carbonate, flexured in front of the external Dinarides thrusts, reaches a depth of more than 1200 m. Considering that at the Karst seafront, the outcrop of the hanging wall of the carbonate at the coastline is up to 240 m, a main deformation zone, with a thrust fault system displacement of about 1200-1400 metres should be placed in the coastal zone of the Karst. A similar tectonic system, with approximately the same location, has been hypothesized by Del Ben *et al.* (1991) as the Trieste Fault.

In the Bouguer gravity anomaly map, the negative anomalies present in the northern part with the East-West trend are due to the Alpine flexure of the crust and carbonates basement, together with the increase of the thickness of the overlying terrigenous sequences. The negative anomalies with NW-SE trend are related to the Dinaric flexure and the negative minimum presents in the north-eastern part of the gulf probably corresponds to the southern prosecution of the Palmanova Line. In the offshore area, the Bouguer gravity anomaly map shows a gravimetric positive anomaly in correspondence of the high at the carbonate platform margin, located at a depth of about 800 m on land, shallowing southward in the offshore area and outcropping at Savudrija Rt in Istria (Croatia).

Conclusion

The Friuli Platform in the Gulf of Trieste is tilted due to the Dinaric tectonic activity, with maximum depth in front of the coastal area, and minimum depth at the shelf margin. The carbonate shelf margin of the Friuli Platform presents mainly the NW-SE Dinaric trend, with minor indentations southward with a NE-SW orientation, in according to the saw-toothed NW-SE Dinaric and NE-SW anti-Dinaric trends present on land. It is characterised by morphological highs, one at a depth of less than 500 m in the northern part of the Gulf of Trieste, and the second at less than 350 m further south. The highs represent a shallowing trend of the shelf margin from the Cesarolo High at about 800 m on land to the limestone outcrops of the Savudrija Rt in Istria (Croatia). The Bouguer gravity anomaly map shows an indicative positive feature in the central Gulf of Trieste representing the southward shallowing trend of the Friuli Platform shelf margin.

The Cenozoic tectonic evolution of the area is related to the Dinaric compressional regime that produced, on a regional scale, the flexure of the Friuli Platform with gentle folding, and low angle reverse faulting, reaching depths of more than 1200 metres at the front of the Karst external Dinarides thrusts. Since no evidence of thrusts with significant vertical throw are present in the seismic profiles, the area of the Karst coastal front and 2-3 km offshore, can be regarded as an accommodation zone of the Karst Dinaric thrust system with an overall vertical displacement of about 1400 m.

Across the Gulf of Trieste a compressional tectonic feature with Dinaric orientation has been identified. The structure links up to the Dinaric thrusts and folds of the Tinjan Structure present in the Debelj Rt of Istria Peninsula. Reverse faults, having SW and SE vergence on the western and eastern side respectively, deformed the Flysch, in particular the lower part of the sequence, while the underlying carbonate sequence is gently folded with low-angle faults. As the carbonates do not provide evidence of such magnitude of deformation, their top probably acts as a detachment surface. The Pliocene unconformity, at the top of the Flysch is disrupted by thrusts and backthrust with up to 30 m of vertical throw.

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