Dinaric tectonic features in the Gulf of Trieste (northern Adriatic Sea)

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ABSTRACT Seismic investigation in the Gulf of Trieste allows the identification of the extension and activity of the External Dinarides tectonic structures. The Gulf of Trieste belongs to the Adriatic Apulian foreland, consisting of the tilted Paleocene - Mesozoic carbonate platform overlaid by the Eocene foredeep Flysch deposits and by recent Quaternary sediments. The data set consists of 250 km of multichannel seismic profiles, 16 km of high resolution data, collected offshore, and 5 km of multichannel seismic profiles collected onshore since 2003. The main tectonic features identified in the study area are: a) the Trieste fault zone, occurring on the Karst coastal front, up to 2-3 km offshore; it is a Dinaric thrust system with about 1400 m of total vertical displacement in the carbonates, possibly affected by neotectonic activity; b) Dinaric frontal thrusts, present in the Gulf of Trieste and in the southern Friuli Plain, deforming the Flysch sequence and producing low angle faults in the carbonates; c) occurrence of possible NE-SW faults dissecting the Dinaric thrusts.

1. Introduction

The geophysical investigation of the Gulf of Trieste began in the 1960s with high resolution single-channel sparker surveys that provided the mapping of the seafloor morphologies (Mosetti, 1966) and the identification of the sandstone-bedrock surface (Mosetti and Morelli, 1968), near the top of the Flysch, and two seismic refraction profiles that identified the marker of the carbonates at about a 1000 m depth, close to the coast and disrupted by faults (Finetti, 1965, 1967). This was the only geophysical data set published until the CROP M-18 multichannel seismic profile was acquired for crustal investigation in 1995 (Scrocca *et al.*, 2003; Finetti and Del Ben, 2005).

The geological setting and, in particular, the offshore tectonic features, were mainly inferred from the onshore geological information and scarce geophysical data (Cavallin *et al.*, 1978; Carulli *et al.*, 1980; Carobene and Carulli, 1981; Carulli, 2006).

About 250 km of multichannel seismic profiles were acquired in the Gulf of Trieste in 2005. This data set identifies the setting of the Carbonate Platform, the overlying Flysch draped by Pleistocene sediments and the occurrence of the main tectonic features (Busetti *et al.*, 2008).

In this paper, we examine the tectonic structures of the area, in particular the Dinaric thrusts, identified both offshore in the Gulf of Trieste and onshore. Moreover, the data provide some constraints regarding the location of the thrust faults of the Karst, and its neotectonic activity.

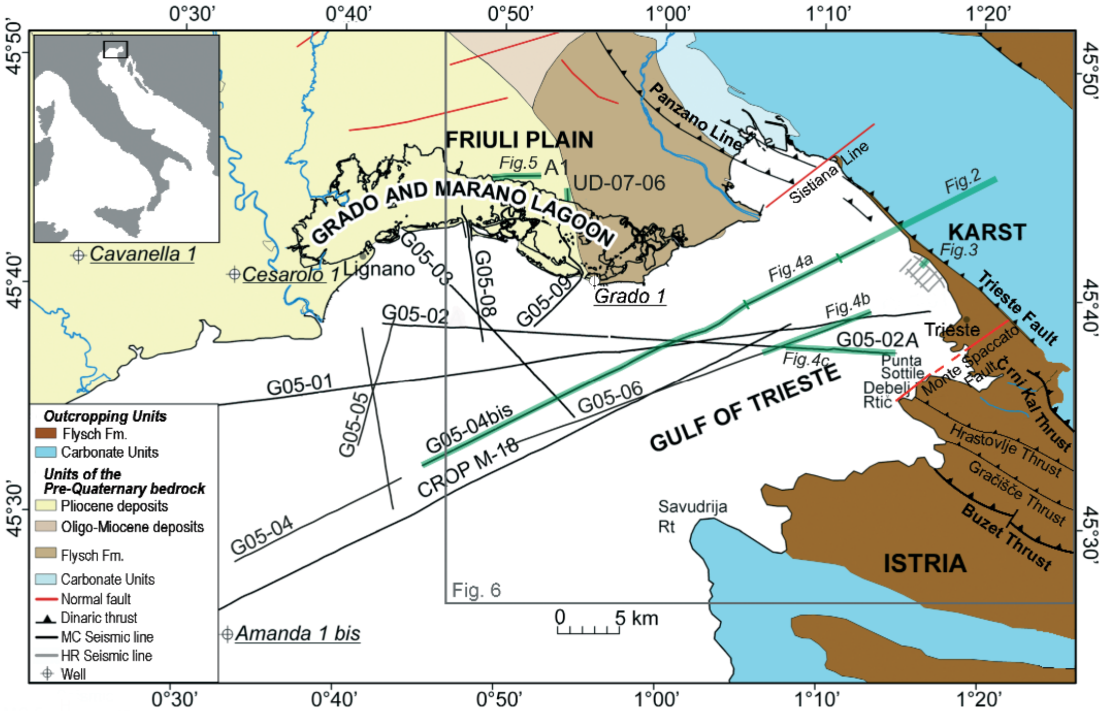

Fig. 1 - Position map of the multichannel (MC) seismic lines acquired offshore and onshore (black line) and the high resolution (HR) seismic collected near the coast (grey line). Outcropping units and units of pre-Quaternary bedrock from Nicolich *et al*. (2004), Panzano Line from Carulli *et al*. (1980) and Nicolich *et al*. (2004), Trieste Fault from Carulli *et al*. (1980), Sistiana Fault from Carulli *et al*. (1980) and Nicolich *et al*. (2004), Monte Spaccato Fault from Cavallin *et al*. (1978) and Carobene and Carulli (1981), Buzet, Graščiče, Hrastovlje and Črni Kal Thrusts from Placer (2007).

2. Geologic setting

The Gulf of Trieste, together with its surrounding onshore areas (Istria, Karst, and Friuli Plain) is part of the Adriatic Apulian foreland. It is composed of the Mesozoic Adriatic Carbonate Platform (sensu Vlahović *et al*., 2005), Paleocene-Eocene carbonates and Eocene Flysch, outcropping onshore and buried below the Late Cenozoic sediments of the Friuli Plain (Fig. 1).

The western paleo-shelf margin of the Friuli Carbonate Platform (middle Jurassic-lower Cretaceous), orientated NW-SE with NE-SW saw-tooth trends, is presently located between the Friuli and Venetian plains (Cati *et al*., 1987; Casero *et al*., 1990; Nicolich *et al*., 2004) and continues through the Gulf of Trieste, shallowing up to the limestone outcrops of the Salvore Point [Savudrija Rt in Istria, Croatia; Busetti *et al*. (2008)]. 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 600-700 m below sea level (b.s.l.), and down to over 3500 m b.s.l., towards the N/NW, at the front of the Alpine thrusts (Nicolich *et al*., 2004). Similarly, in the Gulf of Trieste, the carbonate platform dips eastwards, from a 300-500 m depth at the shelf margin to the west down to more than 1200 m b.s.l. close to the coast and the Karst plateau, and is covered by the Flysch sequence

(Busetti *et al*., 2008).

The Gulf of Trieste, being the Dinaric foredeep, was filled by the turbidites of the Flysch formation (Eocene) and by Paleocene-Early Eocene carbonates both outcropping along the Trieste coastal front and in Istria and drilled in the Grado-1 well (Della Vedova *et al*., 2008). During the Late Oligocene - Miocene, the South Alpine compressional phase determined the continental to coastal deposition of the so-called Cavanella (Aquitanian to Langhian) and Molassa (Late Miocene).

During the Messinian, a complex interplay between the marine regression and the compressional events induced the sub-aerial exposure of the northern Adriatic (Fantoni *et al*., 2002). In the Gulf of Trieste, this reflects in the development of the erosion of the Flysch formation (Busetti *et al*., 2008), resulting in a surface with a complex morphology with valleys and highs characterised by terraces and escarpments (Mosetti and Morelli, 1968). The Messinian erosion was followed by a marine transgression, with deposition of draping Pliocene terrigenous and marine sediments. Another erosive episode occurred in the Early Pliocene (Fantoni *et al*., 2002).

Dinaric structures are present, on land, in eastern Friuli, with buried thrusts below the plain, one of which is thought to continue offshore in the Gulf of Trieste, 3-4 kilometers from the coastline (Cavallin *et al*., 1978; Carulli *et al*., 1980; Carulli, 2006), as the Golfo di Panzano - Baia di Muggia Line (Carobene and Carulli, 1981). Del Ben *et al*. (1991) suggest that the Trieste Fault should correspond to the Karst frontal thrusts, as a result of the transpressive deformation with a consistent dextral strike-slip component, generated in Middle-Alpine orogeny (Paleogene) and reactivated during the Neo-Alpine phase. Placer (2008) hypothesizes that the Trieste Fault continues in Slovenia as the Črni Kal thrust fault. Busetti *et al*. (2008) inferred from seismic data that the Karst coastal front and the 2-3 km offshore belt, can be regarded as an accommodation zone of the Karst Dinaric thrust system with a vertical component of about 1400 m.

A main tectonic feature, with thrusts and backthrusts having a SW and SE dip in the westward and eastward side respectively, crosses the Gulf of Trieste with a NW-SE orientation (Busetti *et al*., 2008). The authors refer to this structure as the continuation of the onshore Tinjan Structure (in the hanging wall of the western Hrastovlje Thrust) present in the Flysch outcroppings in the Istria peninsula (Placer, 2005). Moreover, Placer *et al*. (2004), proposed the more external Buzet Thrust Fault (Fig. 1), again in the Flysch *s*equence, to be the outermost SW margin of the Karst Thrust Edge.

NE-SW faults, the Sistiana and Monte Spaccato Faults, are present on the northern and southern part of the Karst (Cavallin *et al*., 1978; Carobene and Carulli, 1981).

3. The seismic data

The seismic data set, with various levels of resolution, consists of 250 km of multichannel (MC) seismic profiles and 16.2 km of high resolution (HR) single-channel seismic profiles (Fig. 1).

The MC seismic data consist of: a) 158.6 km of seismic profiles acquired by R/V OGS Explora in the Gulf of Trieste, 26 km acquired across the Lagoon of Grado and Marano by OGS and 4 km acquired on land by the University of Trieste. This whole data set was collected in 2005 in the framework of a study commissioned by the Regione Autonoma Friuli Venezia Giulia -

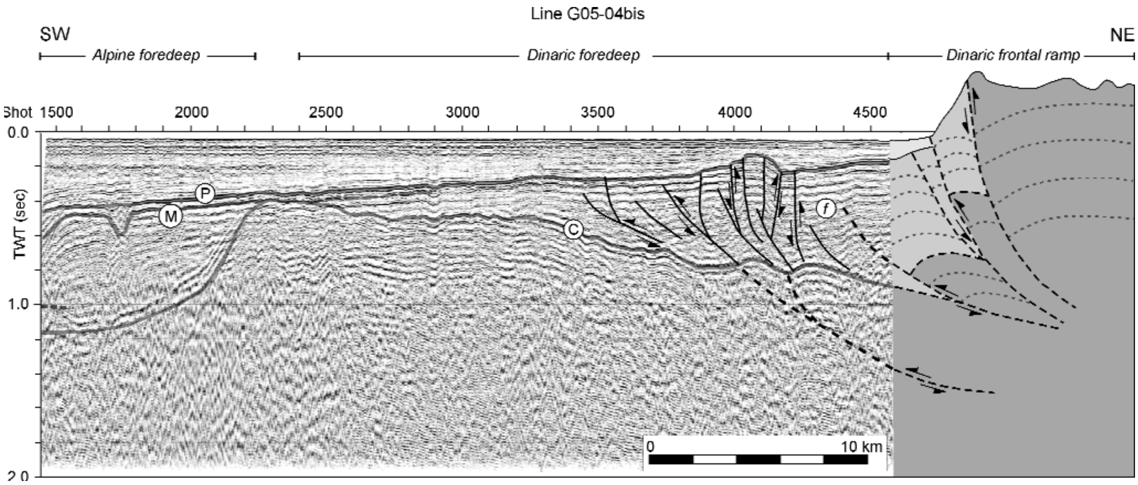

Fig. 2 - MC seismic profile G05-4bis across the Gulf of Trieste [modified after Busetti *et al.* (2008)]. The Friuli Carbonate Platform (top reflector indicated by "C") is flexured below the External Dinarides frontal ramp down to 900 ms (about 1200 m). The shelf margin to the west is the highest area of the platform at 400 ms (about 350 m). The Friuli Carbonate Platform is overlain by the Eocene Flysch terrigenous sequence "f", filling the Dinaric foredeep and affected by thrusts. Plio-Quaternary marine sediments drape the Messinian erosional surface "M" in the western part, while an erosional episode "P", due to the Pliocene marine regression, affected the overall area, as the final Pliocene-Pleistocene marine transgressional phase. Onshore geological section modified after Carulli (2006).

Direzione Centrale Ambiente e Lavori Pubblici – Servizio Geologico; b) 58.85 km of seismic profiles acquired in the Gulf of Trieste in 2005 by R/V OGS Explora; c) 1.1 km onshore seismic profile collected by OGS in 2007 in the framework of the VECTOR project (one of the FISR Programs).

A preliminary standard processing was applied to the seismic data; consequently, considering the different types of seismic signal, a post-stack deconvolution (spike and fxdecon) was then applied to the offshore data, whereas pre-stack migration was used to depth convert the land data.

The main lithological units in the offshore multichannel seismic profiles (Busetti *et al.*, 2008) were calibrated with the closest exploration wells, Cavanella-1 and Cesarolo-1 on land, and Amanda-1bis offshore (AGIP 1972, 1977, 1994), together with published oil exploration seismic profiles (Amato *et al.*, 1977; Casero *et al.*, 1990) and the deep crustal seismic profile CROP M-18 (Fantoni *et al.*, 2003; Scrocca *et al.*, 2003; Finetti and Del Ben, 2005). Onshore, the seismics were calibrated with the Grado-1 well, drilled in 2008. The well recovered Mesozoic platform carbonates from a bottom depth of 1108 to 1001 m, Paleocene-Eocene carbonates from 1001 to 616.5 m, the presumed Miocene Molassa from 616.5 to 280 m and, above, Quaternary sediments. A main fracture zone, at 736-740 m to the bottom depth was found (Della Vedova *et al.*, 2008).

The high-resolution, single-channel data set consists of 16.2 km seismic profiles recorded by OGS in 2003, with a boomer source, close to the coast of Trieste (Fig. 1). The seismo-stratigraphy of the single channel data were calibrated with four 14-27 m long cores located some tens of meters from the coast and crossed by strike profiles. The cores recovered marine sediments, and

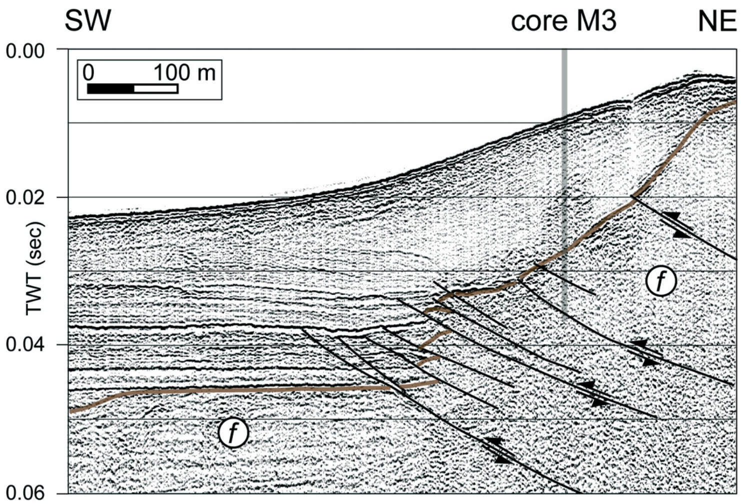

Fig. 3 - Offshore, single-channel, HR profile showing inverse faults in the Flysch (calibrated with the core M3) overthrusting the Late Quaternary marine sediments (modified after Romeo, 2009).

Flysch from the bottom.

4. Results

Offshore, seismic data show the occurrence of tectonic deformation characterised by folds and faults, both in the carbonate and in the Flysch sequences (Fig. 2).

The carbonate sequences are tilted, going from 300-400 m (0.4 s Two-Way-Time, TWT) deep to the west at the shelf margin, to almost 1200 m (0.9 s TWT) deep near the eastern coast (Fig. 2). The carbonates are characterised by gentle folds ranging from several hundreds of metres to 2-3 km wide and up to 100 m high. The wider folds, together with the occurrence of faults, are evident mainly in the eastern part of the G05-04bis seismic profile (Fig. 2).

Eastwards, close to the coast of the Karst, the Flysch sequence shows a deformation with gentle folds. The top of the Flysch, identified in the HR seismic profiles collected near the coast and calibrated with the cores, shows a morphology characterised by escarpments and erosional surfaces some hundred meters wide (Romeo, 2009). The escarpment closest to the coastline, with an overall step of about 15 m, shows (Fig. 3) inverse faults disrupting the Flysch and probably also onlapping the Late Quaternary sediment (Romeo, 2009). Iso-oriented faults in the Flysch, with a 10°-20° dip, filled by calcite, also occur in the cores.

Tectonic deformation in the Flysch sequence is characterised, in its deepest part, by thrusts and folds up to 1 km wide and up to some hundred meters high. Most of the thrusts are westward vergent and terminate at the base of the Flysch without disrupting the underlying carbonate; usually, they appear not to be concordant with those in the underlying carbonate (Fig. 4).

The main zone of deformation in the Flysch is represented by a tectonic feature crossing the

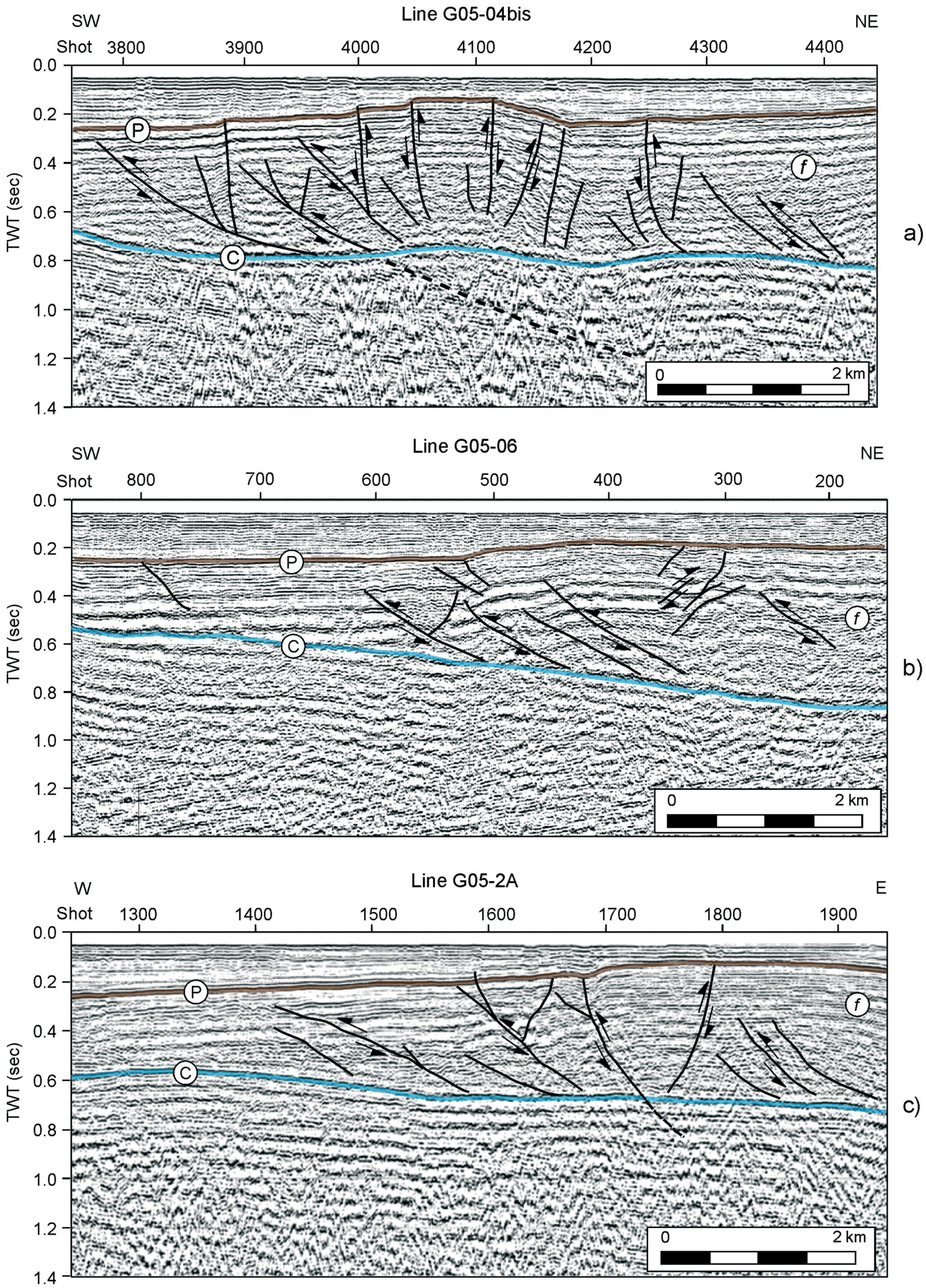

Fig. 4 - Offshore MC seismic profiles a) G05-04bis, b) GO5-02A and c) G05-06 across the tectonic deformation of the Flysch sequence “f”. The underlying Friuli Carbonate Platform (top reflector “C”), exhibits a gentle fold with low angle faulting. The Flysch “f” is affected by thrusts with the detachment level along “C”, top of the carbonate. The erosion surface “P”, that includes the Messinian and Lower Pliocene erosive phases, in a) is affected by a fault escarpment up to 30 m high.

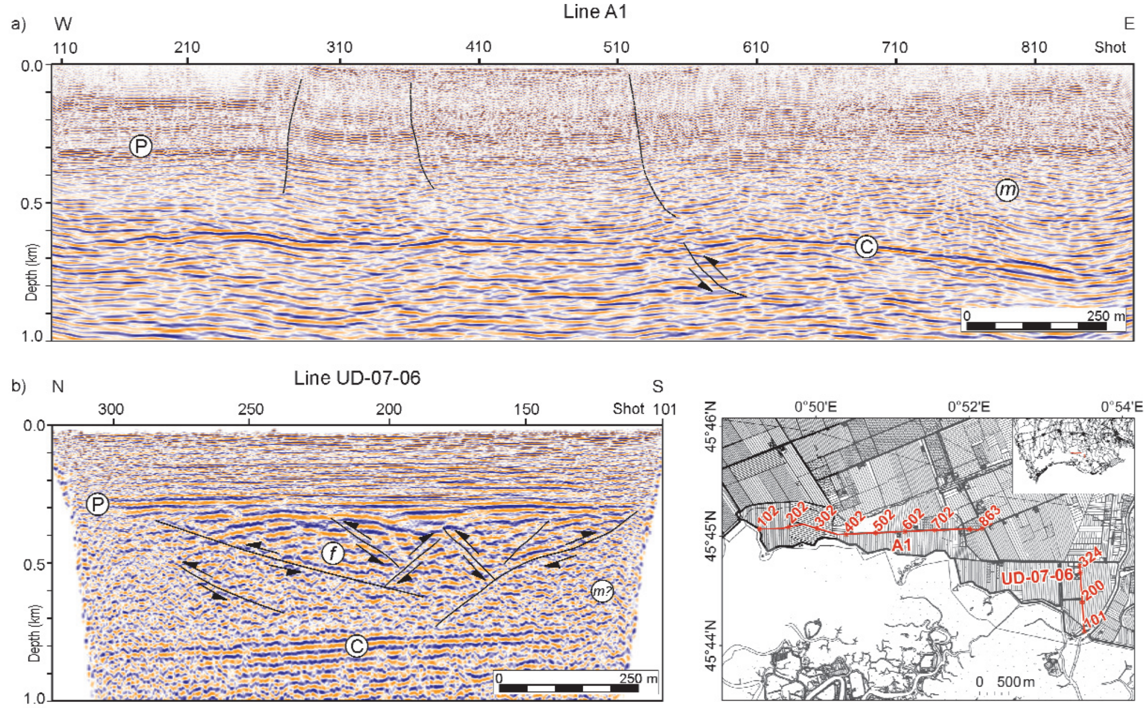

Fig. 5 - Onshore MC seismic profiles: a) the E-W line A1, recorded with explosive source and depth converted with pre-stack migration, and b) the N-S line UD-07-06, acquired with a mini-vibrator source, and depth converted. In Fig. 5a, "C" represents the carbonate, probably of Paleocene-Eocene age, cored at the same depth (about 600 m) in the Grado-1 well, but the presence of sandstones and conglomerates of the Cavanella formation (Late Oligocene – Middle Miocene) cannot be excluded; "m" indicates the Miocene deposits (Molassa) and "P" marks the base of the Plio-Quaternary sediments, on both profiles. The reflecting markers are gently folded, probably disrupted by a thrust fault on the eastern side and with two structural highs to the east and west, respectively, and accommodating a gentle structural depression in the middle between SP 300 and 550. In Fig. 5b, at 700-800 m depth, a high-amplitude horizon gently dipping northwards should represent the top of the carbonates "C". The sequence "f" is characterised by folds and faulted high-amplitude reflectors with a character similar to the Flysch units occurring offshore. The seismic facies of the interval between the carbonates and the Pliocene unconformity is quite different on the two seismic profiles, as the Flysch probably overthrusts the Molassa sequence "m" in an area located between the two profiles.

Gulf of Trieste with a NW-SE orientation, characterised by folds and SW-verging thrusts (Figs. 2 and 4). A more intense and recent deformation is present in the north-western part, where fault escarpments of about 30 m cut the Messinian/Early Pliocene erosional surface. The carbonates display a gentle fold about 4 km wide and possibly disrupted by a low angle fault (Fig. 4a).

Onshore, on the internal side of the lagoon, both seismic profiles, exhibit, a series of high-amplitude, subparallel horizons acoustically similar to the top of the carbonate in the offshore profile (Fig. 5) at a 600-800 m depth. These reflectors are probably the Paleocene-Eocene carbonates occurring in the Grado-1 well. In the 4 km long E-W pre-stack migrated line A1 (Fig. 5a), the horizons are gently folded and faulted, whereas in the 1.1 km long N-S UD-07-06 profile (Fig. 5b) these horizons are gently dipping northwards, without any deformation. The interval between the carbonates and the Pliocene unconformity presents different seismic

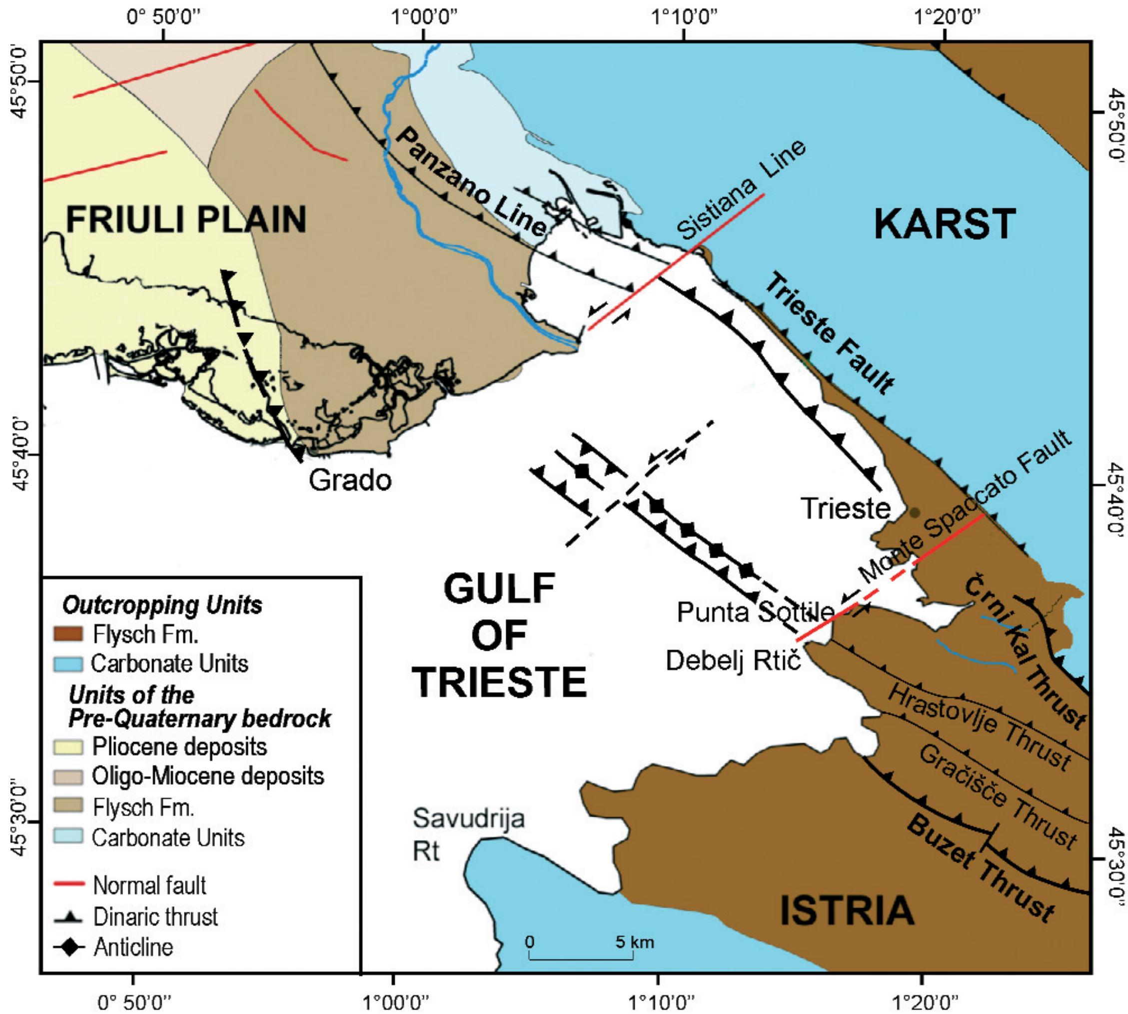

Fig. 6 - Tectonic sketch map of the Gulf of Trieste and surrounding areas with the Dinaric Thrust system and the NE-SW faults. See Fig. 1 for reference of onland geology.

characteristics along the two onshore profiles. On the A1 seismic line (Fig. 5a), the interval is characterized by low-amplitude and high-frequency reflectors, interrupted by gentle folds, faults and thrusts providing the occurrence of two structural highs in the eastern and western part, respectively, with a gentle structural low in the middle (between Shot Point 300 and 500). On profile UD-07-06 (Fig. 5b), the sequence above the carbonates is characterised by folds and faulted, high-amplitude reflectors, more similar to the Flysch sequence occurring offshore.

Above the carbonates, on the A1 seismic line, the sediments are deformed by gentle folds, faults and thrusts providing the occurrence of two structural highs in the eastern and western part, respectively, with a gentle structural low in the middle (between Shot Point 300 and 550).

5. Discussion

The eastern coast of the Gulf of Trieste represents the accommodation zone of the Karst Dinaric thrust system with an overall vertical component displacing the carbonate sequence of about 1400 m (Busetti *et al*., 2008). The Panzano Line was thought to continue offshore (Cavallin *et al*., 1978; Carulli *et al*., 1980; Carobene and Carulli, 1981; Carulli, 2006), approximately 4 km from the coast. No seismic evidence of significant thrusts exists offshore along the supposed prosecution of the Panzano Line. Instead, the main fault zone in the gulf is located from the Karst coastal front to 2-3 km offshore (Busetti *et al*., 2008). The Panzano Line and the Trieste Fault are shifted apart by 1-2 km by the NE-SW Sistiana Fault, a normal fault with a left transcurrent component (Fig. 6). The HR profiles close to the coast, show recent tectonic activity of thrusts with strands in the Flysch sequence, overthrusting the Late Quaternary unconsolidated sediments (Romeo, 2009).

The main tectonic feature deforming the Flysch sequence has a NW-SE orientation with thrust folds dipping NE and evidence of backthrusting in the northern part (Fig. 6). The Dinaric orientation and dip of the faults are the same as the NW-SE thrust fault of the Hrastovlje Thrust in Istria within the Flysch (Placer, 2005). As suggested by Busetti *et al*. (2008), the offshore compressional structure is linked to the onshore thrust. However, the tops of the hills on land have ~200 m of elevation while offshore the top of the Flysch lies at an ~120 m depth. The difference in elevation could be related to the NE-SW fault, located in the coastal area of Debelj Rtič and Punta Sottile, dissecting the onshore, from the offshore thrust fault. Its occurrence was hypothesized as the continuation along the Istria coast of the right transcurrent fault of Monte Spaccato in the Karst (Cavallin *et al*., 1978; Carobene and Carulli, 1981). In the Debelj Rtič and Punta Sottile area, the data confirm the main normal component of the fault, even if the right transcurrent component cannot not be excluded. Moreover, the ~1 km shift in the direction and the different pattern of deformation between the southern part (NW dipping thrusts) and the northern part (NW dipping thrusts and SE dipping backthrusts) suggest that the feature is probably segmented by a NE-SW transcurrent fault system, that separated two zones with different tectonic regimes. This hypothesis is also supported by the more intense internal deformation in the northern sector where the Plio-Quaternary tectonic activity produced faults with throws of up to 30 m at the Messinian/Early Pliocene erosional unconformity. In addition, the morphology of the top of the Flysch (Morelli and Mosetti, 1968) shows two highs in correspondence to the northern and southern part of the thrust respectively, that are separated by a valley. The valley could be further evidence of the hypothesized NE-SW fault.

Most of the faults in the Flysch sequence are not related to those in the carbonate one. This tectonic style suggests that the top of the underlying carbonates, gently folded and cut by low-angle faults, acted as a detachment surface for the Flysch deformation above (Busetti *et al*., 2008).

The onshore seismic profiles (Fig. 5) put in evidence the fact that the main tectonic deformation is associated to a thrust system, with faults in the carbonate and with overthrusting of the Flysch on the Miocene sediment. This thrust system is probably linked to those shown by the Grado-1 well, where both the Mesozoic and Eocene carbonates are fractured. We infer that the thrust system should represent the westernmost Dinaric frontal thrust, below the Friuli Plain.

6. Conclusion

The tectonic setting of the Gulf of Trieste is characterised by Dinaric thrust systems segmented by faults with NE-SW orientation and possible transcurrent components. The frontal thrusts are characterised by thrusts and folds in the Flysch with the detachment level coincident with the top of the carbonates, and low angle thrusts in the carbonates.

The tectonic features, present in the Gulf of Trieste and surrounding onshore areas, have been identified by analyzing seismic data sets. Three main Dinaric thrust systems occur (Fig. 6):

a) the Trieste Fault zone, located from the Karst coastal front to 2-3 km offshore , with an overall vertical component of about 1400 m (Busetti *et al*., 2008), connecting the Dinaric thrusts system of the eastern Friuli Plain to the Črni Kal Fault in Slovenia. The NE-SW Sistiana Fault, with a left transcurrent component, displaces the Panzano Fault which is NW by approximately 1-2 km from the Trieste Fault which is on the SE;
b) the thrust system in the Flysch, which crosses the Gulf of Trieste with Dinaric orientation and is connected with the Hrastovlje Thrust in Istria. The thrust system is probably offset by a NE-SW normal fault almost parallel to the eastern coast border, and by NE-SW faults located in the middle of the gulf, dividing the northern part characterized by thrusts, backthrusts and Plio-Quaternary tectonic activity, from the southern part characterized by thrusting and an overall less intense deformation;
c) the westernmost frontal Dinaric thrust across the Grado Lagoon limiting the Flysch basin to the west and probably overthrusting the Flysch units on the Molassa deposits.

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