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NEOTECTONIC REACTIVATION OF MESO-CENOZOIC STRUCTURES IN THE GULF OF TRIESTE AND ITS RELATIONSHIP WITH FLUID SEEPINGS

M. Busetti[1], F. Zgur[1], M. Vrabec[2], L. Facchin[1], C. Pelos[1], R. Romeo[1], L. Sormani[1], P. Slavec[3], I. Tomini[1], G. Visnovich[1], A. Zerial[3]
[1] *OGS - Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Italy*
[2] *Faculty of Natural Sciences and Engineering, University of Ljubljana, Slovenija*
[3] *Harpha Sea d.o.o. Koper, Slovenija*

Introduction. In 2005 and 2009 the Italian part of the Gulf of Trieste was investigated by geophysical survey, which provided insight into the deep structure and stratigraphy of the area, and also suggested the possibility of recent tectonic activity (Busetti *et al.*, 2010a, b). The existing survey was recently extended to Slovenian waters with the 2013 multichannel seismic and high resolution seismic data, collected in Italian - Slovenian collaboration. The complete datas*et al*lows the correlation of offshore geological structures with the structures that are exposed in the coastal part of the Istria peninsula. The seismic profiles provide evidences of not only of the deep structure, but also of neotectonic deformation that drives, along the main active fault zones, the migration of fluids, such as biogenic gas seeping and thermal springs.

Geological setting. The Gulf of Trieste and the surrounding coastal areas belong to the northern part of the Adriatic Foreland, consisting of the Mesozoic-Paleogene carbonate platform, overlaid by Eocene turbidites, and buried below the Plio-Quaternary marine and continental sediments of the Friuli Plain and the Northern Adriatic Sea.

During the Jurassic rifting the extensive carbonate platform of Triassic Dolomia Principale fragmented into separate paleogeographic units. In the Belluno Basin to the west, deepwater carbonates (Jurassic-Cretaceous) were deposited, followed by the Scaglia Alpina marly limestones (Eocene-lower Aptian), and Gallare Marls (Eocene) which filled the basin. In the east, the Friuli Carbonate Platform, a northern part of the Adriatic carbonate platform, persisted until Cretaceous.

In the Tertiary Dinaric and Alpine compressive phases, the carbonate platform was flexured and buried by Eocene turbidites (Flysch) and by Late Miocene continental and coastal Molassa deposits.

During the Messinian marine regression the subaerial exposure and erosion produced complex morphology with valleys and ridges. In the western part of the Gulf of Trieste, Pliocene marine progradation draped the Messinian erosional topography with marine sediments, followed by further regression in the Late Pliocene.

In the Pleistocene regression and transgression cycles, forced by glacial and interglacial periods, the alternation of marine, transitional and continental sediments was deposited (Busetti *et al.*, 2010a, b).

The pronounced NW-SE-trending structural grain of the area is defined by compressional structures of the Dinaric fold-and-thrust system. The main structure is the topographically prominent Dinaric frontal ramp, running along the north-eastern coast of the Gulf. Belonging to the same system structural system is the Palmanova Thrust in the Friuli Plain and its eastward continuation along the north-eastern boundary of the Istria Peninsula (Busetti *et al.*, 2010a, b; Placer *et al.*, 2010). The foredeep in front of the ramp has been inverted by compressional tectonic, with thrusts dissecting and deforming the Flysch, such as the Buzet and Buje thrusts that were mapped onshore (Placer *et al.*, 2010). The main detachment of this frontal thust system is following the contact of Flysch with the underlying carbonates (Busetti *et al.*, 2010a, b).

The seismic dataset. The offshore geology of the Gulf of Trieste has been investigated in several geophysical surveys. In the Italian part of the Gulf, in 2005 and 2009 were acquired 524 km of multichannel seismic (MCS) and high resolution Chirp profiles. The 2013 survey in Slovenian territorial waters, done in collaboration with the University of Ljubljana and the

Harpha Sea d.o.o. of Koper, acquired 132 km of multichannel seismic and 150 km of Chirp data (Fig. 1). All geophysical surveys were conducted with the R/V OGS Explora.

Major lithologic units in the subsurface were identified on seismic reflection profiles by Busetti *et al.* (2010a, b). Additional subsurface data were provided from the Grado-1 well,

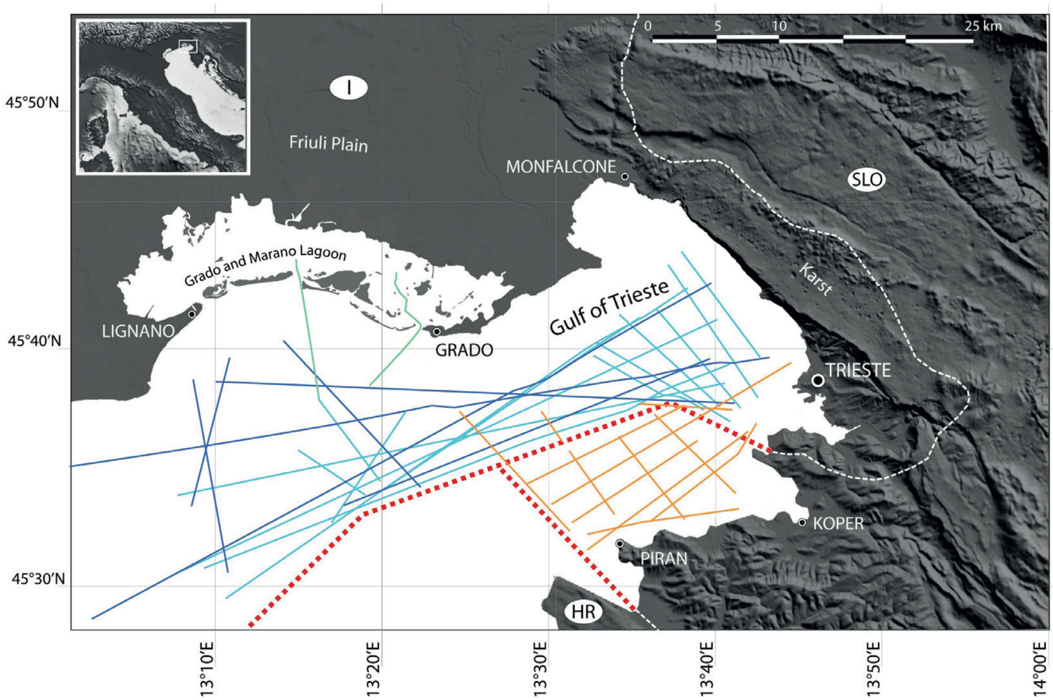

Fig. 1 – Position map of the multichannel seismic and high resolution Chirp data collected by N/R OGS Explora in 2005 (blu lines), in 2009 (light blue lines), and in 2013 (orange lines), for a total of 656 km. Dashed red lines are the offshore national borders.

drilled in 2008 for geothermal surveys on the northern coast of the Gulf (Della Vedova *et al.*, 2008; Cimolino *et al.*, 2010). The Grado-1 well recovered Upper Cretaceous platform carbonates from the well-bottom depth of 1108 up to 1007 m, and Paleogene carbonates from 1001 to 616,5 m. Those two units correspond to similar rocks outcropping in the Karst and Istria. Salty hot water at 42°C occur in two major fracture zones, encountered at 736-740 m, and from 1040 to the well bottom. Carbonates are followed by about 300 m of terrigenous sediment, interpreted to comprise 50-60 m of Eocene Flysch, followed by about 250 m of Miocene Molassa. The topmost sedimentary unit consists of Plio-Quaternary sediments with less than 300 m of thickness (Della Vedova *et al.*, 2008; Cimolino *et al.*, 2010).

Results and discussion. The main seismo-stratigraphic units and horizons interpreted from the multi-channel seismic profiles (MCS) are the Carnian Unconformity, the Meso-Cenozoic carbonates (Friuli Carbonate Platform in the east, and Scaglia in the west in Belluno basinal area), the Eocene turbidites of the Flysch, the Eocene Gallare Marls, the Pliocene progradation sequence and the Quaternary sediments of continental and marine origin (Busetti *et al.*, 2010a, b).

The Carnian Unconformity was encountered in the Amanda well (drilled offshore westward the study area) at 5340 m, and marks the base of the Late Triassic Dolomia Principale. The Carnian Unconformity is a well-known horizon in the seismic exploration data of the Friuli Plain, where it is considered to be one of the detachment levels of the thrusts (Poli and

Zanferrari, 2008). In the MCS collected in the gulf, the Carnian Unconformity is a prominent, well-defined reflector, and is also the lowest interpretable horizon, occurring at about 1.8 - 2.0 seconds.

The Friuli Carbonate Platform developed mainly in the Mesozoic. During the Paleogene, carbonate deposition occurred locally in intraplatform basins, as documented by the Grado-1 well that recovered about 400 meter of Paleogene limestones, similar to those present on land in the Karst and Istria (Cimolino *et al.*, 2010). On the seismic reflection profiles from our study area, several kilometres wide tectonically-controlled intraplatform basins occur, filled by well-stratified horizons (Fig. 2).

The Mesozoic extensional phase with NW-SE oriented extensional faults is still recognizable at the paleomargin of the carbonate platform, in the western part of the Gulf of Trieste. The tectonic structure of the margin-slope carbonate system is characterized by the master normal fault verging westward, associated with antithetic east-verging normal faults exhibiting block rotation and syntectonic sedimentation.

The south-westward propagation of the Dinaric thrust system that started in the late Cretaceous reached the study area in the Eocene. The foredeep of the External Dinarides thrust system was filled by the turbidites of the Eocene Flysch. Presently the Dinaric frontal ramp is located at the coastline, where it is called the Trieste Thrust, that involves both the carbonates and the overlying Flysch with a vertical component of displacement exceeding 1000 m (Busetti *et al*, 2010a, b). North-westward contination of this structure, covered by the Plio-Quaternary sediments of the Friuli Plain, is the Palmanova Thrust, that is separated from the Trieste Thrust by the sinistral Sistiana Fault. The Palmanova Thrust originated in the Dinaric thrusting episode and was subsequently reactivated as a frontal structure of the Late Cenozoic South Alpine thrust system (Poli and Zanferrari, 2008). South-eastward into Slovenia and Croatia, the Dinaric frontal ramp continues into the Črni Kal Thrust (Placer, 2008; Placer *et al.*, 2010).

The foredeep was affected by compressional tectonic, producing a series of folds and thrusts in approximately NW-SE orientation, with the detachment level at the top of carbonates (Busetti *et al.*, 2010a, b). A post-thrusting tectonic phase produced subvertical transpressional

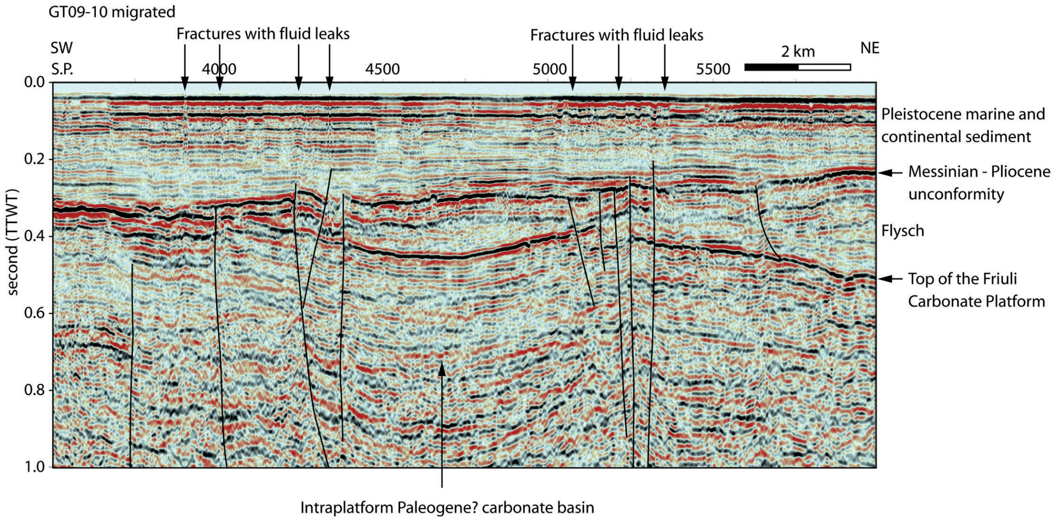

Fig. 2 – Multichannel seismic profiles across the intraplatform basin filled by Paleogene carbonate recovered in the Grado-1 well. The tectonically controlled basin is filled by well stratified limestones. In the post Miocene the faults were reactivated in a transpressional style. The fault strands disrupted the Messinian-Pliocene unconformity with 10-20 meter of vertical displacement. Above the fault zones, the Quaternary sediment have low amplitude signals, suggesting pervasive occurrence of fluids seeping through fracture zones.

faults, that cut the previous Dinaric thrusts, involving the Mesozoic carbonates, which produced a series of positive flower structures and related structural highs. Neotectonic activity of the flower structures is indicated by fault strands which displace the Messinian-Pliocene erosional surface at the top of the Flysch with several meters of throw. As suggested by Busetti *et al.* (2010a, b) these structures are the northwestward continuation of the Hrastovlje Thrust that deforms the outcropping Flysch in the Istria Peninsula in the foreland of the Dinaric Frontal Ramp (Placer *et al.*, 2010).

The newly acquired MCS dataset clearly shows that the structures outcropping along the southeastern coast of the Gulf of Trieste continue westward into the offshore area. For example, one of the most prominent structures is a several kilometers wide anticline in the carbonates, that corresponds to the Izola anticline, a small isolated limestone outcrop along the coast entirely surrounded by the Flysch (Fig. 3). Our seismic profiles show that the axis of the anticline continues into the gulf in the NW-SE direction and plunges moderately towards the NW. The conformably overlying Flysch layers on the top of the carbonates are affected by folding, and the anticline is covered by sub-horizontal Quaternary sediments, which demonstrates that the onset of folding postdates the deposition of the Flysch, and that the deformation terminated by the Quaternary.

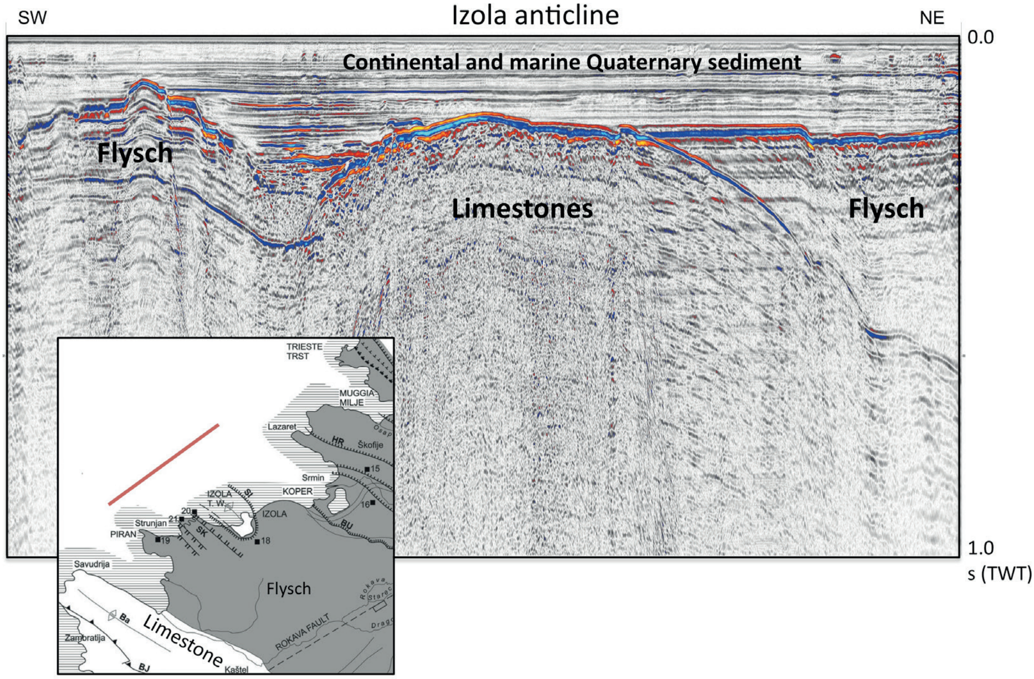

Fig. 3 – Brute stack of the multichannel seismic profiles acquired along the Istrian coasts, across the Izola Anticline. Inset map with onshore location of the Izola Anticline and the seismic profiles (red line).

Post-thrusting transpressional reactivation affected both the Mesozoic extensional faults at the paleoshelf margin and slope system of the carbonate platform, and the faults controlling the Paleogene intraplatform carbonate basins, as well as the Cenozoic thrusts and folds. These faults are subvertical and displace the Carnian Unconformity, and are associated with transpressional flower structures that deform the carbonates and the Eocene Flysch. Additionally, the fault strands clearly vertically offset the Pliocene Unconformity for several meters to several tens of meters. Weak deformation of the overlying marine and continental Quaternary sediments can also be inferred. We attribute this transpressional activity to the ongoing northward movement of the Adria microplate, well documented by GPS data (i.e. Weber *et al.*, 2010). In the Gulf of Trieste and its immediate surroundings, no historical records of local seismic events are known, and only low magnitude events (< M 4) with both shallow and deep hypocenters have been recorded by the Sismometric Network of the OGS, operating since 1977. However, the very modest seismic record may be influenced by the low deformation rate and/or long recurrence times of earthquakes.

Both the MCS and Chirp data show seismic evidence of fluid occurrences and migration in the Quaternary sediment covering the main fault zones (Fig. 2). These fluids can be related to either water or gas occurence, as the presence of both is well documented in the area.

Low enthalpy waters occur within the carbonates and constitute the geothermal reservoir of the region (Calore *et al.*, 1995). They are well known in the coastal Friuli Plain, were they are already used as geothermal resources. To further exploit the geothermal potential, the Grado-1 well was drilled in 2008. The well encountered thermal water in fractured carbonates at 42-45° C at depths between 736 and 740 meters, and from 1040 to downhole at 1108 meters (Della Vedova *et al.*, 2008; Cimolino *et al.*, 2010). Low-entalphy (about 40°C) natural springs of sulphurous-salty-alkaline waters (Doro, 1939) are present on land close to the northeastern coast of the gulf at the Roman Baths of Monfalcone, which are exploited since ancient times. The springs are located few meters below the plain, and are coming out along faults and karstic conduits. On the southeastern coast of the Gulf, close to the town of Izola, eight submarine thermal springs occur with temperature from 22 to 30°C (Žumer, 2004).

The low-frequency horizons in the carbonate sequence, seen in our multichannel seismic profiles, are usually considered as an indication of the presence of fluids. They may indicate the occurrences of salty low-enthalpy waters, belonging to the same reservoir system that was drilled in the Grado-1 well. The Izola hot springs are located close to the crest of the Izola anticline. This geological setting provides suitable conditions for the rising of the thermal water from the reservoir to the sea floor.

Fluid seepings from the sea floor, mainly related to gas, are also quite frequent in the Gulf. They are well known to the local population in the Northern Adriatic, as they favour the development of carbonatic concretions that form up to a few meters of relief on the seabed and are called *trezze* or *grebeni* by local population (Gordini *et al.*, 2004, 2010). High-resolution seismic data show the presence of biogenic gas pockets in surface sediments, which chemical analyses revealed that the gas consists primarily of methane (81-84%), nitrogen (15-18%) and oxygen (0.7-1.3%) (Gordini *et al.*, 2004, 2010).

In multichannel seismic profiles, up to several hundred metres wide areas with very low amplitude signals occur in the Quaternary sedimentary sequence. These low-amplitude areas may indicate the presence of fluids within the sediment. In Chirp profiles, fluid accumulation zones in the late Pleistocene sediments are characterized by transparent acoustic facies. Accumulations of fluids are usually associated with major fault zones occurring in the underlying pre-Quaternary carbonate and turbidite sequence, especially with the faults that indicate Quaternary activity. We therefore speculate that the origin of accumulations is related to fluid migration along the main fracture/fault zones.

Fluids can also rise up to the sea floor as plumes in the water column that were recorded in the Chirp profiles. Fluid seepings produce small relief forms on the seabed, such as the abovementioned *trezze* or *tegnue*, but also small mud volcanoes and small pockmarks a few meters in diameter. As already documented by Gordini *et al.* (2004, 2010) these resiliences are constituted mainly of methane of biogenic origin.

The fracture systems may therefore facilitate the migration of both deep and shallow fluids, that constitute of low enthalpy thermal waters in carbonates, as well as of gas, primarily methane, occurring in the Quaternary and Neogene sediments.

Conclusions. Interpretation of seismic data demonstrated a polyphase tectonic evolution of the area, which started by Mesozoic rifting and deposition of a several km thick carbonate succession, dissected by normal faults. During Cenozoic orogeny, the gulf area represented the frontal part of the SW-ward advancing Dinaric thrust system, and was initially buried by foredeep flysch sediments of Eocene age, then affected by thrusts in the final stage of Dinaric deformation. In Late Cenozoic continuing convergence of the Adriatic microplate towards Eurasia produced transpressional reactivation of the faults, which might be continuing into the present time, as seismic profiles have revealed that tectonic deformation is affecting the Quaternary marine and continental sediments. We found geophysical evidence of fluid migrations through the sedimentary units, that are spatially associated with major neotectonic fault zones. Neotectonic activity provides permeable fracture systems along which the fluids migrate. The fluids may come both from the low-enthalphy carbonate reservoir, as well as from the terrigenous sedimentary sequence bearing biogenic gas.

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