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Gas seeps linked to salt structures in the Central Adriatic Sea

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ABSTRACT

The analyses of about 800 km of Chirp sub-bottom profilers and 600 km^2 of Multibeam data acquired during the 2005 and 2007 surveys of the R/V OGS Explora, and their correlation with one new, and several public, multichannel seismic profiles, allow us to propose a relation between the distribution of gas seepages, fracture systems and deep salt features present in the Central Adriatic Sea. Gas seepage is evident from pockmarks on the seabed and in the shallow sub-bottom, where acoustic chimneys and bright spots have been highlighted and analyzed. The Mid-Adriatic Depression (MAD) is a distinct morphological feature in the Central Adriatic Sea elongated in a NE–SW direction. The area is affected by salt doming of Triassic evaporites which cause the two main alignments of the Mid-Adriatic Ridge as far as the Palagruza High and the Jabuka Ridge. These salt tectonics have existed since, at least, Paleogene times and are still active: they characterize sectors with less resistance to deformation produced by successive regional compressive regimes that have affected the area differently during the different geodynamic phases. Gas-seep features are distributed preferentially above and along the fracture systems produced above and around the salt mounds.

INTRODUCTION

The study area is characterized by fluid leaks testified by the presence of gas-related morphologies as pockmarks, mud volcanoes, mud-carbonate mounds. Seabed pockmarks are shallow, crater-like, cone-shaped depressions on the seafloor, related to focused fluid flows and generally found in permeable, fine-grained, soft sediments. Their formation could be associated to fluid escapes as gas eruptions, water escaping or hydrocarbon gas migration (King & MacLean, 1970; Hovland & Judd, 1988). They often occur in characteristic patterns and can be found along fault trends, which is a clear indication of fault leakage (Ligtenberg, 2005). Sometimes, pockmarks are reported in seismically active regions, where the seabed, according to Hovland & Judd (1988), is 'hydraulically active' due to the increase of deep fluid pressure before earthquakes. The presence of pockmarks in the Adriatic Sea was first reported by Van Straaten (1970) who misinterpreted them as erosional channels; successively, Stefanon (1981) hypothesized their presence and described the ones southeast of offshore Ancona (Central Adriatic Sea) and Stefanon *et al.* (1983) and Stefanon (1985) described those on the north-western Adriatic shelf. Several authors have described gas seepages in the Central Adriatic Sea (i.e., Curzi & Veggiani, 1985; Mazzotti *et al.*, 1987; Hovland & Curzi, 1989; Trincardi *et al.*, 2004) and documented the presence of free gas at very shallow stratigraphic levels. In the Mid-Adriatic Depression some authors (Curzi & Veggiani, 1985; Mazzotti *et al.*, 1987) have observed pockmark fields comparable to those located above the salt domes of the North Sea (Hovland & Judd, 1988) and also Fernandez-Puga *et al.* (2007) correlated gas-related morphologies with diapiric structures in the Gulf of Cadiz. Hovland & Judd (1988) highlighted the fact that the pockmarks, and associated subseabed columns of the Adriatic Sea periodically experience violent events, triggered by earthquakes.

The mud volcanoes are seafloor extrusions of mud accompanied by fluids, often by methane gas, which commonly tend to build up a solid mud deposit, which may have a conical or volcano-like shape (Hovland & Judd, 1988). The mud-carbonate mounds may have irregular, cylindrical or conical shape and are generally originated by carbonate concretions around seafloor release of methane (Kopf, 2002).

The aim of this paper is to identify the link between gas seepage features (such as pockmarks, mud volcanoes, mud-carbonate mounds) with the gas pulls present inner the sedimentary sequence (testified by gas chimneys and shallow bright spots) and with the deeper tectonic features as fractures and diapiric structures. The core composition, development, and distribution of these last have been pinpointed utilizing the multichannel seismic data (MCS). The relations of the diapiric structures with shallow effects on seabed morphologies have been analyzed with

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sub-bottom profiler data and swath Multibeam bathymetric data acquired by the R/V OGS Explora (Istituto Nazionale di Oceanografia e Geofisica Sperimentale).

REGIONAL GEOLOGICAL SETTING

The Adria block, nowadays located in the central part of the Mediterranean Sea, was part of the Tethyan margin during Mesozoic times. The Permian to Anisian sequences show siliciclastic beds or limestones and dolomites, interbedded by salt and gypsum deposits, calibrated by some Croatian wells and outcropping onshore Croatia (Grandic *et al.*, 2004). In Carnian-Norian times the main lithofacies in the periadriatic region were the Dolomia Principale/Burano Formations from the extensive tidal to the evaporitic platform. The Burano evaporites (mainly salt and anhydrite) are present mainly in the central and southern sectors of the Adriatic Sea (Mattavelli *et al.*, 1991), extending to onshore Umbria, Marche and southern Tuscany. In Middle Liassic times, the main Tethyan rift phase caused the break-up of the previously unique carbonate platform; this generated the intraplatform pelagic domain of the Umbria-Marche and South Adriatic Basins, filled by a carbonate sequence of Cretaceous–Paleogene age (Cati *et al.*, 1987) and separating the Dalmatian (also called Istrian or Adriatic) and the Apulian carbonate platforms, respectively, to the NE and to the SW (Fig. 1b). At the end of the Late Cretaceous, the Early Alpine compressive phase, generated by the major closure of the Tethys domain, induced the overthrusting of the Alpine Chain onto the Europe plate. During the Cenozoic, this compressive regime originated the Southern Alpine, the Dinaric (from Paleocene–Eocene times) and the Apennine (from Oligocene times) Chains. The Dinaric and Apennine fronts gradually migrated in a SW and a NE direction, respectively, toward the central axis of the Adriatic Sea (Channel *et al.*, 1979) determining the clastic sequences of the upper Eocene–Oligocene age; their frontal thrust are outlined in Fig. 1b, by Grandic *et al.* (1999) and by CNR-PFG (1991), respectively. During the Lower Pliocene, the eastward migration of the Apennine front induced the tilting of the Adriatic foreland below and in front of the orogenic front, determining the deposition of a variable Pliocene thickness (CNR-PFG, 1991) and of Quaternary prograding sequences. The upper south-east-ward prograding sequence, developing in the north-central Adriatic Sea, finally represents the Late Quaternary Low Stand Wedge, according to Trincardi *et al.* (2004).

The compressive tectonics often caused the inversion of some pre-existing normal faults (Argnani *et al.*, 1991; Calamita *et al.*, 2003) and the halokinetic activity of deep evaporite sequences from the Burano Formation and from the older Triassic evaporites, as described by Grandic *et al.* (1997) and by Finetti & Del Ben (2005). The so-produced diapiric structures, that deform the Mesozoic and Cenozoic sedimentary sequences, are very common in the Dalmatian carbonate Platform and in the pelagic domains, and are generally interpreted as being often joined to strike-slip movements (Grandic *et al.*, 1997, 1999; Finetti & Del Ben, 2005). A late orogenic north-west (NW)—south-east (SE) strike-slip faulting along the Dinaric-Hellenic side of the peri-Adriatic region, is hypothesized by Picha (2002), indicating the existence of escape tectonics. Furthermore, the evaporite sequences often represent the detachment surface of the thrusts, emphasizing the structural effect of both compressive and transcurrent tectonics. In the Central Adriatic Sea, halokinetic activity is the origin of the Jabuka Islet (Grandic *et al.*, 1999), carrying up to the subsurface the igneous rocks, that Balogh *et al.* (1994) interpreted as an ensialic intrusion of Upper Triassic age (about 200 Myr), during the extensional tectonics of the Tethys. These intrusions are a peculiarity of the Islands of Jabuka and Vis (CNR-PFG, 1991); on this last island, intrusions outcrop together with the evaporite sequence. On the base of some seismic reflection profiles, Herak *et al.* (2005) interpreted the Jabuka-Andrija fault and the Vis-Southern Adriatic fault as reverse tectonic structures elongated in a NW–SE direction (Fig. 1b); their computed fault plane solution for the March 2003 earthquake sequence shows an almost S–N direction of the compressive stress (Fig. 1a).

In the Central Adriatic Sea, an evident morphological feature is represented by the Meso-Adriatic Depression (MAD), also called Jabuka Trough or Pomo Trough or mid-Adriatic deep. It extends for about 125 km, between Sibenik (Croatia) and Pescara (Italy) in a NE–SW direction, with a maximum depth of 270 m (Fig. 1a). The morphology of the MAD is characterized by two main basins, about 260 m deep, separated by a high of about 190 m. This last belongs to the NW–SE trending Mid-Adriatic Ridge (MAR) of Finetti *et al.* (1987), also named Central Adriatic Deformation Belt by Argnani & Frugoni (1997). It corresponds to an alignment of structural highs, extending south-eastwards to the Palagruza High, also named Gallignani-Pelagosa ridge by Ridente & Trincardi (2006), and identified by Grandic *et al.* (1997) and Finetti & Del Ben (2005) as an halokinetic structure. The MAR has been interpreted as a forebulge by De Alteriis (1995) or as the result of compressive tectonics of the external Apennine (Argnani & Frugoni, 1997; Scrocca, 2006, 2007) or Dinaric (Finetti & Del Ben, 2005) Chains.

As the bathymetric map shows (Figs. 1a and 2), the MAD displays different escarpment morphologies: steeper to the north–west with a step of 140 m, and more gentle to the south–east. The northern margin of the MAD was correlated to the northern Adriatic coastline during the marine regression of the Last Glacial Maximum (Trincardi *et al.*, 1994). The present SE-margin, more or less parallel to the northwestern one, shows a more irregular slope, with complex tectonic systems and topography.

METHODOLOGIES

MCS reflection data

Hydrocarbon exploration of the Central Adriatic Sea has been carried out since the 1960s through seismic surveys

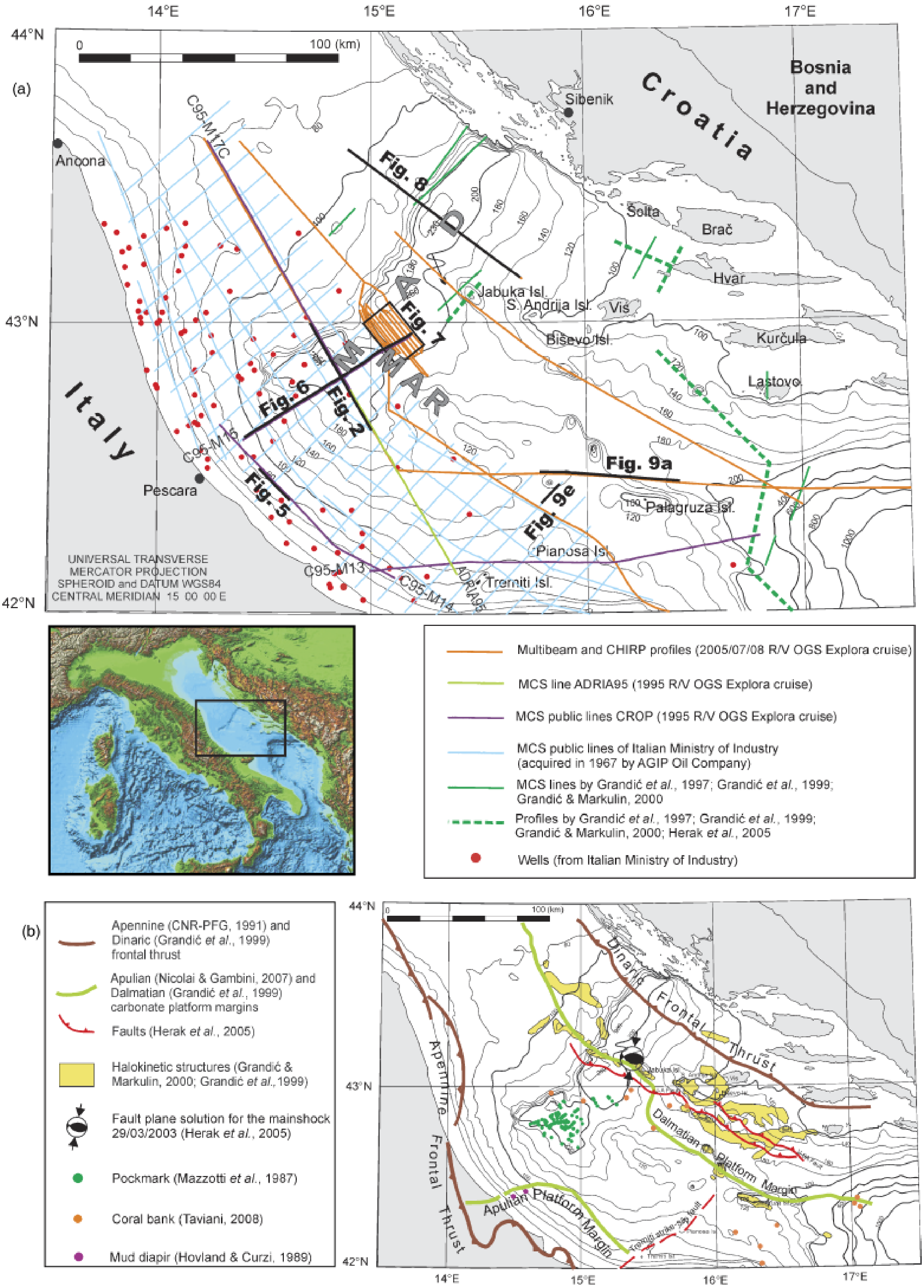

Fig. 1. (a) Bathymetric map of the Central Adriatic Sea and location of geophysical (MCS profiles, Chirp sub-bottom profiles and Multibeam) and well data used in this study. (b) Sketch map showing the main geological structural features (orogenic frontal thrust, halokinetic structures in the Croatian offshore and platform margins) and position of pockmarks and f deep-water coral banks described in literature.

and drillings (Mattavelli & Novelli, 1990). The first seismic data set (medium resolution – petroleum target) was acquired offshore the Italian Adriatic coast (public data set from the Italian Ministry of Industry), and many boreholes were drilled in different settings (Cati *et al.*, 1987; Mattavelli & Novelli, 1990). In 1995, about 800 km of deep crustal MCS profiles within the framework of the Italian Deep Crustal Exploration Project (CROP) (Scrocca *et al.*, 2003; Finetti, 2005), and of 100 km of the, till now, unprocessed ADRIA95 profile, were collected in the Adriatic Sea (Fig. 1a) by the R/V OGS Explora (Istituto Nazionale di Oceanografia e di Geofisica Sperimentale). The acquisition parameters of the CROP and of the ADRIA95 profiles (Table 1) were designed for deep crustal exploration (frequency from 15 to 35–40 Hz).

The Croatian offshore has been investigated by a detailed seismic network and boreholes acquired by INA-Naftaplin for hydrocarbon exploration. These data were discussed and partially published (see location on Fig. 1a) by Grandic *et al.* (1997, 1999, 2004), Grandic & Markulin (2000).

As part of the present study, a specific processing flow was applied to the original field of the northern part of the ADRIA95 profile (Fig. 3), in order to highlight the presence of seismic anomalies such as velocity and polarity inversions linked to bright spots, acoustic chimneys and salt layers (Fig. 4). The main steps of the processing sequence applied to the profile (Table 2), using the seismic processing software Focus™ by Paradigm™ are:

- the best possible preservation of the relative amplitude of the seismic data in the prestack analysis with accurate gain-curve application to identify amplitude variation with offset that is a diagnostic element for gas–fluid recognition;
- advanced stacking velocity analysis on each horizon of interest (i.e. bright spots, phase inversion), by the iterative method, in Normal and Dip Move Out corrections (Yilmaz, 2001); the interval velocities are derived by stack velocity using the Dix formula (Dix, 1955). Also prestack, partial time migration using the DMO correction was applied to produce real geometries (Yilmaz, 2001). Considering the vertical resolution of the data, the frequency of vertical picking in the velocity analysis is the most accurate possible, with an interval picking of 50–100 ms, except in the semi-transparent zone (Fig. 4a and b) where only a few faint events can be highlighted.
- evaluation of the presence of gas pulls, on the basis of the fall of the seismic velocity, for even a small percentage of free gas, in the pore spaces (Domenico, 1977): this produces strong reflection zones, also called 'bright spots', testifying to the presence of gas accumulations (Taner *et al.*, 1979, 1994); reflection strength, also known as instantaneous amplitude or envelope amplitude (Taner & Sheriff, 1977), providing a display independent by the phase, has been utilized to this purpose.

Table 1. MCS recording parameters of the CROP (Scrocca *et al.*, 2003; Finetti, 2005) and ADRIA95 profiles, acquired in 1995 by the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS)

Acquisition parameters
Operators R/V OGS explora
Time period 1995
Group interval 25 m
Shot interval 50 m
Source type air-guns (32U) 77 lt
Number of groups 180
Recording System Sercel SN 358 DMX
Coverage 4500%
Record length 17 000 ms
Streamer length 4500 m
Sampling rate 4 ms
Streamer depth 12 m

Chirp sub-bottom echosounder

During the R/V OGS Explora 2005 and 2007 surveys, about 800 km of Chirp sub-bottom profile data were acquired in the studied area (Fig. 1a), using the Benthos CAP 6600 echosounder with 16 transducers and a sweep-modulated bandwidth from 2 to 7 kHz. Absorption compensation and the Hilbert filter application are automatically applied by the system. The output corresponds to very high-resolution reflection strength profilers. The Chirp profiles yield a detailed image of the structures up to about 80 m of sediments depending on lithology and on seafloor dip. The vertical and horizontal resolutions of these data are, respectively, about 1 and 4 m considering a depth of 200 m and a velocity of 1550 m s^{-1}.

Swath bathymetric data

At the same time as the recording the Chirp profiles, about 600 km^2 of swath morpho-bathymetry data (Fig. 1a) were acquired by the Multibeam echosounder Reson Seabat 8111 with a frequency of 100 kHz. The recorded data were depth-converted using the seawater velocity functions obtained by the Sound Velocity Probe (Reson SVP 25).

RESULTS

Stratigraphy and seismic-stratigraphic analysis

Previous seismo-stratigraphic analyses, performed on the MCS profiles and controlled by several boreholes (by the Italian *Ministry of Industry*, Fig. 1a) have provide the basis for an interpretation of the major units seen in the data presented here. The acoustic characteristics of these main units visible in Figs 2, 5 and 6, are summarized below and explained in the context of the existing literature. This provides the framework for the next section 'Deep Fea-

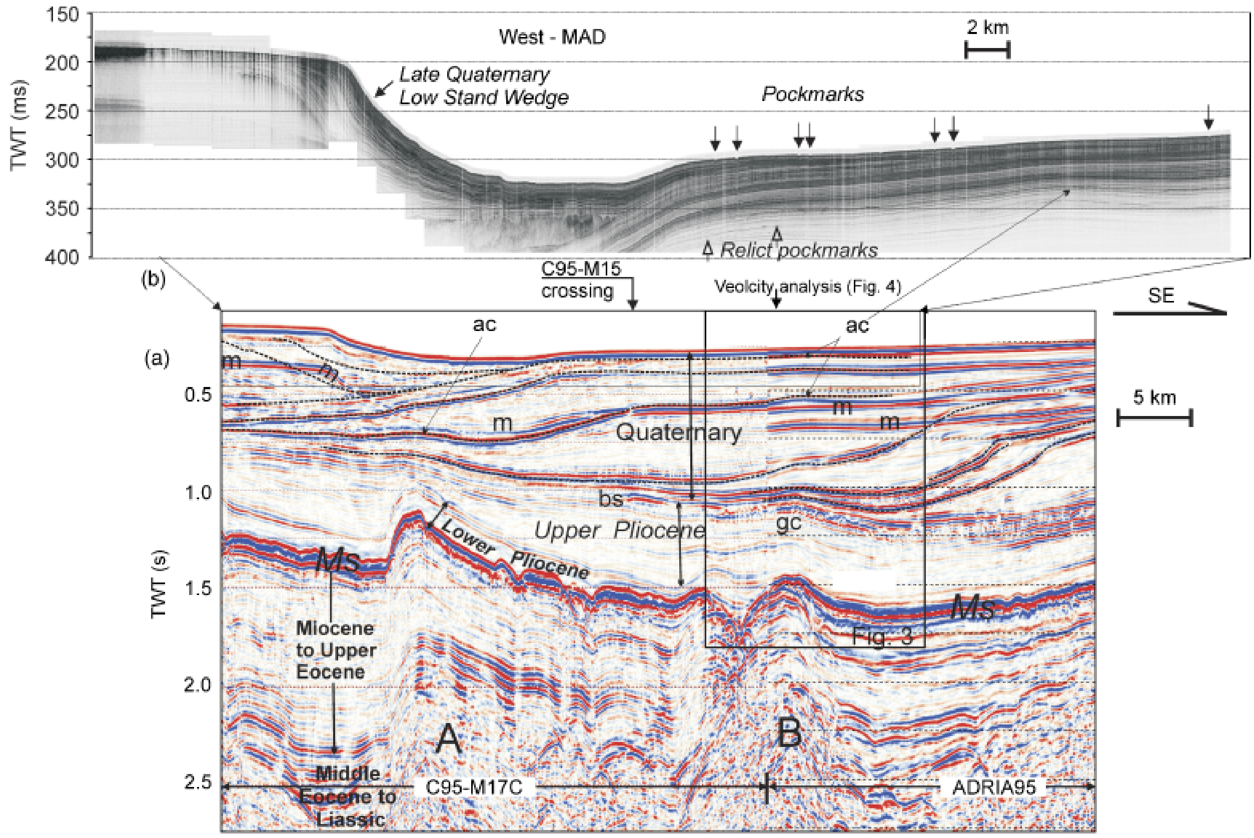

Fig. 2. (a) South-eastern part of C95-M17C and North-western part of ADRIA95 seismic profiles, crossing the study area in a NW–SE direction (position in Fig. 1): the Quaternary deeper NW-ward and shallower SE-ward prograding sequences, characterizing respectively, the southern and the northern margins of the Mid-Adriatic Depression, are highlighted by dotted lines; 'm' labels multiple reflections; the strongest reflector (Ms) at about 1,5 s two-way travel-time (TWT) is the Messinian evaporites event that highlights the deformation originated by the Triassic salt structures indicated 'A' and 'B'. Also, the Quaternary sediments are weakly deformed by a persistent uplift of the diapirs, as testified by the gentle anticlines (ac) produced by diapirs, involving the gas distribution brought in evidence by bright spots (bs) and gas chimneys (gc). The Chirp sub-bottom profile (b) is located in the same position as the seismic data in (a); along the South–eastern margin some pockmarks are evident on the seafloor and inside the recently deformed plastic sediments, above the uplifting salt bodies depicted in the seismic profile in a) and in greater detail in the Chirp profile (see undulations at about 0.35 s of depth).

tures' which focuses on the relationships between gas seeps, fractures and deep structures.

The main units are as follows:

- The Permian-Middle Triassic sequence is the lowest unit considered. It often shows seismically well-stratified beds (P-MT in Fig. 5). On the base of the Puglia-1 well (Butler *et al.*, 2004) these are though to be continental to transitional argillites and sandstones. The Alessandra-1 well penetrates about 800 m of Lower Triassic shaly sequence (Patacca *et al.*, 2008), previously interpreted by Bally *et al.* (1986) as Upper Permian red clastics. Their low velocity (3900 m s^{-1}, Bally *et al.*, 1986) originates a high impedance contrast with the overlaying sequence and the often clear reflector on the top. Offshore of Croatia the coeval sequences of tidal-subtidal limestones and dolomites are interbedded by salt and gypsum deposits (Grandic *et al.*, 1999).
- The overlying, shallow water carbonates, developed in the main part of the studied area. The lower, Norian-Rhaetian part of the sequence is dominated, in the Central-South Adriatic Basin and in the offshore of central Apennine, by the Burano Anhydrite (Martinis & Pieri, 1963), often representing a decollement zone in the Apennine and Dinaric Chains. In the Alessandra-1 well the Burano Anhydrite is substituted by Giurassic-Triassic dolomites with an interval velocity of 6000 m s^{-1} (Bally *et al.*, 1986). This shallow water domain, recognizable through a semi-transparent seismic facies in all the Adriatic Basin (Cati *et al.*, 1987; Grandic *et al.*, 1999; Finetti & Del Ben, 2005), is topped by a high amplitude reflector (Fig. 5). It persisted until the Tertiary time on the Apulian and Dalmatian carbonate platforms and until the Liassic time between them.
- Since the Liassic, a pelagic domain developed between the Apulian and the Dalmatian carbonate platforms. This basin, filled by Liassic to Middle Eocene carbonate muds, marls and cherts (Cati *et al.*, 1987; Zappaterra, 1990; Mattavelli *et al.*, 1991; Grandic *et al.*, 1999), is seismically associated to a package with high-amplitude, subparallel internal geometry (Figs 2, 5 and 6).

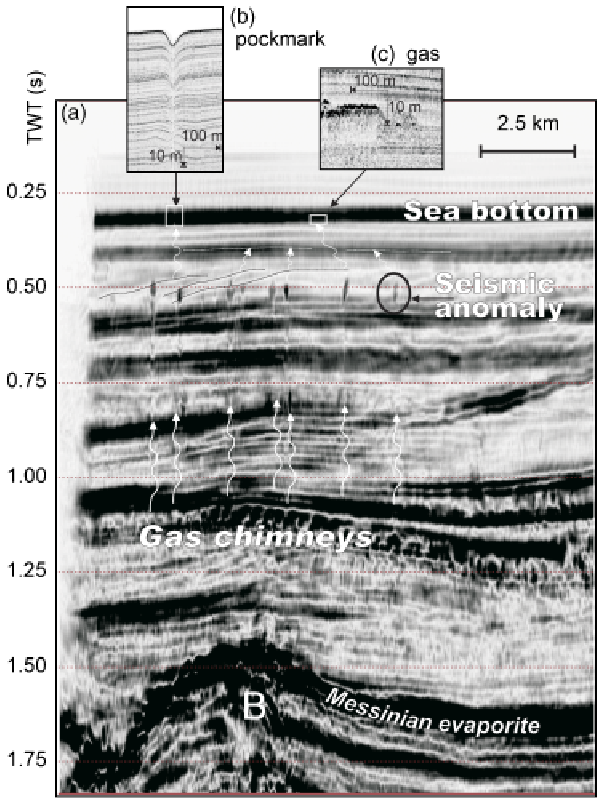

Fig. 3. Detail of ADRIA95 seismic profile of Fig. 2. (a) the reflection strength of the migrated section: high-amplitude events (seismic anomalies) and gas chimneys above the top of the salt structure 'B' (the same of Fig. 2) are highlighted by complex attribute analysis. The sub-vertical alignments of these seismic anomalies with their acoustic caps at the top (0.4–0.5 s TWT) suggest up-ward gas/fluid-migration through fractures. (b) A pockmark (about 80 m wide and between 8 and 10 m deep) is shown in the Chirp data acquired during the 2007 OGS Explora cruise in the same position as the seismic profile. Presence of gas in the sub-seafloor is suggested by very high-amplitude reflection strength events and underlying acoustic blank zones in the Chirp data, as the example in (c).

- The carbonate pelagic sequences were gradually replaced by flysch and coarse clastic sequences originated by the surrounding orogenic systems (Mattavelli *et al.*, 1991); this is characterized by low-frequency, continuous reflectors of, generally medium amplitude, topped by the strong package of the Messinian 'Gessoso Solfifera'. This last, constituted by a few tens of meters of evaporites, representing a relatively short episode of sea-level fall, is typically used as a good seismic marker for its high-amplitude reflection (Ryan *et al.*, 1971).
- The platform margins are regionally depicted in Fig. 1b, and are well evident along the seismic profiles of the Apulian (Fig. 5; see also Finetti & Del Ben, 2005; Nicolai & Gambini, 2007) and Croatian (Grandic *et al.*, 1999; Del Ben, 2002; Finetti & Del Ben, 2005) offshore by means of characteristic carbonate build-up structures (Bubb & Hatlelid, 1977). The top Messinian reflector clearly describes the Pliocene westward

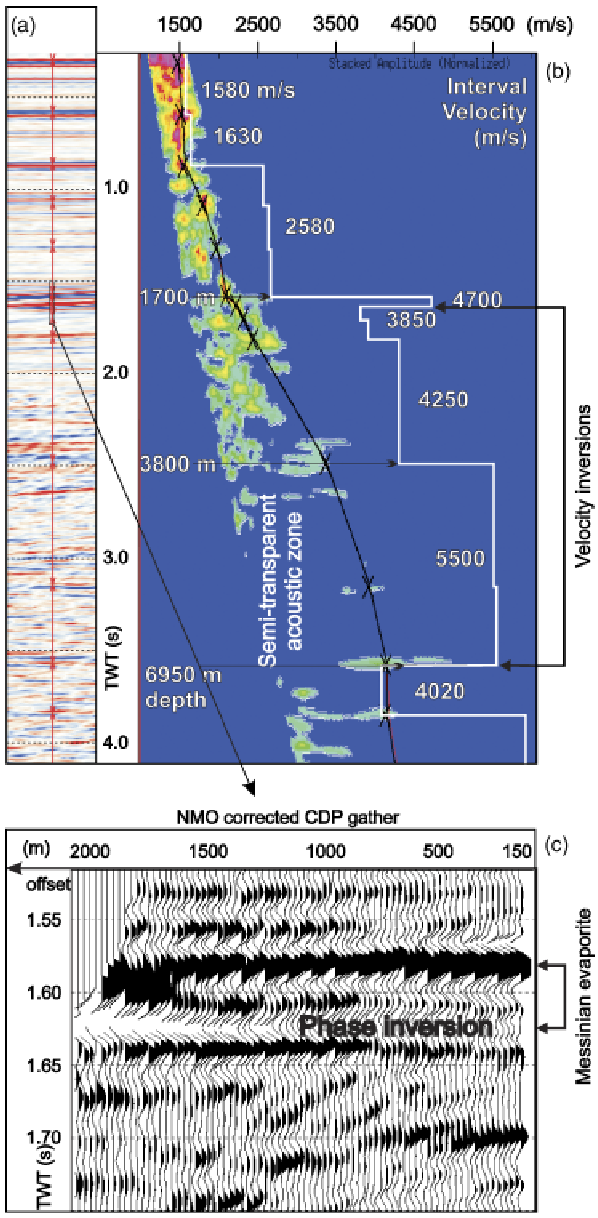

Fig. 4. Velocity analysis on the ADRIA95 seismic line on Common Depth Point (CDP) gather where the deep reflectors show the salt deformation (see Fig. 2 for position): (a) stack test relating to velocity function obtained from the semblance coherence map picking (Yilmaz, 2001) on (b): the interval velocity diagram (white line), calculated applying the Dix formula (Dix, 1955), shows two velocity inversions: one at the base of the Messinian evaporitic event (1.65 s) and the other at about 3.5 s, interpreted as the base of the Triassic salt sequence. The interval velocity calculated for the diapir structure was about 5500 m s^{-1}, for a thickness of 3150 m. (c) Detail of the Messinian events on the central CDP gather of the stack in (a) after NMO correction and the corresponding semblance contour, representing the coherence of the stacking velocity. The thickness of the Messinian sequence is about 50 ms (near the limit of the vertical resolution) and the wavelet phase inversion on the base of the high velocity (4700 m s^{-1}) of the evaporitic layers is evident. Below it, a sharp increase of the seismic velocity characterizes the top of the uplifted Triassic salt (b).

Table 2. MCS processing flowchart applied to the ADRIA95 profile showed in Fig. 3

Main processing sequence
Spherical divergence correction
Preliminary velocity analysis
DMO correction procedure
Velocity analysis
NMO correction
Stacking (45-fold)
Time migration
Hilbert transform

subsiding Adriatic foreland (Fig. 5 on the left part) outside the Apennine front. The overlying Pliocene sequence, reaching about 1200 m, thins towards the Central Adriatic Sea. It is constituted by clayey, silty and sandy turbidites (Mattavelli *et al.*, 1991) characterized by some continuous reflectors onlapping the tilted pre-Pliocene sequence.

- The Pleistocene level is represented by thick, prograding sediments with a well-developed topset-clinoform package, with clear offlap breaks (as in Emery & Myers, 1996) north-migrating for some tens of kilometers, and sigmoidal-clinoform high-amplitude reflectors (Figs 2 and 5 on the left).
- Finally, the NW margin of the MAD highlights the presence of the Low Stand Wedge (Trincardi *et al.*, 2004), well described by the Chirp and also by the MCS data (Fig. 2): it is characterized by prograding, high-frequency, medium-amplitude reflectors deposited in a SE direction, SE thinning and quickly vanishing along the slope and in the actual depocenter of the basin. The Late Quaternary Low Stand Wedge characterizes the morphology of all the NW margin of the MAD with a step of about 130 m, overlying the NW-ward prograding sequence of Pleistocene age.

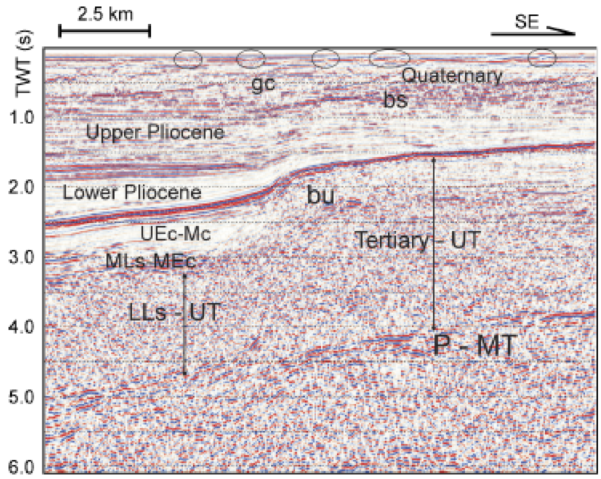

Fig. 5. Detail of C95-M14 seismic profile crossing the study area with a NW–SE direction (position on Fig. 1a). The margin of the Apulian carbonate platform is clearly evident by the typical features (Sheriff, 1980): the build-up structure (bu), separating the semi-transparent seismic facies of the carbonate platform on the right from the coeval pelagic sequence on the left. This last is represented by the medium amplitude reflectors of Upper Eocene-Miocene times (UEc-Mc) on the high amplitude reflectors of Middle Liassic-Middle Eocene times (MLs-MEc). Both the two different domains are underlying by the carbonate sequence of Lower Liassic-Upper Triassic times (LLs-UT) and by the deeper, seismically well-stratified Permo-Middle Triassic carbonate sequence (P-MT). In the Plio-Quaternary sequence typical features as bright spots (bs) and gas chimneys (gc) testify the presence of gas pulls. The irregular morphologies of the seafloor highlighted by circles could be joined to gas escape producing the mud reliefs showed in the same position, along Chirp profiles, by Hovland & Curzi (1989) and Trincardi *et al.* (2004).

Deep features

The Central Adriatic Basin is characterized by the presence of some deep, high features generally deforming the Cenozoic sequence. They are notably evident along the MCS profiles through the undulation and faulting of the Messinian layer and by undulation and piercement of the pre-Messinian layers (i.e. A and B structures in Fig. 2 and C, D, A and E structures in Fig. 6). These features are commonly interpreted as salt structures generated by the uplift of the evaporite sequences (Mattavelli *et al.*, 1991; De Alteriis, 1995; Finetti & Del Ben, 2005) on the base of the recognizing of the typical features associated to salt mobility (Jenyon, 1986). On the interpreted seismic data set the top of the salt rocks are hardly recognizable because generally the upper Meso-Cenozoic sedimentary cover depletes the lower deep seismic signal. The base of the evaporite sequence is still further depleted because of the high acoustic absorption of the lithology. Owing to these intrinsic complexities the ascription of the deep features to salt structures has never been approached in detail in the literature of the Adriatic Sea, so we have devoted an analysis to a sample of them along the ADRIA95 profile.

Composition of the diapirs

The velocity functions produced during the processing phases provide details of two clear velocity inversions (Fig. 4b). The upper inversion occurs at about 1.63 s TWT (Fig. 4b and c), where the interval velocity drops from 4700 m s^{-1} of the Messinian evaporite thickness to 3850 m s^{-1} of the underlying pre-Messinian layers. Below the pre-Messinian weakly stratified sequence (about 0.85 s TWT), the velocity rises to 5500 m s^{-1}; at 3.6 s TWT the lower inversion occurs where interval velocity drops to about 4020 m s^{-1}, in good agreement with the velocity of about 3900 m s^{-1} of the Permian sandstones by Bally *et al.* (1986). On the basis of the so-calculated interval velocities and considering the approximation due to the velocity–depth ambiguity (Yilmaz, 2001), the depth of this seismic event can be estimated at about 6950 m, in according to the depth of the Triassic evaporitic base interpreted by Mattavelli *et al.* (1991) on the West Central Adriatic profile.

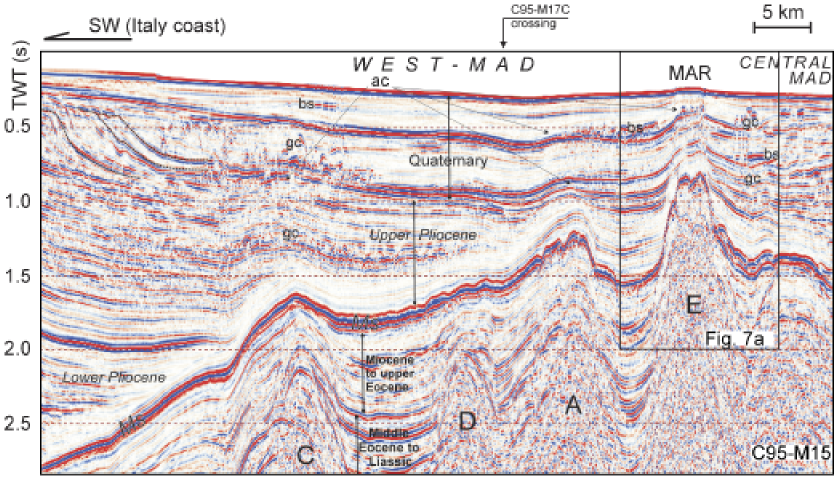

Fig. 6. C95-M15 seismic profile crossing the study area with a SW–NE direction (position on Fig. 1a). The highest amplitude package of horizons is the Messinian evaporites (Ms). The pre-Messinian sequence is SW-ward tilted below the front of the Apennine Chain located onshore, and overlain by the Pliocene foredeep deposition. The Quaternary prograding sequences, coming from the Apennines, are highlighted by dotted lines. Typical evidence of gas presence such as bright spots (bs) and acoustic chimneys (gc) are outlined. The Triassic salt structures C, D, A and E have been uplifting, at least, since Neogene times (the pre-Messinian reflectors are more deformed than the post-Messinian) and partially continue to the Present, as testified by the seafloor deformation above the Mid-Adriatic Ridge (MAR), separating the West and the Central sub-basins of the MAD.

The 5500 m s^{-1} sequence corresponds to a semi-transparent seismic facies with typical lack or scarcity of reflectors inside anticlinal structures (Fig. 2). The lateral boundaries of the diapir B are weakly recognizable in Fig. 2, mainly by the transition to the stratified sequences of sediments which are deformed and pierced by the evaporitic body. By analogy, therefore, we infer that the other similar structures of the studied area, are salt domes (i.e., positive structures A, B, C, D and E in Figs 2 and 5). Generally, above these features there is a strong deformation for the pre-Messinian sedimentary cover and a weaker one with variable intensity for the Plio-Quaternary sediments, sometimes reaching the sea bottom, as along the MAR (Fig. 7) and in the Jabuka structure (crossed by a seismic profile of Grandic *et al*., 1999).

Halokinetics

The C95-M17C, C95-M15, ADRIA95 and the public seismic profiles have been analyzed relative to the effects of the salt bodies on the Plio-Quaternary sedimentation/deformation and to the seafloor morphologies. The first deformation phase seems to have begun in pre-Pliocene times as suggested by the deformation of the pre-Messinian sequences being stronger than the Plio-Pleistocene one (see Fig. 6). The activity continued throughout the Pliocene, especially in some diapirs (as the one corresponding to MAR) up to the present, as highlighted by the deformation of the more recent sediments and of the seafloor. In the northern margin of the eastern MAD, the morphology along the Chirp profile (Fig. 8) depicts a structural high with tilted and fractured horizons and some normal faults that we have attributed to a halokinetic origin, on the base of the diapiric structure described by Grandic *et al*. (1999) in the same area (Fig. 1b).

Spatial distribution of the salt structures

The salt structures have typical widths of 5–10 km and turn out to be mainly placed on the MAR (Fig. 10), SE-ward continuing into the Palagruza High (Fig. 9), and along the Dalmatian Platform Margin. The Island of Jabuka, located on the South-Eastern margin of the MAD and constituted by magmatic rocks uplifted by halokinetic tectonics (Grandic *et al*., 2004), belongs to this last alignment, here called Jabuka Ridge. Other minor salt structures have been interpreted on the offshore Italy (Fig. 10): they seem generally connected to thrust faults, mainly active during the Upper Pliocene time.

The 3D interpretation of the structure A (Figs 2 and 10) shows an ENE–WSW direction, also locally recognized by the F structure in Fig. 10 and by the diapir G (Fig. 10) by Grandic & Markulin (2000). This direction crosses the main NW–SE regional trend and is the same of the Tremiti strike-slip fault, already associated to a halokinetic activity (Finetti & Del Ben, 2005).

Carbonate platform margins

In the studied area, the carbonate platform margins represent deep features, highlighted by build-up structures along the seismic profiles. They separate the semi-transparent seismic facies of the carbonate platform from the coeval stratified pelagic sequence. The overlying Plio-Quaternary cover is often interested by differential compaction over the reef (Sheriff, 1980): this produces anticline structures favoring the gas accumulation. Bright spots and gas chimneys above the platform margins, could easily cause gas-related morphologies, as seems to be suggested by the mud reliefs showed by Hovland & Curzi (1989) and Trincardi *et al*. (2004) on the offshore Ortona,

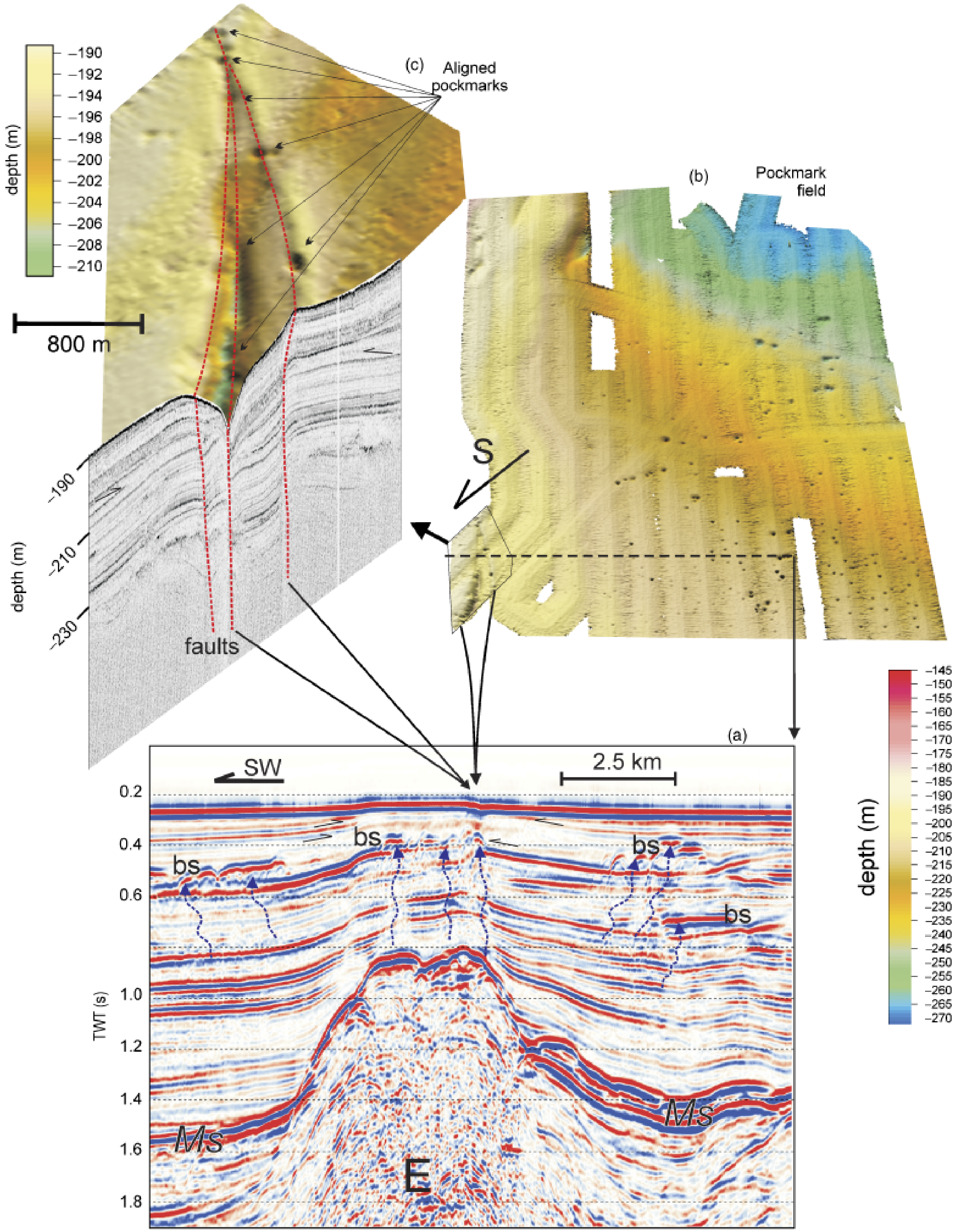

Fig. 7. Integrated geophysical methodologies applied to the study area: their different resolution and penetration allow us to correlate the sea bottom and shallow features with deeper structures. The detail of the C95-M15 profile (a) shows that, above the salt structure that gives origin to the Mid-Adriatic Ridge (MAR), several bright spots (bs) at the top of the fracture systems indicate gas/fluid escaping (blue arrows), producing pockmark fields pointed out in the Multibeam (b) and Chirp sub- bottom (c) data. (c) A pockmarks alignment along an active fault, on the margin between the MAR and the Central Adriatic Sea, is shown. (a and c) The pinch-out geometries (black thin arrows) of the upper sediments, also confirm the persistent activity of the salt structure.

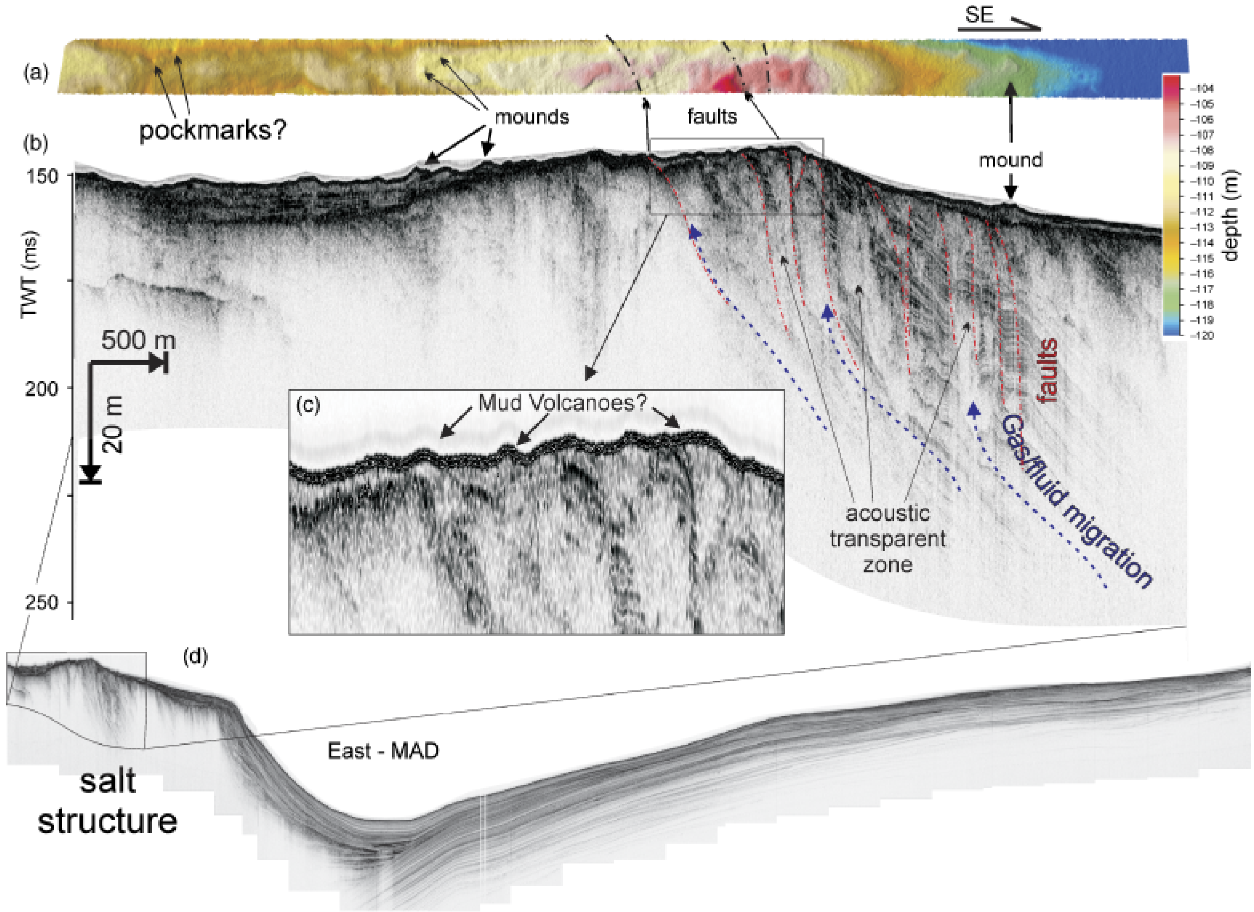

Fig. 8. Multibeam data (a) and Chirp sub-bottom profile (b) crossing the East-MAD in a NW-SE direction (see position in Fig. 1a). According to Grandic & Markulin (2000) the northern margin of the MAD is here located above a diapiric structure (see Fig. 1b), causing deformation and fracture system of the Quaternary prograding sequence. Across these fractures the gas leaks give origin to mounds (mud volcanoes and/or carbonate mounds) and pockmarks, especially diffuse in the upper margin as depicted in (b) and more detailed in (c). The regional Chirp profile (d) shows both the margins of the East-MAD.

above the North margin of the Apulian carbonate platform (Fig. 5).

SEISMIC AND MORPHO-BATHYMETRIC EXPRESSIONS OF FLUID MIGRATION

Nature of the evidence for fluids

In the MCS profiles, within the Plio-Quaternary deposits, the presence of gas can be deduced by several bright spots (strong wavelet phase inversion and high-amplitude reflection strength), the most common seismic gas indicators, which can often be found at the top of acoustic chimneys (Figs 3 and 6). Both the bright spots and the acoustic chimneys are mainly distributed above and around the diapirs, as evident in the seismic data set (i.e., Fig. 6). In Fig. 3a, the path of a swarm of acoustic chimneys above a diapir, becomes well defined from about 0.4 s down to 1 s deep, where caps with a high-amplitude, seismic wavelet characterize their tops. These caps, located at the same depth, even if in different clinoform layers, are probably gas pulls. This acoustic signature is typical of the presence of shallow gas (Judd & Hovland, 2007) and thus a gas-rich fluid is the most likely fluid source at the origin of the pockmarks. Other potential origins for amplitude anomalies can be (1) presence of CO_2 in the rocks, that reduces the V_P even for moderate saturation (Arts *et al.*, 2004), (2) interference of reflections from the top and the bottom of a thinning unit (Anstey, 1977), presence of (3) coal and lignite beds, (4) low-velocity shales (Jeffrey *et al.*, 2007), (5) volcanic ash (Friedman, 2006) that display a decrease in the sonic and density curves, or (6) channel-base gravels (Sharp & Samuel, 2004) However, the frequent occurrence of gas in the Plio-Quaternary sequence is well-known from several wells and gas fields in the Adriatic Sea (Mattavelli *et al.*, 1991) and we favor this explanation.

Association of the fluids and recent deformation

The Chirp and MB data have often allowed us to recognize a recent deformation of old, deep structures interpreted on the MCS profile: e.g. in Fig. 2, we can see how the salt

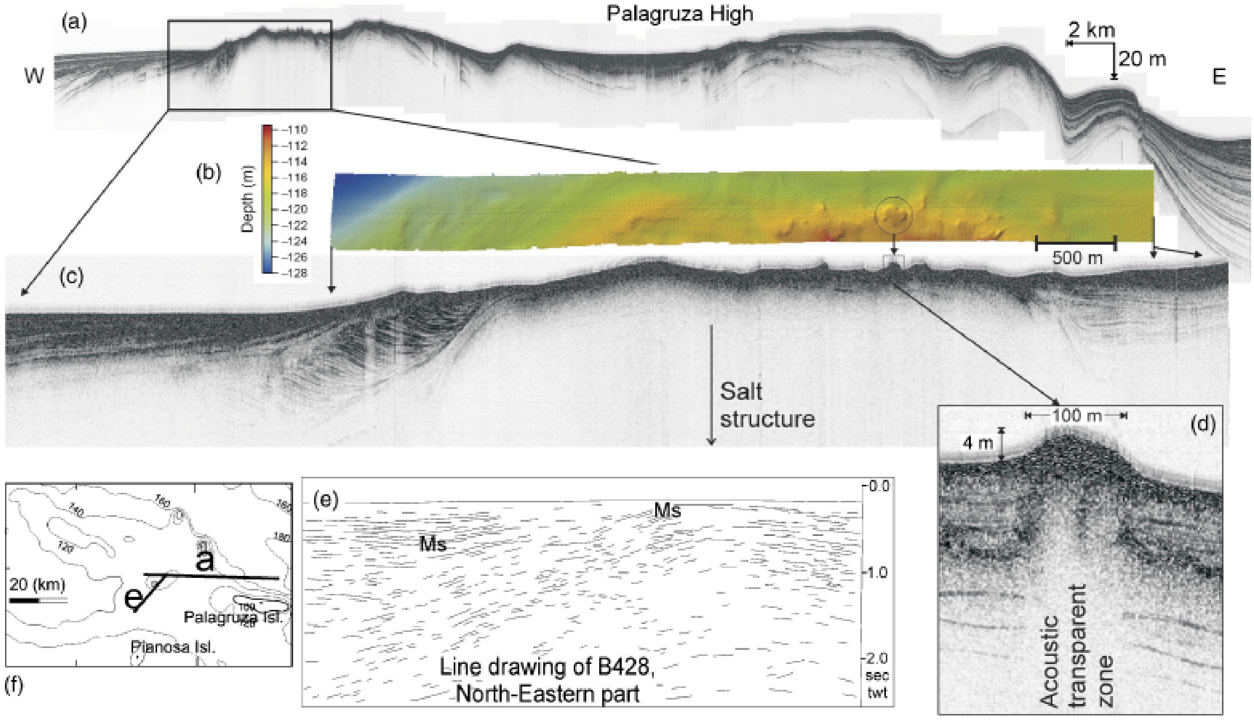

Fig. 9. Chirp sub-bottom profile (a) crossing the Palagruza High in a W–E direction (see position in the inset f and in Fig. 1a). The western margin shows a high density of mounds, more evident on Multibeam data (b), and in the blow-up of the Chirp profile (c). (d) A very fine detail shows a bottom feature characterized by an acoustic transparent zone denoting high absorption of the signal by a strong reflecting seafloor: this seismic facies and the morphology on the Multibeam (b) could suggest a coral bank origin for this feature. (e) The line-drawing of part of the B-428 seismic profile shows a deep structure joined to a salt activity, in agreement with Grandic *et al.* (1997).

structure 'B' clearly deforms the top of the Messinian sequence, and does so more weakly in the Pliocene to the prograding sequence, as testified by the small anticline at about 0.5 s TWT in the MCS profile and at about 320 ms TWT in the Chirp profile (labeled 'ac'). Also in Fig. 9 the Chirp and MB data confirm the recent activity of the salt dome structures of the Palagruza High, already identified in the MCS data. Some structures related to gas seeps as pockmarks (i.e.: Figs 2b, 3b, 7b and c), mud volcanoes and/or mud-carbonate mounds (i.e.: Figs 8 and 9) have been recognized by the same data, and they seem distributed more intensely on the active fracture systems produced above the dome structures. Some acoustic layers, characterized by very high-amplitude reflection strength events and underlying acoustic blank zones are evident from the Chirp data (Fig. 3c) in the sub-seafloor. Also, several pockmarks (i.e.: Figs 2b, 3b, 7b and c), mud volcanoes and/or mud-carbonate mounds (i.e.: Figs 8 and 9) have been recognized, typically in the active fracture systems produced above the dome structures.

Pockmark and Coral Bank Characterization

The pockmarks are often up to 300 m wide, and between 5 and 15 m deep, and they are more frequent in the southern than in the northern margin of the MAD. From the analysis of the sub-bottom profiles, the main pockmarks have a 'vertical spreading', that means buried pockmarks vertically stacked (Mazzotti *et al.*, 1987) (Fig. 3b) testifying to the presence of persistent gas seeps from the past up to the present. Across the northern margin of the eastern MAD (Fig. 8) the Chirp profile and MB data show a rough sea bottom, characterized by mounds with diametres of 20–30 m and heights of 5–6 m, typically located above faults/fractures. These small conic bodies, characterized by transparent acoustic facies, are probably mud volcanoes. These last were contrasted to the acoustic signature of the Deep Water Coral Banks, recently sampled in the Adriatic Sea (Fig. 1) by Taviani (2008) and correlated to seismic evidence recognized on Chirp and MB data acquired during the 2007 OGS Explora cruise (Geletti, 2008). These features have been observed in the morpho-bathymetric data set of the Palagruza High (Fig. 9) where they are evident on the Chirp profiles between 110 and 140 m. They reach about 4 m above the seafloor and 80–250 m wide, and are characterized by transparent acoustic facies, by an irregular edge and a flat top, as appears from the MB data, different to the cone shaped mud volcanoes.

DISCUSSION

Interpretation of MCS profiles and literature data, have allowed us to compile the distribution of salt structures in

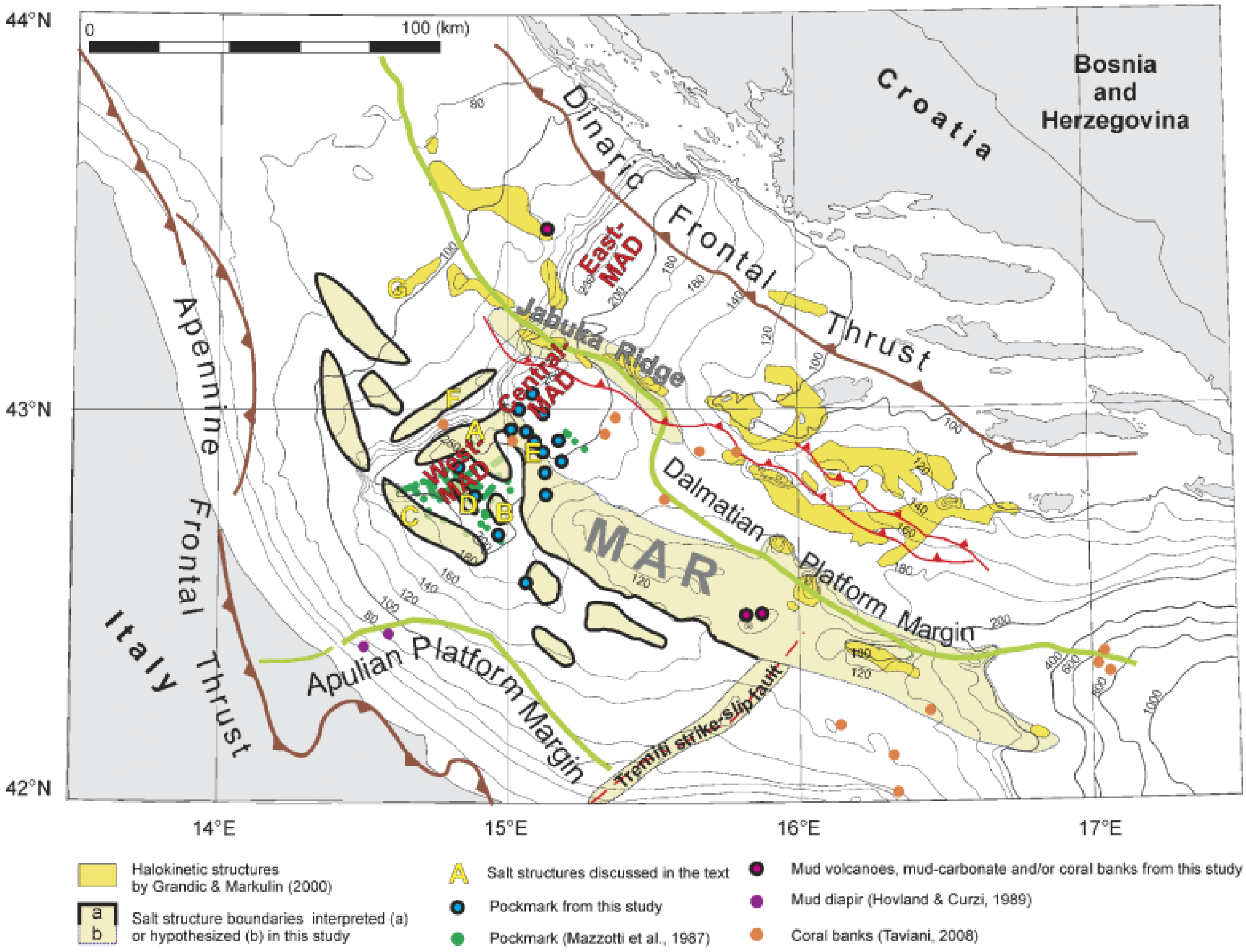

Fig. 10. Sketch map of the Central Adriatic Sea showing the main structural features of the studied area. A strong correlation between the recognized deep features (halokinetic structures and platform margins) and the structures related to gas seep (pockmarks, mud volcanoes, carbonate mounds and coral banks) has suggested.

the Central Adriatic Sea (Fig. 10). Our results indicate two main, almost parallel alignments with a NW–SE direction: the south-western alignment is coincident with the MAR, which through sediment deformation patterns is demonstrated to be presently uplifting. Part of the north-eastern alignment, the Jabuka Ridge, seems connected to the seismically active compressive Jabuka-Andrija fault (Fig. 1b) of Herak *et al.* (2005).

Both salt dome alignments affect the morphology of the MAD, subdividing the NE–SW depocenter into three sub-basins (Fig. 10): the main bathymetric separation between the West and the Central sub-basins is due to the presence of the MAR, while the Jabuka Ridge separates the Central and the East sub-basins.

Gas seepages, that appear as pockmark fields, mud volcanoes and mud-carbonate mounds, are found to be mainly located above fracture systems, in turn, related to the actively rising salt structures. These fractures, apparently sub-vertical in the Chirp data, and weakly sloping on the MCS profiles, have a generally small throw and length, so they cannot be correlated across the seismic profiles. They represent the permeable vertical pathway for gas-rich fluids, presumably focusing hydrocarbon-rich fluids diffusely present in the Plio-Pleistocene sediments. These fluids are also evidenced by the bright spots, which appear particularly commonly above and around the salt structures.

In many cases the halokinetic processes that produced the aligned salt domes of the MAR and Jabuka Ridge deform the overlying sedimentary sequences up to the seafloor. The stress field, that gave origin to the MAR features, is generally ascribed to the regional Dinaric (Finetti & Del Ben, 2005), or Apennine (De Alteriis, 1995; Argnani & Frugoni, 1997; Scrocca, 2006; Scrocca *et al.*, 2007) compressive regimes. In our opinion, the present uplifting deformation along the two parallel ridges does not necessary imply active tectonics in the frontal part of the Apennines (Scrocca, 2006; Scrocca *et al.*, 2007), but a prolonged differentiated regional compressive/transpressive tectonic regime. This is still active, as testified by the seismicity of the area (Herak *et al.*, 2005; Pondrelli *et al.*, 2006), and would have transmitted the stresses away from the orogenic belt to the areas where the sedimentary sequence, due to the presence of evaporites and to a favorable arrangement of the previous structures, loses resistance to deformation.

CONCLUSIONS

New acquired Chirp sub-bottom and morphobathymetric data show several, different seafloor morphologies; pockmarks, mud volcanoes and mud-carbonate mounds. These high-resolution shallow data, supplemented by MCS profiles, allowed us to analyze the link between gas seepages, fracture systems and deep features. On the base of the presence of dry methane in the Plio-Pleistocene sedimentary sequence of the Adriatic Sea and of the applied signal processing, we can conclude that:

- The occurrence of these seafloor and sub-seafloor morphologies in the Central Adriatic Sea is the effect of the mobilization of gas through the fracture systems: these last, working as pathways for gas-escapes, have an origin most commonly related to persistent halokinetic activity of the deep Triassic evaporitic intervals.
- Although the salt structures represent the most common deep features of the Central Adriatic Sea, the carbonate platform margins are often joined to bright spots and acoustic chimneys and probably to gas-related morphologies.
- The documented seismic activity testifies the compressive stress field of the area and represents the most likely mechanism for the expulsion of fluids to the seafloor.
- The salt structures are aligned preferentially along the MAR and the seismically active Jabuka Ridge. These ridges seem to have developed on the distal part of the Apennine and Dinaric foreland, far from the folded belts, and in a regional compressive regime but do not necessarily imply a Late Quaternary rejuvenation of the Apennine thrust front. The Triassic evaporitic intervals present in the deep sedimentary sequences, have determined, since, at least, the Neogene, the salt deformation of the two more or less parallel alignments.
- Some salt structures, almost orthogonal to the regional trend, are present in the analysed area. Their direction and halokinetics activity are analogous to those of the Tremiti fault, and they are likely to be originated from mainly strike-slip tectonics.
- The MAD, whose boundaries are chiefly defined by the Quaternary prograding sequences, is divided in the West, Central and East sub-basins by the two ridges. On these last, the salt uplift is still active, deforming and fracturing the upper sedimentary cover and generating the main part of the gas-related morphologies in the Central Adriatic Sea.

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