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Southern Adriatic Sea as a Potential Area for CO2 Geological Storage

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Abstract — The Southern Adriatic Sea is one of the five prospective areas for CO2 storage being evaluated under the three year (FP7) European SiteChar project dedicated to the characterization of European CO2 storage sites. The potential reservoir for CO2 storage is represented by a carbonate formation, the wackstones and packstones of the Scaglia Formation (Upper Cretaceous-Paleogene). In this paper, we present the geological characterization and the 3D modeling that led to the identification of three sites, named Grazia, Rovesti and Grifone, where the Scaglia Formation, with an average thickness of 50 m, reveals good petrophysical characteristics and is overlain by an up to 1200 thick caprock. The vicinity of the selected sites to the Enel - Federico II power plant (one of the major Italian CO2 emittor) where a pilot plant for CO2 capture has been already started in April 2010, represents a good opportunity to launch the first Carbon Capture and Storage (CCS) pilot project in Italy and to apply this technology at industrial level, strongly contributing at the same time at reducing the national CO2 emissions.

Résumé — Le sud de l’Adriatique, un secteur potentiel pour le stockage du CO2 — Le sud de la mer Adriatique est l’un des cinq secteurs à avoir été évalué pour le stockage du CO2 dans le cadre du projet européen FP7 SiteChar qui a duré trois ans. Le réservoir potentiel de CO2 consiste en une formation de carbonates, les wackestones et les packstones de la formation de la Scaglia (limite Crétacé-Paléogène). Nous présentons dans cet article la caractérisation géologique et le modèle 3D qui ont permis l’identification de trois sites, appelés Grazia, Rovesti et Grifone, au niveau desquels la formation de la Scaglia, d’une épaisseur moyenne de 50 m, présente des bonnes caractéristiques pétrophysiques et est recouverte d’un caprock d’une épaisseur allant jusqu’à 1200 m. La proximité des sites sélectionnés avec la centrale électrique Enel - Federico II (un des émetteurs de CO2 italiens les plus importants), où une installation pilote pour la capture du CO2 a déjà été mise en place à partir d’avril 2010, représente une bonne opportunité pour lancer le premier projet pilote Capture et Stockage du CO2 (CSC) en Italie et pour appliquer cette technologie à un niveau industriel, en contribuant fortement en même temps à la réduction des émissions nationales de CO2.

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INTRODUCTION

Carbon Capture and Storage (CCS) is considered a major option for global greenhouse gas reduction. This technique consists of three main phases: capture of CO₂ emitted by power and industrial plants; transport of CO₂ to a suitable site; CO₂ injection into deep geological formations (saline aquifers, depleted oil and gas fields and coal beds) where it will be trapped for thousands of millions of years. CO₂ storage is achieved through a combination of physical and chemical mechanisms that are effective over different time frames and scales (Bachu et al., 2007; Bradshaw et al., 2007). Among all the storage options, deep saline aquifers have the greatest potential for the storage of CO₂, with a globally estimated storage potential of at least 1000 Gt (Benson and Cook, 2005).

The European Union supports research solutions to reduce CO₂ concentrations through different focused projects. SiteChar project, launched in January 2011 within the Seventh Framework Program (FP7), is specifically dedicated to improve the site characterization for CO₂ geological storage. This project aims to provide a methodology for a full evaluation of potential storage sites, with the creation of a valuable tool for the roll-out of geological storage on industrial scale in Europe.

Within the project, five potential storage test areas representative of different geological contexts have been selected: a North Sea offshore multi-storage area in a hydrocarbon field and in the associated siliciclastic saline aquifer; an onshore siliciclastic saline aquifer in Denmark; an onshore gas field in Poland; an offshore siliciclastic aquifer in Norway; a carbonate saline aquifer in the Southern Adriatic Sea. Among all these sites, the Southern Adriatic Sea represents a peculiar case study since this area, located in proximity of the main Italian CO₂ emission source (the Federico II Enel thermoelectric power plant of Brindisi) (Fig. 1), hosts structures where the potential reservoir lies in a carbonate formation (Upper Cretaceous-Paleogene Scaglia Formation).

Several CCS projects have been performed in carbonate successions worldwide. The best known of them is the IEAGHG Weyburn-Midale CO₂ Monitoring and Storage Project, where, since 1998, about 6 500 tonnes per day are currently injected into the limestones and dolostones of the Mississippian Midale Formation for Enhanced Oil Recovery (EOR) purpose. Another example is the Lacq Pilot Project (France), which is testing the entire CO₂ capture and storage process through the injection into a depleted gas reservoir hosted in a carbonate formation at a depth of about 4 500 m. CO₂ injection in a Lower Jurassic carbonate saline reservoir, which will be able to host about 100 kt, is taking place also at Hontomin (Spain) in the framework of the Compostilla Programme.

The carbonate successions are widespread also in the Italian subsoil, both onshore and offshore and most of them have been and are presently hydrocarbons exploration targets. However, it is noteworthy that giant hydrocarbons fields discovered around the world are producing from carbonate reservoirs (Ahr, 2008). The properties of carbonate reservoirs are unpredictable and generally more complex than their siliciclastic counterparts (Chilingar et al., 1979; Roehl and Choquette, 1985; Mazzullo, 1986). The characteristic of the carbonates is to combine primary porosity related to facies and thus depositional setting with secondary evolution related to dissolution, plugging, and fracturing. Therefore, unlike most sandstone reservoirs, which usually are relatively uniform single-porosity systems (i.e. interparticle pores), reservoirs in carbonate rocks are commonly multiple-porosity systems characterized by significant petrophysical heterogeneity and therefore by wide permeability variations (Lucia, 1993; Mazzullo and Chilingarian, 1992). The distinctive aspects of carbonate rocks include:

- their predominantly intrabasinal origin,
- the dependence of carbonate production on organic activity,
- the strong susceptibility to modifications by post-depositional mechanisms (diagenesis and tectonics).

The latter affect the primary (intergranular and intra-granular porosity) and secondary porosity, fracture network development and ultimately the permeability (Land, 1967; Choquette and Pray, 1970; Halley and Schmoker, 1983; Harris et al., 1985; Moore, 1989).

The potential reservoirs for CO₂ geological storage in the Italian carbonate succession were commonly identified within the fractured shallow marine carbonate platform successions. The pelagic carbonate successions, typically consisting of carbonate mudstones with marly and clayey intercalations, are generally characterized by low porosity and permeability, so that they can be considered as potential caprock (Civile et al., 2013). However, also pelagic successions could present intercalation of resedimented, bioclastic limestones (talus sediments) or could be fractured as the results of tectonic activity and can be considered as good reservoirs (Civile et al., 2013; Casero and Bigi, 2013), as the Upper Cretaceous-Paleogene Scaglia Formation, which represents the potential reservoir in our study area.

In this paper, we present the geological characterization of the South Adriatic area and the 3D geological models for three suitable structural traps.
1 REGIONAL SETTING

The study area is located in the Southern Adriatic Sea (Fig. 1). It is part of the Padano-Adriatic foreland-foredeep domain of the circum-Adriatic orogenic chains, i.e. Apennines, Southern Alps, Dinarides, Albanides and Hellenides (Nicolai and Gambini, 2007) (Fig. 1).

This domain was part of the western continental margin of Africa, known as Adria or Apulia margin, which was composed of platforms and deep-sea basins with a predominantly Meso-Cenozoic carbonate sedimentation (D’Argenio, 1976; Mostardini and Merlini, 1986; Bosellini, 1989, 2004). This configuration was controlled by extensional faulting linked to a Norian-Lias rifting phase which led to the opening of the Mesozoic Tethyan basin (Winterer and Bosellini, 1981; Doglioni, 1987; Bertotti et al., 1993; Bernoulli, 2001; Fantoni and Franciosi, 2010). Several authors have suggested that Adria was a promontory of the African plate (Staub, 1951; Dercourt, 1972; Channell and Horvath, 1976) while others consider it as an independent microplate (Dewey and Burke, 1973; Makris, 1981; Finetti, 1982, 2005; Dercourt et al., 1986; Dercourt, 2000; Stampfli and Mosar, 1999).

The Southern Adriatic Sea shows at a regional scale an antiformal configuration related to the loading produced by the Apennines to the west and the Albanides-Hellenides chains to the east (D’Argenio and Horvath, 1984). This double loading induced the uplift of the Apulian block generating the so called Apulian ridge (Fig. 1), which represents the uplifted flexural outer bulge of the foreland basin (Doglioni et al., 1994). The Apulian ridge consists of a 6-7 km thick Meso-Cenozoic shallow water carbonate succession (Ricchetti et al., 1988), of which lowermost 1000 m-thick succession is composed of Triassic anhydrite-dolomite deposits (Butler et al., 2004).
The Southern Adriatic Sea hosts a more than 1,200 m deep basin, located to the south of the Gargano promontory and can be considered as the Miocene-Pliocene foredeep of the Albanides-Hellenides thrust-fold belt.

The stratigraphy of the Southern Adriatic offshore (Fig. 2), is generally made up of Mesozoic shallow water carbonates. However, a wide range of depositional environments, from evaporitic basins to deep open platforms have recognized. Exploration wells drilled in the area identified three main successions (Fig. 2):

- a basal unit several hundred meters thick, consisting in Mesozoic Burano anhydrites, an intermediate level of platform carbonate of Jurassic age (Calcaire del Massiccio and Corniola), passing to the pelagic limestones of the Maiolica Formation, and the Upper Cretaceous unit of the Scaglia Formation, whose thickness is highly variable in the area ranging from tens to hundred meters locally (Fig. 2);
- a hiatus divides the Oligo-Miocene succession from the Mesozoic units, with the absence of Paleocene-lower Oligocene units. The post- Paleocene is characterized by non-deposition while the Cretaceous and Paleocene have been eroded;
- the 1,000 m thick Upper Oligocene – Miocene succession overlying the hiatus, consists of alternations of limestones and marls (Fig. 2). The Bisciaro Formation
consists of limestones and marls. The upper Schlier Formation consists of argillaceous and marly turbidites. The Messinian appears as an erosional hiatus in which salt is not present;

Plio-Quaternary sediments (~ 400 m) have continental and marine transgressive origin consisting of calcareous and siliceous sands, and clay turbidites, silty and sandy, related to the filling of the South Adriatic basin (Fig. 1).

The structural setting of the area is the result of tectonic regional events occurred from the Lowermost Jurassic up to the Present. In particular, after the early Jurassic rifting, two distinct domains, a carbonate platform to the west and a basin area to the east were generated (Fig. 2). Several structural highs, probably related to salt tectonics, involving since Jurassic the Upper Triassic evaporites of the Anidriti di Burano Formation, and Miocene tectonic uplift have been recognized. A strike-slip tectonics, possibly affecting the Quaternary succession and developed along E-W and NNE-trending tectonic lineaments, have been also identified (De Dominicis and Mazzoldi, 1987; de Alteriis and Aiello, 1993; Morelli, 2002).

The Adriatic region is characterized by high-seismicity in particular along its collisional margins (Anderson and Jackson, 1987; Favalli et al., 1993; Kastelic and Carafa, 2012). At present-day, the Southern Adriatic area is characterized by a relatively moderate tectonic activity mainly concentrated along two main E-W trending lineaments located on the Mid-Adriatic Ridge and close to the Gargano promontory (Scisciani and Calamita, 2009) (Fig. 1). In particular, the most important seismogenetic structure is the broadly E-W-trending “Gondola” lineament, characterized by a general strike-slip regime (Fig. 2), (Ridente and Trincardi, 2006; Ridente et al., 2008; Di Bucci et al., 2009; DISS working group, 2010) representing the offshore continuation of the Mattinata Fault identified in the Gargano Peninsula (de Alteriis and Aiello, 1993; Argnani et al., 2009; Kastelic and Carafa, 2012).

A compressional deformation, affecting also the sea-floor, is located in correspondence of the Grifone-Sparviero folded area, in the central part of the Adriatic basin (Fig. 2).

2 METHODS

This study is based on the analysis of a dataset that has been made available by the Ministry of the Economic Development in the framework of the project “Visibility of Petroleum Exploration Data in Italy (ViDEPI)” (http://www.videpi.com). The dataset consists of a grid of NE-SW and NW-SE oriented lines with a spacing of about ten kilometres for a total of 3700 km of 2D multi-channel seismic lines and 15 wells (Fig. 1). Seismic profiles provided in the framework of ViDEPI project were available in a raster format, so they have been converted into a standard seismic data format (SEG-Y). Seismic lines have been then loaded into the seismic interpretation software HIS Kingdom Suite.

Well data consist of the so-called “composite logs charts” that contain the following information:

- lithology derived from cuttings,
- name and age of the geological formation,
- formation depth,
- lithostratigraphy,
- fluid occurrence,
- depositional environment,
- biostratigraphy,
- geophysical logs (commonly resistivity, self potential, sonic, gamma ray, neutron).

Temperature and pressure measured at a given depth as well as porosity and permeability data from cores and the salinity of the pore water are also reported in places.

In a first instance, stratigraphies and geophysical logs were analyzed in order to identify the lithologies and the petrophysical conditions suitable for CO₂ storage, according to the criteria of the CCS EU Directive. In fact, the identification of reservoir-caprock systems is essentially based on well data analyses, whereas their areal extent has been evaluated through the seismo-stratigraphic interpretation of the 2D seismic data. Particular attention has been paid also to the structural setting, in order to identify the occurrence of major faults which could represent preferential pathways for potential leakages.

2.1 Well Data Interpretation

In the study area, the Scaglia succession consists of mudstones and wackestones and presents frequent detrital packstone intercalations, deposited in slope depositional environment. The thickness of the formation, which is commonly saturated by salt water, ranges from 35 to about 115 m (Table 1).

Although the Scaglia Formation is typically considered a seal, several data revealed that this succession can be locally a good reservoir. To confirm this, Casero and Bigi (2013) show that the reservoirs of mixed oil/gas petroleum systems in the central Adriatic area consist of re-sedimented calcareous bioclastic breccias, interbedded in the Cretaceous/Paleocene portion of the Scaglia Formation. In fact, in the study area, the Aquila hydrocarbon field is presently producing oil from this formation.
It is situated in the lower part of Apulian platform slope and characterized by the presence of fractured peri-platform coarse clastic deposits that represent the regional reservoir rocks.

In the evaluation of the suitable storage conditions, we have considered the following factors: the fluid occurrence, the depositional environments and the tectonic deformations that could have induced an increase of the porosity and permeability produced by fracturing. The co-existence of these characteristics at the analyzed wells led us to identify three potential storage sites, that will be described in the following chapter.

The caprock of the CO₂ potentially suitable sites is represented by 600 to 1 700 m thick Upper Oligocene to Pleistocene succession made of marls, clays, gypsum and limestones, belonging to Scaglia Cinerea, Bisciaro, Schlier, the Messinian Gessoso–Solfifera. Where presents, the Argille del Santerno formation can be also considered part of the caprock.

Suitable conditions for CO₂ storage could also be found in the carbonate deposits lying below the Scaglia Formation (i.e. Calcare Massiccio Formation, Civile et al., 2013). However, at the moment this hypothesis cannot be constrained due to the scarcity of available data.

Log data were used to have a first estimate of the (SPHI) sonic porosity (total porosity), derived from sonic log; for the reservoir rocks (Scaglia Formation).

We used the following Wyllie time-average relation (Wyllie et al., 1956):

\[ \Phi = \frac{\Delta t_{\text{log}} - \Delta t_{\text{matrix}}}{\Delta t_f - \Delta t_{\text{matrix}}} \]

where: \( \Delta t_{\text{log}} \) = the measured interval travel-time, \( \Delta t_{\text{matrix}} \) = the interval travel-time of the rock matrix (47.5 µs/ft for limestone), \( \Delta t_f \) = the interval travel-time of the saturating fluid (185 µs/ft for saltwater mud filtrate).

The porosity values calculated for the reservoir formation at the wells drilled through the selected structures are reported in Table 2. It is important to highlight that since Wyllie’s relation gives an estimate of the total porosity, further analyses on core samples should be performed in order to obtain data on effective porosity and permeability of the potential reservoir unit.

2.2 Seismic Data Interpretation

At a regional scale, the seismo-stratigraphic and structural interpretation led to the identification of the key seismic horizons and the major tectonic features. The seismic data analysis, together with borehole data correlation, led us to identify in the whole study area several structural traps. The quality of the seismic data influence the interpretation; in this study, the available seismic data were acquired for deep exploration, so we can consider an average frequency of 20 Hz at the reservoir depth and an interval velocity of 5 000 m/s for the Scaglia Formation and the resulting seismic resolution is around 62.5 m. Thus, fault throw and seismic events smaller than 60 m cannot be detected using the available seismic dataset.

From bottom to top, the following seismic reflectors are recognized and interpreted in the whole study area: 
- Bottom Scaglia Formation (i.e. bottom reservoir),
- Top Scaglia Formation (i.e. top reservoir),

### Table 1

<table>
<thead>
<tr>
<th>Well</th>
<th>Reservoir Fm. (depth interval)</th>
<th>Age</th>
<th>Caprock Fm.</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grazia 1</td>
<td>Scaglia (1 634 m-1 740 m)</td>
<td>Turonian</td>
<td>Scaglia Cinerea, Bisciaro, Schlier, Santerno</td>
<td>Mid.-Upper Oligocene-Quaternary</td>
</tr>
<tr>
<td>Giuliana 1</td>
<td>Scaglia (1 537 m-1 600 m)</td>
<td>Cenomanian-Senonian</td>
<td>Bisciaro</td>
<td>Lower Miocene</td>
</tr>
<tr>
<td>Rovesti 1</td>
<td>Scaglia (2 417 m-2 533 m)</td>
<td>Cenomanian-Paleogene</td>
<td>Bisciaro, Schlier</td>
<td>Aquitanian-Tortonian</td>
</tr>
<tr>
<td>Grifone 1</td>
<td>Scaglia (2 121 m-2 160 m)</td>
<td>Cenomanian-Senonian</td>
<td>Bisciaro, Schlier</td>
<td>Lower Miocene-Serraval.</td>
</tr>
<tr>
<td>Sparviero 1</td>
<td>Scaglia (2 926 m-2 961 m)</td>
<td>Cenomanian-Senonian</td>
<td>Bisciaro, Schlier</td>
<td>Lower Miocene-Tortonian</td>
</tr>
</tbody>
</table>

### Table 2

<table>
<thead>
<tr>
<th>Well</th>
<th>Porosity from sonic log (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
</tr>
<tr>
<td>Grazia 1</td>
<td>12.29</td>
</tr>
<tr>
<td>Rovesti 1</td>
<td>23.29</td>
</tr>
<tr>
<td>Grifone 1</td>
<td>15.86</td>
</tr>
</tbody>
</table>
– Upper Miocene Unconformity,
– Seafloor.

The structural interpretation allowed to recognize some regional tectonic lineaments, already known from the literature, that affect the Meso-Cenozoic carbonate succession and the Oligocene-Miocene deposits; in some places the Plio-Quaternary deposits seem to be also deformed. The term lineament refers to tectonic features that has a regional influence and extension and that produces a morphological expression. We refer to the term fault when describing its evidence and characteristic on seismic data. The major tectonic lineaments are (Fig. 2):

– Jolly - Imago lineament. It extends parallel to the coast, with a sharp nose in correspondence to Brindisi (Fig. 2). This normal fault lowers the carbonate platform toward NE with a considerable throw from 800 m at the Jolly well to almost 1 000 m in the southernmost part. In some parts, this fault was probably active during the Tertiary (De Dominicis and Mazzoldi, 1987);
– Rovesti lineament. This fault, oriented NW-SE, is evident on seismic profiles as a fault with a lowered northern side. It affects the carbonate platform and the siliciclastic succession up to the top of Miocene;
– Gondola lineament. It is a broadly E-W trending lineament, that corresponds to the offshore prosecution of a well known onshore right-lateral strike-slip system known as “Mattinata Fault” (Nicolai and Gambini, 2007). Push-up structures (Ridente et al., 2008) and reverse faults are commonly associated to this structure which affects the whole investigated sedimentary succession and locally the sea-bottom. Recent studies using high-resolution seismic data have however emphasized the presence of Quaternary deformation that can be traced back to some active tectonic activity in the last 450 ka, thus leading to hypothesize that the Gondola fault zone would still be active (Ridente et al., 2008). This result is of considerable importance in defining the most suitable CO$_2$ storage site in the study area, because the presence of active faults might be a preferential path for CO$_2$ migration from the injection layer up to the surface. Our geological model considers all the interpreted tectonic features affecting the storage complex that could play different roles in the CO$_2$ plume migration and for that should be included in the fluido-dynamic and geo-mechanical modeling.

### 3D GEOLOGICAL MODEL

Four main stratigraphic layers are defined in the geological model (Fig. 3):

– Plio-Pleistocene (yellow): from the “Sea Bed” at the top to the “Top Messinian” at the bottom,
– Caprock (orange): from the “Top Messinian” at the top to the “Top Scaglia” at the bottom,
– Reservoir (green): from the “Top Scaglia” at the top to the “Base Scaglia” at the bottom,
– Pre-Scaglia (light blue): underneath the reservoir layer.

The initial geological and structural model at regional scale was built in the time domain, taking into account horizons and faults derived from seismic interpretation and calibrated on the basis of the information contained in the borehole composite logs. The areal extent covered by the model is about 42 500 km$^2$ (Fig. 1).

The next step was the time-depth conversion of the seismic events (horizons and faults) by producing a velocity model using available velocity functions from five representative wells. The average velocity has been calculated at every “control point”, corresponding to
to well location, for each of the interpreted horizon. The average velocity map is a grid expressed in meters/seconds obtained by means of a proper interpolation algorithm (Ordinary Kriging) starting from the above mentioned control points. In this way, 4 average velocity maps, one for each of the 4 interpreted horizons (Sea Bed, Upper Messinian, Top Scaglia and Bottom Scaglia) have been produced. Once the velocity model was completed, the time geological model was converted to depth and it was compared with the depth of the interpreted horizons reported in wells (well tops). Since no other velocity information were available, depth surfaces were corrected to honor actual depths reported on composite logs for each of the wells available in the study area; this has been performed by means of a proper algorithm that applies a convergent correction not only in the wells area but in the whole surface.

The depth-converted faults and horizons as “raw” grid data have then been converted into tri-meshes, that are triangulated surfaces allowing a flexible surface representation. An accurate editing phase has been performed on the tri-meshes surfaces in order to solve some issues related to intersections at surface boundaries and to obtain the so called “water-tight” configuration for all the surface intersections. The final model represents the storage complex (reservoir and overburden) and the main tectonic features. (Fig. 4).

Finally, in order to create a 3D volumetric grid, a cell size in X-Y (I-J) directions are set to 500 m × 500 m. This cell size provides a very good fitting between the geological surfaces in the structural model and the reconstructed equally spaced sampled surfaces in the final 3D grid model. For the three upper layers (Plio-Pleistocene, Caprock and Reservoir), a further partition in internal layers was made. These internal layers are not actual layers, but only artificial ones allowing to increase the number of k-layers. The vertical resolution of the resulting grid is thus increased, which might be useful when populating the geological model with physical properties.

The final 3D grid model is geometrically characterized by the following parameters (Fig. 5a):
- number of cells in I direction: 356,
- number of cells in J direction: 300,
- number of cells in K direction: 22,
- total number of cells: 2 349 600.

After completing the structural model and the volumetric grid, which are the framework of reservoir and caprock model, the next goal was to populate the entire framework of cells with petrophysical properties (facies, porosity, permeability etc.).

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**Figure 4**
Regional structural model. It is composed by the key horizons (Seabed, top of Messinian, top and bottom of Scaglia) and the regional tectonic lineaments (Jolly, Gondola, Rovesti, Grifone, Rosaria and Cigno).

**Figure 5**
a) Volumetric gridding; b) facies distribution at reservoir level.
Generally, petrophysical properties are highly correlated to facies type and, for this reason, the facies are modeled in order to constrain the subsequent modeling of petrophysical parameters. Stochastic modeling was applied to distribute the facies information obtained from composite log analysis. This type of approach was applied due to sparseness of analytical data available in this study area. Well data have been used as the control points for feeding the simulation algorithm used; many algorithms require parameters which describe the spatial relationship of the data points supplied to them. Therefore, finding out the spatial characteristics of the data is a very important step in facies modeling. For each of the available wells a discrete log, representing the facies distribution in depth has been created; six main widespread facies have been identified within the area: shale; fine sand; marl; platform carbonate; basinal carbonate; dolomite.

The facies logs have been then up-scaled: the discrete value associated with the most represented facies within the cell has been selected.

In order to perform the stochastic facies modeling, the initial proportion of each facies (derived from well data) has been considered and, starting from this initial proportion, the vertical proportion curves that express the probability that a certain facies exists in a certain layer (zone) were derived. The vertical proportion curve tells how the proportion of each facies varies vertically in a stratigraphic zone.

Finally, the experimental variograms along the major, minor and vertical directions have been computed for each facies within each zone in order to define the variogram models. The experimental variograms obtained from the analysis of wellbore data, reveal that the directions of the maximum and minimum spatial continuity correspond to the presence of a carbonate platform oriented NW-SW and NNW-SSE (major range: 130 km) with a passage to deeper depositional environments (i.e. from transitional to basinal) moving towards SE-ESE (minor range: 30 km). The value of the nugget parameter was equal to zero for both directions.

Spatial distribution of the facies of zone 2 (caprock) does not evidence a clear depositional trend of the different terrigenous units that characterize this interval; the experimental variogram gives the directions of maximum and minimum continuity oriented NW-SE and NE-SW (major range: 140 km, minor range: 76 km, Nugget value: 0.6), respectively. These values, used as input for the simulation algorithm, produce a quasi-random distribution of the facies and thus introduce a degree of heterogeneity consistent with the amount and distribution of the available data.

The simulation algorithm used was the truncated Gaussian simulation algorithm. This algorithm should be used in systems where there is a natural transition through a sequence of facies (typical examples include carbonate environments) and for this reason it has been chosen.

The obtained model populated with facies distribution (Fig. 5b) has been considered consistent with the geological knowledge of the area.

4 EVALUATION OF THE CO2 POTENTIAL STORAGE SITES

The geological characterization at regional scale of the Southern Adriatic Sea shows that the potential reservoir represented by Scaglia Formation (Upper Cretaceous-Paleogene) appears to be affected by the identified regional tectonic lineaments. Moreover, in the area located just in front of the coast the depth of the top reservoir appears to be shallower than 800 m, so that the physical conditions to ensure the “dense phase CO2” might not be guaranteed.

Taking into account these aspects and the tectonic and lithological features of the Scaglia Formation, three sites potentially suitable for CO2 storage have been identified in the area: Grazia, Rovesti and Grifone structures. Figure 6 illustrates the location of the three sites along the margin. The reservoir formation contains oil and gas in Rovesti, and salt water in Grifone and Grazia. The reservoir porosity (mean, minimum and maximum values) has been estimated (Tab. 2) with an empirical approach as described in Section 2.1.

4.1 Grazia Structure

The Mesozoic-Tertiary succession of this horst, bounded by NW-trending normal faults, has been drilled by Grazia 1 well (Fig. 7).

The Oligocene-Tortonian clastic succession, belonging to Schlier, Bisciaro and Scaglia Cinerea formations, represents the caprock of the potential storage complex. This clastic succession consists of an about 1 000 m-thick, almost pure marls and clays, separated by an important hiatus from the Upper Cretaceous carbonate succession of the Scaglia Formation. It is constituted by about 100 m-thick mudstones and wackestones with intercalations of bioclastic packstones (Fig. 7). The analysis of the well and of the available seismic lines reveal that the depositional environment of Scaglia Formation was the upper part of a gentle dipping continental slope (Fig. 6). The top of the Scaglia lies at about 1 630 m. The stratigraphic interval corresponding to the Scaglia Formation is contains salt water. Moreover, the occurrence of several high porosity, fractured intervals is evidenced by mud adsorption during drilling operations and by the electrical log response.
The mean porosity has been estimated around 12.29% (Tab. 2), applying the empirical relationship described in Section 2.1 using the available sonic log at Grazia well. The size of the structure is 10.1 km² and the bulk volume estimated at the spill point for the reservoir is of about 1 km³.

Further below, the well drilled a Mesozoic dolomitic complex, characterized by the occurrence of several porous layers, as testified by the occurrence of salty water, which could represent potential CO₂ reservoirs. However, no further geological nor geophysical information are available for this succession to confirm such a hypothesis (Fig. 7).

4.2 Rovesti Structure

The Rovesti structure is an NE-SW trending anticline affecting the Mesozoic carbonate succession and probably produced by salt tectonic (Fig. 8). The target of Rovesti 1 borehole was the Mesozoic succession mainly deposited in a slope depositional environment characterized by frequent intercalations of breccias. The drilled successions are, from top to bottom: Plio-Quaternary sequences consisting of clays with sandy intercalations, Miocene marls with clay (Gessoso-Solfifera Formation) or mudstone intercalations (Bisciaro formation), and, at the bottom, the top of the carbonate platform represented by the Mesozoic formations of Scaglia (Upper Cretaceous-Paleogene), Maiolica (Lower Cretaceous), Calcari ad Aptici (Malm). The bottom of the Rovesti 1 well drilled only a small portion of a dolomitic succession (Fig. 8). Evidence of oil occurrence has been reported in the whole Late Jurassic-Paleogene stratigraphic interval. The Scaglia Formation top lies at about 2 350 m. The formation, composed of about 60 m-thick wackstones and mudstones, intercalated with fossiliferous packstones, reveals the occurrence of an oil-saturated interval.

The composite log of the Rovesti 1 borehole reveals that this interval is characterized by a primary porosity of 13%, but values higher than 20% have been also recorded. Note also that no information about the permeability is available. The areal extent of the structure is of 4.8 km² and the estimated bulk volume of the reservoir at the spill point is around 0.3 km³.

The caprock is an almost 1 200 m-thick Miocene-to-Pleistocene succession, mainly composed by marls and clays.

4.3 Grifone Anticline

The Grifone anticline is part of the so-called Grifone trend (de Alteriis and Aiello, 1993) constituted by an arcuate set
of antiforms in which both Mesozoic carbonates and Tertiary clastic successions are involved (Fig. 6-9).

In the Grifone 1 well, no information are available for the whole Plio-Quaternary succession. The Oligocene-Miocene predominantly marly succession belonging to Scaglia Cinerea, Schlier and Bisciaro formations is about 600 m-thick and represent the caprock of the potential storage complex. Below, the well drilled the typical Mesozoic-Eocene “Umbro-Marchigiana” succession, characterized by a basinal carbonate sequence. Its uppermost stratigraphic levels are represented by the Upper Cretaceous-Paleogene Scaglia Formation, consisting of about 30 m-thick mudstones and wackestones (Fig. 9). The Scaglia Formation top lies at about 2 100 m. A core collected during the drilling of Grifone 1 borehole reveals that mudstone layers within the Scaglia Formation have a maximum porosity of about 24%, whereas permeability is low (about 2.6 mD). We would expect that wackestone layers within this formation are more porous and more permeable, but at the moment no further information are presently available. The areal extent of the potential reservoir at Grifone is considerable comparing with the other identified structures (75 km²), with a bulk volume at the spill point of about 75 km³. The technical report of the Grifone 1 borehole indicates that the absence of hydrocarbons in the target formation could be related to the occurrence of a fault, just to the East of the Grifone anticline, which would have prevented the hydrocarbon migration into the structure.

Figure 7
Grazia structure: a) lithological interpretation of well data; b) depth image of the top reservoir formation; c) interpreted seismic profile.
5 DISCUSSION AND CONCLUSIONS

The Southern Adriatic Sea is one of the perspective areas for CO₂ storage, being evaluated under the three years EU SiteChar project. This study represents the first comprehensive geological evaluation of the occurrence of suitable conditions for CO₂ storage in the Upper Cretaceous carbonate successions in the Southern Adriatic Sea.

From a CCS point of view, the potentially suitable reservoir for CO₂ storage is represented by the wackstones and mudstones of the Scaglia Formation (Upper Cretaceous-Paleogene). It has an average thickness of 50 m and hosts a saline aquifer. The caprock is represented by the Oligo-Miocene predominantly marly succession and where presents by the Plio-Pleistocene clays. As pointed out, the basinal sequences (i.e. Scaglia Formation) may have petrophysical characteristics (high porosity and permeability) to be considered a suitable reservoir for CO₂ storage under the specific conditions:

- When it is composed by calcareous breccias deposited nearby carbonatic shelf margin (talus sediments) (Casero and Bigi, 2013);
- When the tectonic deformation has induced an increase in porosity and permeability by fracturation.

The analysis of the well log data showed that Scaglia Formation at the three identified structures

Figure 8
Rovesti structure: a) lithological interpretation of well data; b) depth image of the top reservoir formation; c) interpreted seismic profile.
can be considered as a potential reservoir because it reveals that:
- at Rovesti structure, the Scaglia Formation deposited in a lower slope environment. It reveals the occurrence of oil-saturated levels and good porosity conditions, with values up to 20%;
- at Grazia structure, the Scaglia Formation deposited in an upper slope environment; here well logs evidenced some high porosity, fractured intervals;
- the carbonate succession of Grifone structure has been deposited in a completely different environment, being represented by the deep basin facies of the Umbro-Marchigiana succession. However the Scaglia Formation presents good values of porosity, despite of the fact that the well is dry. The structure is clearly originated from Jurassic salt tectonics, involving Upper Triassic evaporites (Anidriti di Burano Formation), re-activated in the more recent (Quaternary) episodes of strike-slip tectonics (De Dominicis and Mazzoldi, 1987; de Alteriis and Aiello, 1993).

Detailed analyses and additional data are required to evaluate the potential storage capacity of the identified structures. Moreover, it is important to highlight also the opportunity to use the CO₂ storage for the EOR perspective at the Rovesti structure, where oil occurrence has been reported. We do not exclude that suitable conditions for CO₂ storage may occur also in the deeper
platform carbonate formations, whose information are presently too scarce to confirm or reject such an hypothesis.

Among the identified structures, Grazia anticline has been selected as storage site for the fluido-dynamic and geo-mechanical modeling to predict the behavior of the injected CO₂ in time, not included in this paper. The criteria applied for the final selection are the closeness with the potentially source of CO₂ (i.e. Brindisi power plant), the water depth that is the shallowest of the three sites (around 180 m) and the no interference with other usage, i.e. Rovesti is under permit for hydrocarbon exploration. The selected sites lie almost in front of the major Italian CO₂ point source, represented by the Enel (Italian electrical company) Federico II power plant. It provides is a good opportunity to apply CCS at industrial level, then representing a strong contribution to reduce national CO₂ emissions. Moreover, this case study would represent also an opportunity to launch the first CCS pilot project in Italy, taking advantage of the vicinity of a major source emission where a pilot plant for CO₂ capture has been already started in April 2010. However, the dynamic simulations of the CO₂ behavior after injection are required in the final assessment of this area for the application of CCS techniques.

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