3D modelling and capacity estimation of potential targets for CO_2 storage in the Adriatic Sea, Italy

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Abstract

One of the most innovative and effective technologies developed in recent decades for reducing carbon dioxide emissions to the atmosphere is CCS (Carbon Capture & Storage). It consists of capture, transport and injection of CO_2 produced by energy production plants or other industries. The injection takes place in deep geological formations with the suitable geometrical and petrophysical characteristics to permanently trap CO_2 in the subsurface, which is called geological storage. In the development process of a potential geological storage site, correct capacity estimation of the injectable volumes of CO_2 is one of the most important aspects. There are various approaches to estimate CO_2 storage capacities for potential traps, including geometrical equations, dynamic modelling, numerical modelling, and 3D modelling. In this work, generation of three-dimensional petrophysical models and equations for calculation of the storage volumes are used to estimate the effective storage capacity of four potential saline aquifers in the Adriatic Sea offshore. The results show how different saline aquifers, with different lithologies at favourable depths, can host a fair amount of CO_2, that will imply a further and more detailed feasibility studies for each of these structures. A detailed analysis is carried out for each saline aquifer identified, varying the parameters of each structure identified, and adapting them for a realistic estimate of potential geological storage capacity.

Of all the actions that are being developed to reduce CO_2 emissions and that can lead to a low-carbon energy system, CCS (Carbon Capture and Storage) is perhaps the one that can make the greatest contribution and more rapidly than other technologies. This process, which has seen significant development in the last twenty years, consists of capture of CO_2 generated by power plants or other large stationary industrial sources, transport through pipelines or by ships, and injection into deep geological formations that have suitable characteristics to trap CO_2 (IEA, 2004; IPCC, 2005). To achieve this, the potential storage sites must be identified, defining the exploitable part, and estimating the volume of CO_2 that can be injected. There are many institutions and projects aiming to characterize sites and estimate CO_2 storage potential in Europe, such as EU-projects EU-GeoCapacity, CO2Stop, and, in the case of Italy different research institutes and private companies (http://www.geocapacity.eu; among many others, Vangkilde-Pedersen et al., 2009a; 2009b; Donda et al., 2011; Civile et al., 2013; Volpi et al., 2015; Berenblyum et al., 2018).

The CO_2 storage capacity is estimated at four different levels of detail structured in a pyramid (Fig.1), where from the base to the top the storage capacity value decreases as the estimate of the volume is refined (Doughty et al., 2001; Bachu et al., 2007; Bradshaw et al., 2007; Kopp et al., 2009).The four levels are characterized as: *theoretical* physical limit that the system can host, then the total or partial volume of the pores, based on the presence of fluids; *effective*, which counts the geological and engineering limitations and estimates the actual volume that can effectively be exploited; *practical*, estimated considering the legal, regulatory, and economic aspects, and the presence of infrastructure; and *matched*, a volume that takes into account the logistical aspects between sources and CO_2 storage sites, with respect to capacity, injectivity and quantity of produced CO_2.

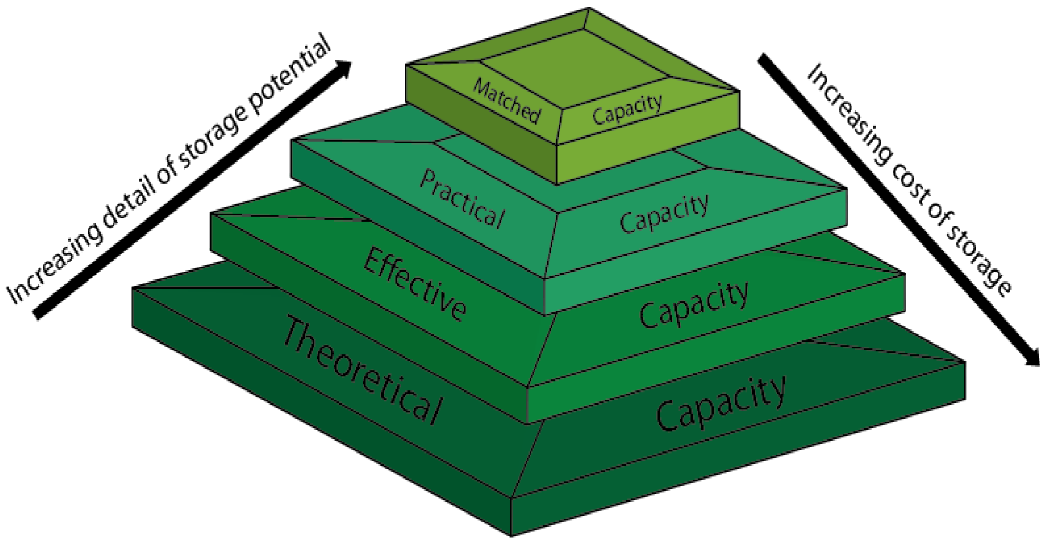

Fig. 1. Pyramid of the capacity estimation. The detail increase toward the top of the pyramid and the cost of storage increases toward the bottom (After 'Bachu et al. 2007').

In this paper, we estimate the effective storage capacity of four potential structural traps for the geological carbon dioxide storage in the Adriatic Sea (Italy). These are saline aquifers hosted into thrust-related anticline structures buried in the Adriatic Sea under Plio-Pleistocene post-thrusting deposits, named from the wells name drilled for hydrocarbons research in 80's years: Cornelia, Patrizia, Elga and Serena anticlines (Fig.2). The calculations were carried out based on three-dimensional models developed using Petrel software (Schlumberger, academic licence) populating them with petrophysical parameters such as porosity and permeability distribution defined on the basis of the available well log data. Moreover, the total pore volume obtained with this approach is used to calculate the *theoretical storage* capacity using the equation proposed in the literature. Finally, the introduction of an efficiency factor based on several observations also enabled estimation of the effective capacity.

Study area

The Adriatic domain is the outer and younger sector of the Apennine accretionary system (Fig. 2). The Adriatic Sea geology comprises the foredeep-foreland domain of the Apennine Chain (Fig. 2), which is the result of convergence between the Eurasian and African plates (Boccaletti et al., 1990; Bernoulli, 2001; Rosenbaum and Lister, 2004). The westward subduction of the Adria plate generates the flexure of the Adria lithosphere and the eastward migration of the Apennine a fold-and-thrust belt (Malinverno and Ryan, 1986; Doglioni et al., 1999).

The Mesozoic and the Paleogene are characterized by a predominantly carbonate epi-continental sedimentation linked to a complex paleogeographic configuration formed by deep basins and open platforms (Calamita and Deiana, 1988). This sedimentation was more continuous in the deep basins and discontinuous in the open platforms, with different periods of emersion and erosion, such as in the Middle and Upper Cretaceous and the Paleogene (Zappaterra, 1990). The flexure of the lithosphere coupled with the eastward migration through time, generates a series of foredeep basins parallel to anticlines and filled by terrigenous sediments derived from the progressive erosion of the incipient belt (Ori et al., 1986). The two main detachment levels are the structural elements that drive the fold-and-thrust belt and the foreland area, one at the top of the Triassic succession, within the Triassic evaporites, and one within the Messinian evaporites (Koopman, 1983).

During this geodynamic evolution, the marine Jurassic and Cretaceous sedimentary successions were stacked and incorporated in the fold-and-thrust belt and today compose the Apennine orogenic wedge (Cavazza et al., 2004; Carminati and Doglioni, 2012). The result of this geological evolution is the occurrence of fault-related anticlines, with detachment located mainly on the Triassic evaporites, and aligned in the Apennine direction (NW-SE) which constitute, at the present day, the structural setting of the Adriatic domain (Argnani and Frugoni., 1997; Carminati et al., 1998; Castellarin, 2001; Casero, 2004; Patacca and Scandone 2004; Bigi et al., 2013; Casero and Bigi, 2013, Cazzini et al., 2015).

As evidenced by the intense exploration activity of the oil companies during the 1970s and 1980s, the tectonic and sedimentary evolution generated the conditions for the formation of hydrocarbon fields on both sides of the Adriatic Sea (Casero and Bigi, 2013). At present, hydrocarbons exploration is finished but thanks to this, the area is covered by a quite large (although dated) dataset. This domain has already been identified as a potential area for geological storage of CO_2 (Buttinelli et al., 2011; Donda et al., 2011; Civile et al., 2013; Volpi et al., 2015, Saftić et al. 2019) for the occurrence of saline aquifers occurring into the mentioned anticlines and all these studies enable identification of the calcareous and sandy formations as potential storage reservoirs.

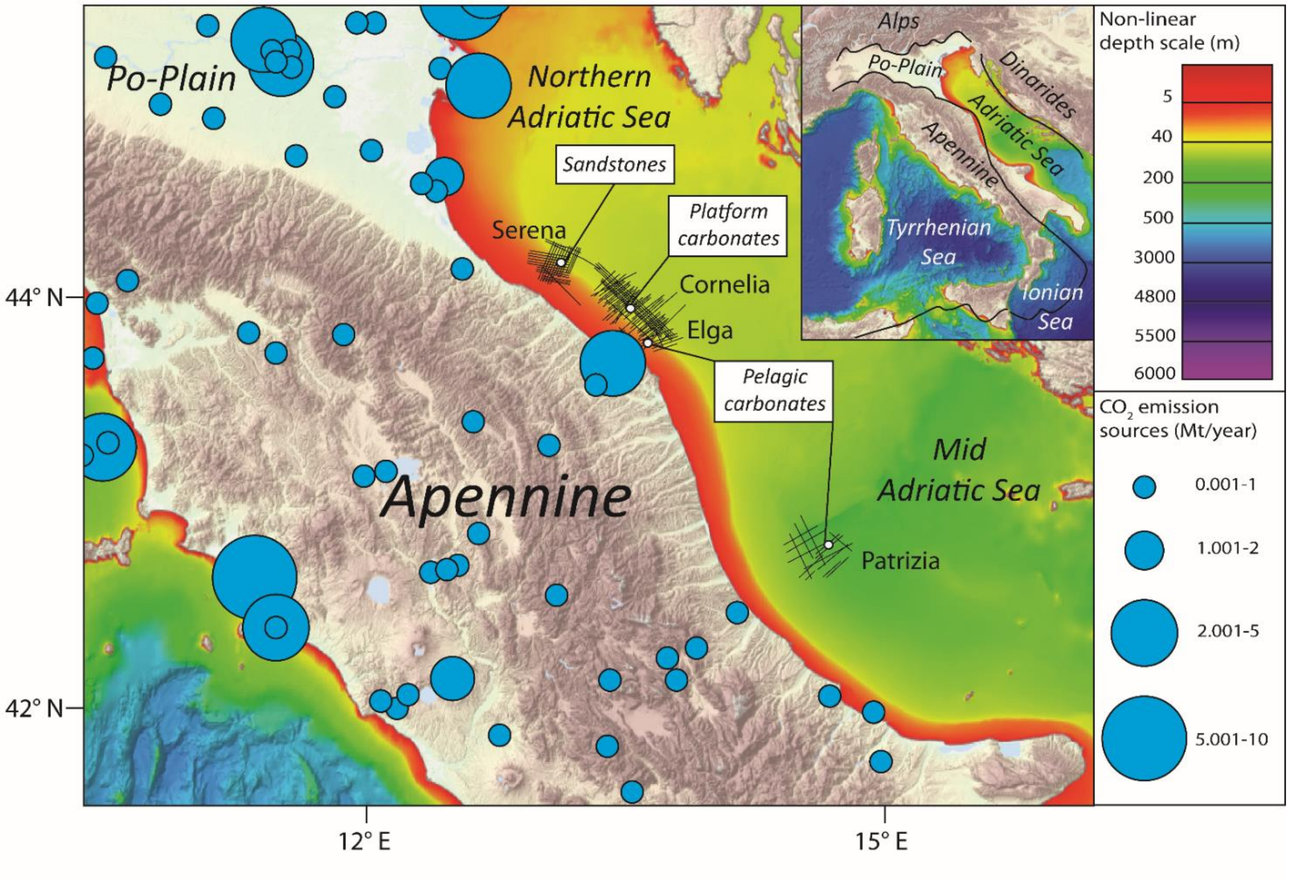

Fig. 2. Area of site screening in the central part of Italy. The location of the identified reservoir is on the offshore of the Adriatic Sea. The bathymetry is highlighted to show the depth of the seafloor in correspondence of the selected sites. For the wells is indicated the lithology of the identified saline aquifers and the seismic dataset that allowed the reconstruction of the structures. The main sources identified in the Geocapacity project (modified by 'Vangkilde-Pedersen et al., 2009b') are indicated with the blue circles, their size depends on the amount of emitted CO_2. (Bathymetry form 'GeoMapApp – Ryan et al., 2009').

Data and method

The basis of this work is interpretation of seismic reflection data, analysis of well logs data and structural maps in the Adriatic Sea, using a combination of public and confidential data. The public data are available (Fig. 2 and 3) through the 'Visibility of Petroleum Exploration Data in Italy (ViDEPi)' project (Ministry of the Economic Development), a public database deriving from the petroleum exploration activity conducted in Italy from 1960s up to 2015 (https://www.videpi.com/videpi/videpi.asp). The public database was supplemented and improved with seismic reflection datasets from the same areas provided by ENI (National Hydrocarbons Authority), through a confidentiality agreement.

With the solid framework obtained with seismic interpretation, it was possible to construct 3D geological models of the saline aquifers hosted into anticlines structures, to obtain an estimate of the potential volume of CO_2 that can be stored in the selected structures.

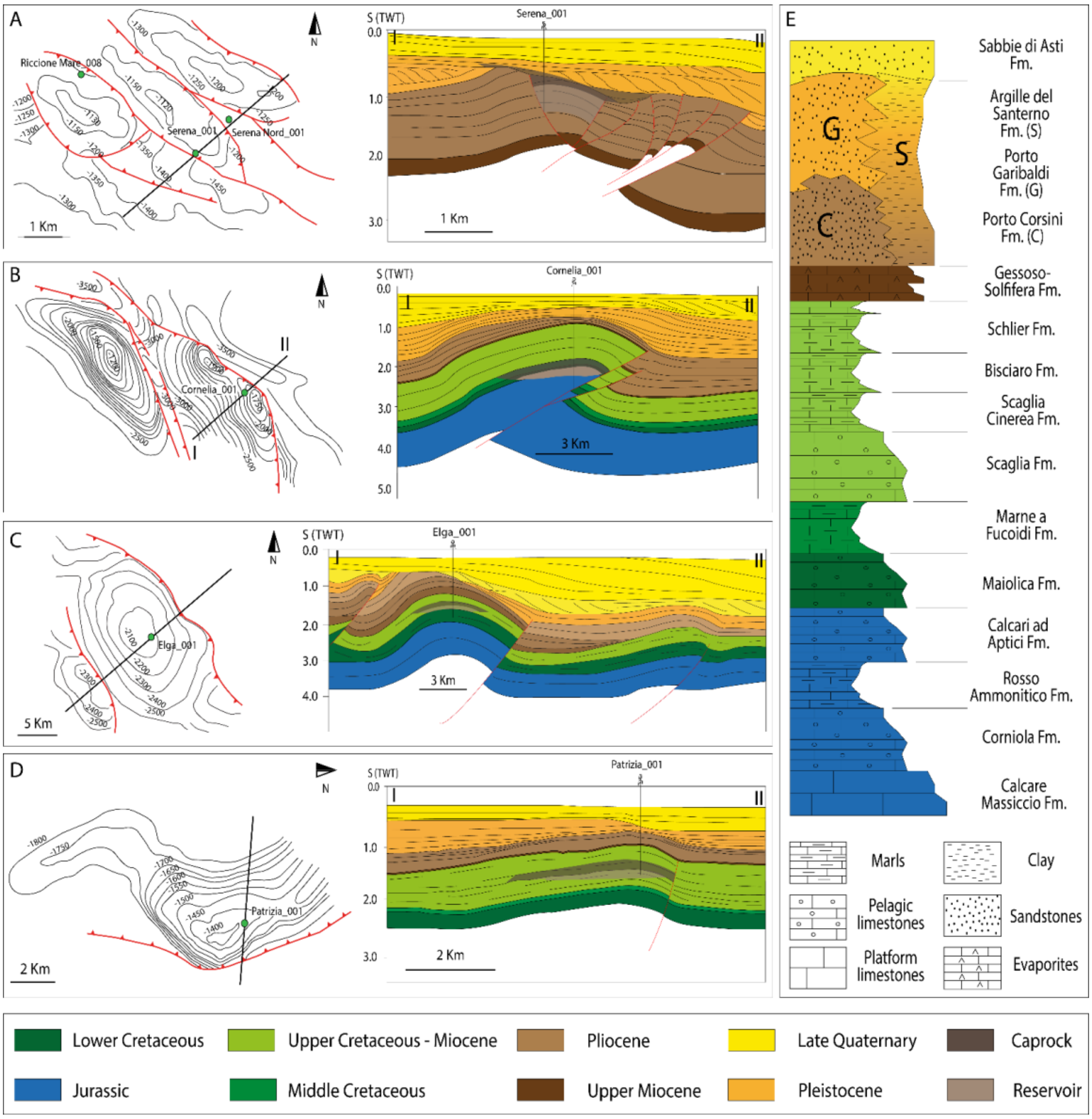

Fig. 3 Structural setting of a) Serena, b) Cornelia, c) Elga and d) Patrizia structures identified as possible CO_2 storage sites in this work (see Figure 2 for location) and stratigraphic log of the Mid Adriatic Sea (d, formation thicknesses are not in scale). **a**) Isochrone map (in milliseconds of an interval near the top of the 'Porto Corsini' Fm., Pliocene) and interpreted cross section of the Serena structure. This anticline is characterized by several thrust sheet and a very thick sandy-clay succession, the caprock of the identified saline aquifer is the clay succession of the 'Argille del Santerno' Fm. **b**) Isochrone map (in milliseconds of the 'Marne a Fucoidi' Fm., Middle Cretaceous) and interpreted cross section of the Cornelia anticline. Cornelia is a large anticline with a deep basal detachment, the reference figures indicate the location

of the Cornelia_001 well, the level identified as a possible reservoir in the platform limestone formation of 'Calcare Massiccio' and the potential caprock in the formation of the 'Marne a Fucoidi'. **c**) Isochrone map (in milliseconds of the interval of 'Scaglia' Fm., Upper Cretaceous) and interpreted cross section of the Elga structure. This structure hosts a suitable reservoir in the fractured calcareous member of the pelagic limestone formation of 'Scaglia' and the potential caprock in the formation of the 'Scaglia Cinerea'. **d**) Isochrone map (in milliseconds of the 'Scaglia' Fm., Upper Cretaceous) and interpreted cross section of the Patrizia anticline. The figures indicate the location of the Patrizia_001 well and the structural map that shows in this area a main fault plane, linked to the Patrizia anticline. Patrizia is similar to Elga anticline for the structural setting, and it has the same identified formations as the caprock and the reservoir. **e**) Stratigraphy of this sector of the Adriatic domain, the thickness of the formations is not in scale. In the lower part of the log the lithology of the formations is indicated.

On the basis of various equations, it is possible to estimate the potential volumes (effective capacity), combining the area, thickness, and porosity of the saline aquifer with the N/G ratio and the density of the CO_2 in reservoir conditions (Bachu et al., 2007; Van Der Meer and Yavuz, 2009; Vangkilde-Pedersen et al., 2009a; Goodman et al., 2011). The greater detail and reliability of the data contribute to better definition of capacity and to lowering the cost of using this technology. However, even the theoretical values serve for the authorities in charge and the companies to evaluate the potential of an area and its use. The most used and most efficient equation (1) for calculation of capacity is that established by the USDOE (United States Department of Energy), used for most of the published volume calculations and by the geological storage Atlases (Bradshaw et al., 2011; Wright et al., 2013; Bentham et al., 2014; Riis and Halland, 2014; Ketzer et al., 2015).

$$MCO2 = A\ x\ h\ x\ \varphi\mathrm{m}\ \mathrm{x}\ \rho\mathrm{CO2}\ \mathrm{x}\ \mathrm{E} \qquad (1)$$

where:

MCO_2 = Mass of CO_2

A = Areal extension of the saline aquifer

h = Average thickness of the saline aquifer

φm = Average porosity of the saline aquifer

ρCO_2 = Density of CO_2 in saline aquifer conditions

E = Storage efficiency factor of the saline aquifer

In this work, the area and average thickness were substituted by direct estimation of the volume provided by the 3D modelling using dedicated software. The 3D volumes obtained were then populated with the detailed porosity models derived from well log data. To provide the density of CO_2 required in equation (1), the depth of each saline aquifer and the regional geothermal gradient of the Adriatic domain were used (http://geothopica.igg.cnr.it/; Bachu, 2000; Kovscek, 2002; Holloway, 2005; Suekane et al., 2005; Gough and Shackley, 2006; Ramírez et al.; 2010; Aminu et al., 2017).

The petrophysical parameters to populate the 3D geological models were obtained with analysis of the available well logs. Data from four wells, one for each structure, named as the corresponding structure, were used to populate the models. More in detail, the porosity data were obtained from the sonic logs, by transforming the transit times into porosity with the correlation curves between velocity and porosity for carbonates, dolomites, and sandstones (Wyllie et al., 1956,1958,1962; Raymer et al., 1980; Crain, 1986). In this way, a vertical porosity profile with a detail of 10 m was obtained along the well for the saline aquifer thickness interval. These data were upscaled to a 50x50x10 m 3D grid. The method applied to simulate the porosity distribution in the 3D geo-cellular model is Sequential Gaussian Simulation (SGS). The choice of this simulation algorithm is based on the studies by various authors (Journel and Alabert, 1989; Verly, 1993; Al Musawi and Jawad, 2019) who, with several experimental tests of different variogram models, proved that this simulation of porosity distribution is statistically representative. The SGS method is in fact a geostatistical method that is available in Petrel software; it performs a redistribution of the porosity values into the rock volume based on the statistical distribution obtained from the well log analysis. It performs a normal score transformation of the porosity distribution and calculate the probability distribution of porosity values for each node of the grid, starting from a random point and repeated the procedure covering all the volume. The result of the SGS simulation is a statistical distribution of the petrophysical value (in this case porosity) and it is greatly conditioned by the quality and quantity of dataset. It is the most used algorithm for the upscaling of petrophysical properties in saline aquifer modelling as evidenced by the numerous published papers (Guerreiro et al., 2000; Nezhad and Tabatabaei, 2017; Zare et al., 2020; Trippetta et al., 2021). In this work, the main limitation is associated with the use of data from just one well log for each structure; this did not allow the control of the geographical distribution parameter (to simulate a kriged grid) increasing the uncertainties of the procedure (Kavousi and Gao, 2013; Xu, 2017).

Despite the limitation due to the source of data represented by one well log for each site, the use of the SGS method represents one of the many possible representations of the porosity distribution within the aquifers. This could be improved by multiple repetition of the same method, through a more detailed statistical analysis. Although we are aware of the limit of our SGS simulations determined by the limited data available, we believe that they can still provide a useful indication for example for the expected heterogeneity.

However, despite these uncertainties, this method provides a distribution of the measured property even in the case of few data (as in this case) and represent a first approximation of the available pore volume.

In fact, the distribution of vertical and horizontal porosity within the geocellular model also results in a pore volume value, which can be representative of the theoretical porosity of the aquifers. A similar single pore volume value can be obtained simply by multiplying the gross rock volume by the average porosity from each well; in this light, the advantage of using the SGS simulation is to obtain a representation of the heterogeneity (statistical) of the porosity in the aquifers.

A realistic value of the pore volume and the distribution of porosity is achieved through the choice of factors called variograms, which drive the possible realizations of the cell models. Variograms control the spatial variance of properties that can be attributed to a distribution model. In the case of models referring to a geological formation, these will drive heterogeneities in the distribution of properties such as facies, porosity or permeability, and fluids. There are some parameters that must be defined to distribute these properties such as angles, ranges, anisotropies, means and standard deviation.

Behind the choice of the various parameters that govern the variograms there can be different approaches, from well data to outcrop analogues. For the population of the aquifers in this work we adopted parameters on the base of geological constraint described in detail in the next paragraph.

From equation (1), once the pore volume (3D volume x φm) is obtained from the geo-cellular model, the CO_2 density ($\rho\ CO_2$) should be estimated at the saline aquifer condition (Doughty et al., 2001; Bachu et al., 2007; Vangkilde-Pedersen et al., 2009a; Goodman et al., 2011).

The main factors that influence the density of CO_2 are pressure and temperature. Therefore, when calculating the density of CO_2, the effective pressure and temperature of the saline aquifer must be defined. According to Terzaghi (1925; 1936) the effective pressure of the saline aquifer is calculated by:

$$\sigma_{effective} = \sigma_{lithostatic} - \sigma_{pore} \quad (2)$$

where $\sigma_{lithostatic}$ = pressure of the water column (if the saline aquifer is offshore) plus the head of the rock column. the pressure of the water column depends on the density and depth of the sea water as well as the density and thickness of the rocks above the reservoir (Carrozzo et al, 1990; Venisti et al., 2004); σ_{pore} is the pore pressure within the saline aquifer and depends on the hydrodynamic condition of the saline aquifer itself; $\sigma_{effective}$ represents the real pressure state of the saline aquifer (Avseth, 2010; Smith et al., 2011).

Pore pressure data were obtained from public sources (wells from ViDEpi), and estimation of pressure in depth was performed using the Petroleum Systems Modeling Software PetroMod. Pore pressure was modelled with 1D models considering only pure hydrostatic conditions.

The storage efficiency factor (E) is one of the most important variables for calculation of storage capacity. It is derived from many site operations and dynamic or numerical simulation, such as the Monte Carlo simulation (NETL, 2008), during injection. The storage efficiency factor in saline aquifers is based on a series of parameters and components that represent different physical limits and barriers that prevent the injected CO_2 from filling the entire pore volume in a certain saline aquifer or basin. These limits are dependent on the total volume, the total porosity, the effective porosity, and the permeability, so the reason for including the storage efficiency factor in Eq.1 is to quantify the volume that can be used to store and inject CO_2. This coefficient is not unique, it varies according to many factors such as net to total area, fraction of an area with suitable formation present, net to gross thickness, fraction of geological formations with minimum petrophysical characteristics suitable for injection, ratio between total and effective porosity, areal displacement efficiency, geological formation heterogeneity, presence of fault, vertical displacement efficiency, gravity, capillarity, brine salinity, buoyancy, microscopic displacement efficiency, water saturation of the aquifer (NETL, 2006, 2008; IEA GHG, 2009). These factors are grouped into a single parameter called Storage Efficiency Factor which defines the percentage of the pore volume that can be exploited, since the inclusion of all these parameters within E considers all the possible variables. The variability of the values of the different parameters indicated by the different authors is an approximation; it is intended to be representative for various structural arrangements, depositional systems, and lithological characteristics that have different boundary conditions.

Considering all these variables, the proposed range for the storage efficiency factor for open aquifers is between around 1% and 4%, based on the type of saline aquifer (Doughty et al., 2001; Bachu et al., 2007;2015; Vangkilde-Pedersen et al., 2009a; Goodman et al., 2011). In closed structures, such as anticlines or domes, the storage efficiency factor assumes values between 1% and 20% (Gorecki et al., 2009; Vangkilde-Pedersen et al., 2009a; 2009b; Marek et al., 2011; Knopf and May, 2017). The higher value reflects the fact that in the anticlines the mechanism of structural confinement plays a very important role, which significantly increases the trapping efficiency and the value of E. In this work values of 7% for fractured pelagic carbonates, of 10% for fractured platform carbonates and 13% for sandstones are considered. The choice of the E value for pelagic and platform limestones is in accordance with the storage efficiency factors proposed for saline aquifers identified in closed structures (Gorecki et al., 2009; Marek et al., 2011; Knopf and May, 2017); in the case of Serena anticline, which hosts a siliciclastic reservoir E should be higher, close to about 18%. The choice of a lower value is due to the fact that Serena is fault bordered and injection at high pressure could cause a reduced displacement of the native fluids, thus limiting the storage efficiency during the injection phase.

These E values, adopted from the previously mentioned studies, are based on different lithologies and reservoir boundary conditions and can be corrected and specified with future detailed research. The importance of the lateral heterogeneity of the aquifers and its behavior, the interaction with capillary pressure and the possible lateral migration of CO_2 can affect - in most cases reduce - the effective storage capacity and efficiency of the geological formations (Williams et al., 2013).

Structures

Of the areas and structures (Donda et al., 2011; Civile et al., 2013) identified as possible storage sites in the Adriatic offshore, four structures largely covered by ample datasets are chosen. These structures (Fig. 2) are located offshore in the Northern-Mid-Adriatic Sea: Cornelia, Elga and Serena anticlines in the north and Patrizia anticline in the centre Adriatic Sea All of them have already been identified as excellent targets for CO_2 storage in previous studies on both the regional (Buttinelli et al., 2011; Donda et al., 2011; Civile et al., 2013) and local scale (Cappelletti et al., 2012; Teatini et al., 2014). Figure 3 shows the geological setting and the stratigraphy of Cornelia, Patrizia, Serena and Elga anticlines, the latter being very similar to the Patrizia structure both in the setting and the lithology.

The Serena anticline (Fig. 3a) is in the northern Apennines offshore, in an area where the Plio-Quaternary siliciclastic succession is involved in thrusting. It is characterised by several thrust sheets that affected the Pliocene deposits, composed of a thick sandy-clay succession with marked lateral facies heterogeneity. The saline aquifer of the Serena anticline is recognized in the thick Pliocene siliciclastic sequence on the top of the Adriatic Mesozoic formations, the Porto Corsini Formation delimited at the top by tens of metres of clay succession of the ‘Argille del Santerno’ Formation (Fig. 3e) (Castellarin, 2001; Patacca and Scandone 2001; Artoni, 2013).

Cornelia is a thrust-related fold (Fig. 3b) in the northern-Apennines offshore, in an area that includes many compressive structures linked to as many reverse faults. In the case of Cornelia, the main thrust fault plane splits into another minor plane cutting the forelimb of the anticline. The anticline is composed of the Mesozoic succession, covered by the Plio-Quaternary siliciclastic facies (Casero and Bigi, 2013). For the Cornelia anticline, the target reservoir is the ‘Calcare Massiccio’ Formation a thick Jurassic formation consisting of fractured and dolomitized platform limestones. The porosity is due to fracture intensity and dolomitization, two excellent properties for a site in view of the possibility of storing carbon dioxide. The caprock is identified in the ‘Marne a Fucoidi’ Formation (equivalent), composed of calcareous micrites and marl intercalations (Fig. 3e). This formation is generally recognized by oil exploration companies as a very good seal in the Adriatic area. In this structure, the base of the reservoir is around 2700 m in depth, while the base of the caprock approximately 200 m above.

Elga (Fig. 3c) is a fault-related anticline in the offshore of northern Apennines, close to the anticline of Cornelia. In the case of the Elga structure, the formations identified as reservoir and caprock are the Scaglia Formation and the Scaglia Cinerea Formation, respectively. These formations are the same as can also be recognised in the case of the for Patrizia anticline (Fig. 3d), located further south; the only difference lies in the depth of these formations, greater in Elga. These structures are mainly composed of the Cretaceous carbonate succession and are covered by the Plio-Quaternary siliciclastic sequence. The potential reservoir for the CO_2 storage is the calcareous member of the 'Scaglia' formation, composed of fractured pelagic limestones; more in detail, this is made up by calcareous layers and marly intervals with a high level of fracture intensity on outcropping analogue (Tavani et al., 2008; Petracchini et al., 2012). The Patrizia reservoir has a thickness of around 100 m, while in the Elga anticline the thickness is around 270 m. A very good factor in these anticlines is the large areal extension, resulting in the very large potential reservoir volume of the structures. The caprock is the Scaglia Cinerea Formation, an alternation of marls and calcareous marls, for about 250 m of thickness (Fig. 3e).

Saline aquifer volume calculation

The 3D geological models are generated from a dense 2D seismic lines interpretation framework, with an average line spacing of about 600 m, which is the basis for the volumetric modelling of the saline aquifers, subsequently populated with the porosity derived from well data.

In the Cornelia, Patrizia and Elga structures the maximum depth of the exploitable saline aquifer volume is determined above the depth at which the saline aquifer formation is in contact with the thrust fault; in this way, the role of the fault as a potential conduit is avoided. In fact, since its behaviour is unknown, this choice considerably reduces the risk of leakage through the fault. For these three structures (Fig. 4), the top surface of the saline aquifer formations (z-values surface) and a flat 'artificial' surface (in white) are modelled to identify a "spill-point" which is limited by a fault at that depth, assumed to be the maximum depth for feasible CO_2 injection. This procedure is applied to all carbonate saline aquifers, while in the siliciclastic saline aquifer of Serena the maximum exploitable depth was taken to be that of the bottom of the well itself.

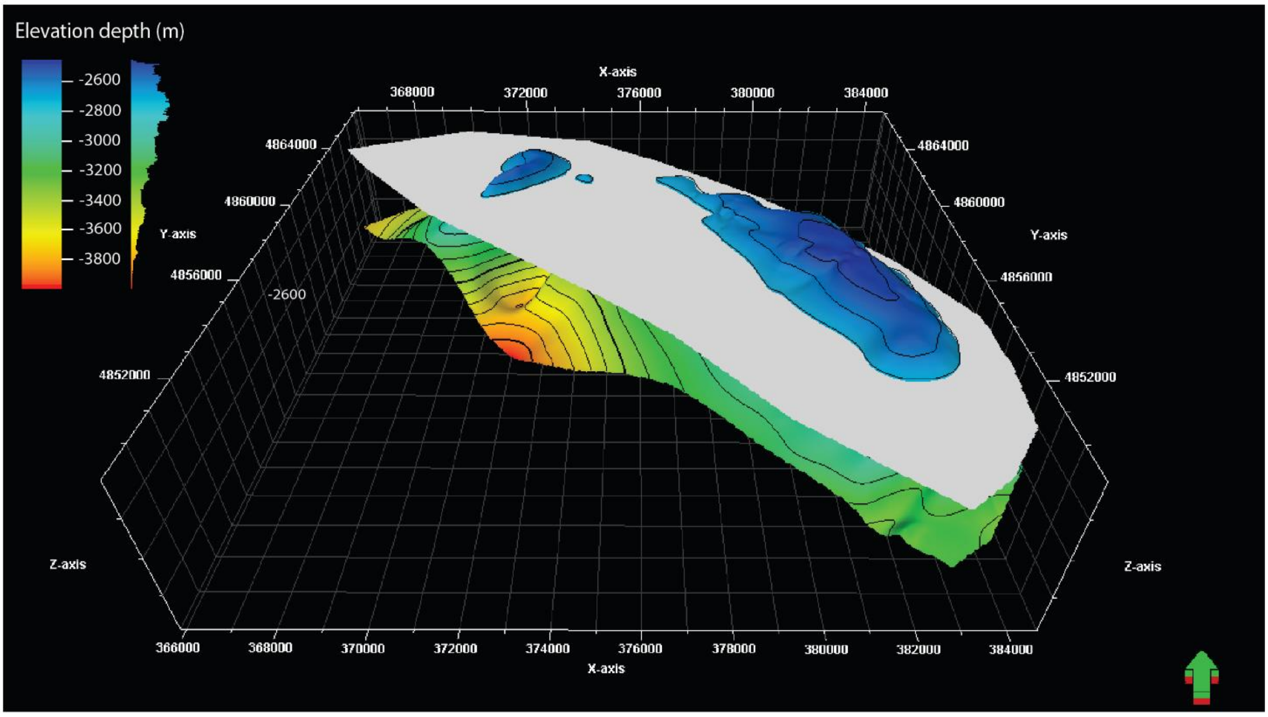

Fig. 4. 3D modelling arrangement for the determination of the exploitable part of the saline aquifer formation. This model refers to the Cornelia anticline. The colour-scale surface represents the top of the formation with good reservoir characteristics, whereas the white flat surface represents the lower depth for the storage interval. The blue-scale surface of the formation above the flat surface is the interval in the right depth range, therefore exploitable for storage.

In Cornelia, the base depth of the reservoir is 2700 m, and it was chosen on the basis of the data analysis of the Cornelia 001 well, which shows good porosity and fracture intensity conditions down to this depth. For Elga the basal limit is 2350 m, corresponding to the base of the saline aquifer formation, whereas for the Patrizia structure, the basal limit is the maximum depth of 1648 m.

In the case of Serena, the reservoir is bordered laterally by two faults, so an evaluation of the behaviour of these faults is required. However, it is difficult to determine their behaviour as no direct data are available for this kind of evaluation, we lack detailed stratigraphy of the siliciclastic succession in the hanging wall and in the footwall of the faults, as well as data on the amount of the offset of the faults themselves (Yielding et al., 1997; Freeman et al., 1998; Harris et al., 2002). The only indication on fault behaviour in the Serena structure can come from the occurrence of fluids, just water in the Serena well, detected in other wells located in adjacent sectors for the same stratigraphic interval. In fact, in well Serena Nord 001 and Riccione Mare 008 (Fig. 3a), that are located respectively at a distance of about 1.1 km and 5 km from the Serena well, for the same stratigraphic interval, that is at depth between 1084 and 1300 m, the report of the wells indicates that there are formation water and the occurrence of gas, and this difference is probably linked to the lack of communication between the wells. This observation leads to the assumption that essentially these faults act as a barrier and does not favour fluid migration. Of course, the seal effect is also connected with the capillary pressure exerted by the supercritical CO_2 once injected into the saline aquifer, but the observed distribution of water can also support the occurrence of a sufficient threshold of capillary pressure.

3D models

The frequency distribution logs of porosity values shown in Fig. 5, is obtained from sonic log analysis. The composite logs available for the analysed wells also comprise the resistivity and the spontaneous potential logs, as well as the description of several core samples at different depths within the saline aquifer interval. In the case of the Patrizia well, where the potential reservoir is in the Scaglia Formation, the occurrence of fractures is described in one core sample, whereas no data are available for the Elga well. The description of lithologies in the Cornelia well indicates the occurrence of fractures in both the calcareous and dolomitic reservoir interval, whereas there is no indication of fracture intensity for the Patrizia well. For these reasons, the porosity distribution obtained from sonic log can be considered as representative of both the primary and secondary porosity without any possibility to distinguish between them. Of course, at least in the case of the Cornelia and Patrizia wells, some of the porosity values measured are due to the occurrence of fractures but on the evidence of the above-mentioned dataset it is not possible to define the fracture intensity contribution to the total porosity.

Considering the range and average values, the highest porosity values concern the siliciclastic saline aquifer of Serena (Fig. 5a) with a range from 27% to 40%. For the carbonate saline aquifer, the values are generally lower: the platform limestone formation of the Calcare Massiccio Formation of the Cornelia anticline shows porosity ranging between 5% and 24% (Fig. 5b), whereas Elga (Figs. 5c, 5d) has porosity values ranging between 3% and 16%, and between 1% and 18%, for Patrizia. Despite these average values, the Scaglia Fm shows thin intervals with slightly higher values, even up to porosity greater than 30%; these levels correspond to calcareous turbidites deposits intercalated within the pelagic mudstones and /or to dolomitic levels.

For the choice of the parameters of the variograms in all the structures, an angle of 135 ° with respect to the north was set, therefore NW-SE, since the lateral heterogeneity, linked to both the depositional system of the formations and the current geological structure, follows the orientation of the Apennine chain. For the property values, the mean, and standard deviation, a 'from upscaled log' distribution was used, which then follows the well log values. In this way, these aquifers show several differences in the spatial ranges of the internal anisotropies of the aquifers, which depend on the different formations.

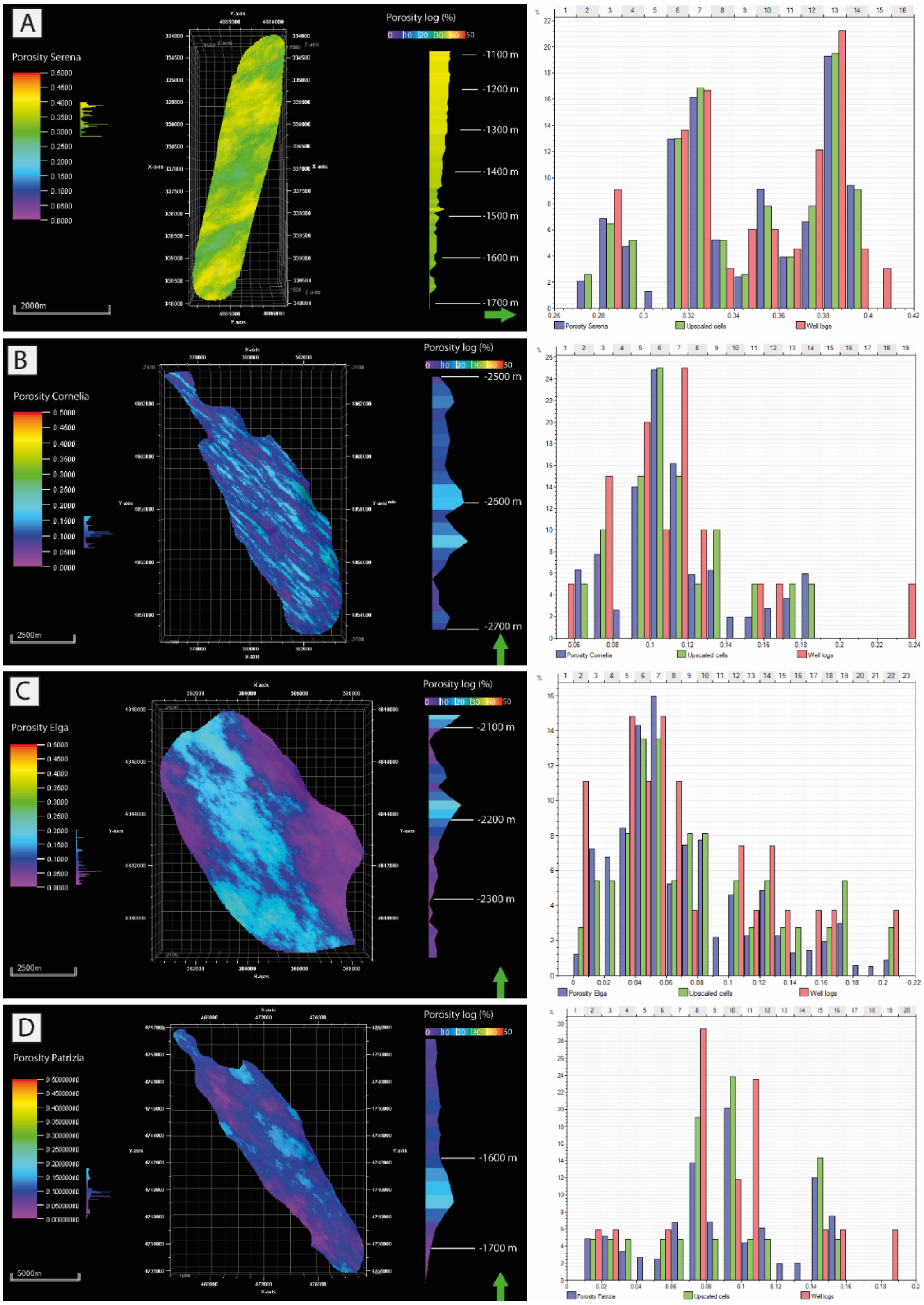

Fig. 5. 3D petrophysical models of the exploitable part of the saline aquifer. For each storage site model is shown the data relative to the porosity frequency and to porosity log values in depth. The histograms are included to illustrate the statistical distributions of the porosity for each structure, derived from upscaled log and upscaled cells. These histograms represent the relationship between porosity values and percentage of the total volume. **a**) Serena structure; **b**) Cornelia anticline; **c**) Elga structure; **d**) Patrizia anticline (See Fig. 2 for the location).

The Serena anticline hosts a siliciclastic reservoir that was deposited in a context of thrust-top basin (Ori et al., 1986), thus a basin that received sediment flows from an eroding chain behind it. The heterogeneity of the sands is therefore oriented in the direction of the advancing chain and the basin has an elongated shape in the NW-SE direction of the order of a kilometre, and a lateral variation in a range between 300 and 400 m (Ghielmi et al., 2013). The range of anisotropies chosen in this case is therefore 1000 x 350 m, in accordance with studies on the sedimentology of these deposits. The Cornelia structure hosts a saline aquifer composed of platform limestones from the Calcare Massiccio formation. The platform limestones generally show a great lateral heterogeneity, deriving from the facies, the depositional system and the nature of the carbonate platforms which is very dynamic. The geometry of the anisotropies was strongly elongated to fit with the facies in the carbonate systems (Fig.5b) (Brigaurd et al., 2014), and the range chosen is 1000 x 150 m, to represent even the structural control of the anticline.

For the structures of Elga and Patrizia the saline aquifers have been identified in the Scaglia Formation, a formation composed of carbonate pelagic deposits. This formation consists of pelagic mudstones mainly composed of planktonic foraminifera and carbonate mud, except in the areas close to the platforms where carbonate calcarenite flows are present (Colacicchi et al, 1986; Fabbi et al., 2016). Apart from these latter deposits, the Scaglia formation is almost totally homogeneous laterally, so the ranges chosen for the anisotropies are very large, about 7000 x 3000 m, and are intended to represent the lateral variability related to the anticline structuring.

CO_2 density estimation

Calculation of the potential capacity of the structures considered called for definition of average values for porosity and its distribution and CO_2 density. For the latter, the effective pressure and temperature in the saline aquifer has been reconstructed.

The reconstruction of the pressure-depth trend was performed using Petromod software by Schlumberger, adopting 1D models. It could be improved by introducing analysis in 2D and 3D, which requires data on the stress generated by the occurrences of faults and the pressure distribution under salt layers. In this case, only the 1D reconstruction was performed, and it revealed two different scenarios in the wells analysed (Fig. 6). The main problem resulting from the lack of the spatial relations data is that, in this condition, it is not possible to determine the outflow pressure below the potential impermeable layer, but only to define the occurrence of an overpressure. Moreover, we were unable to include the tectonic stress from possible surrounding faults (at Serena) when the modelled pressure was too low. The pressure information was drowned from the Schlumberger DST (drill stem test) data as shown in the composite logs of the wells analysed, and in some cases confirmed by the mud weight used while drilling (Fig. 7).

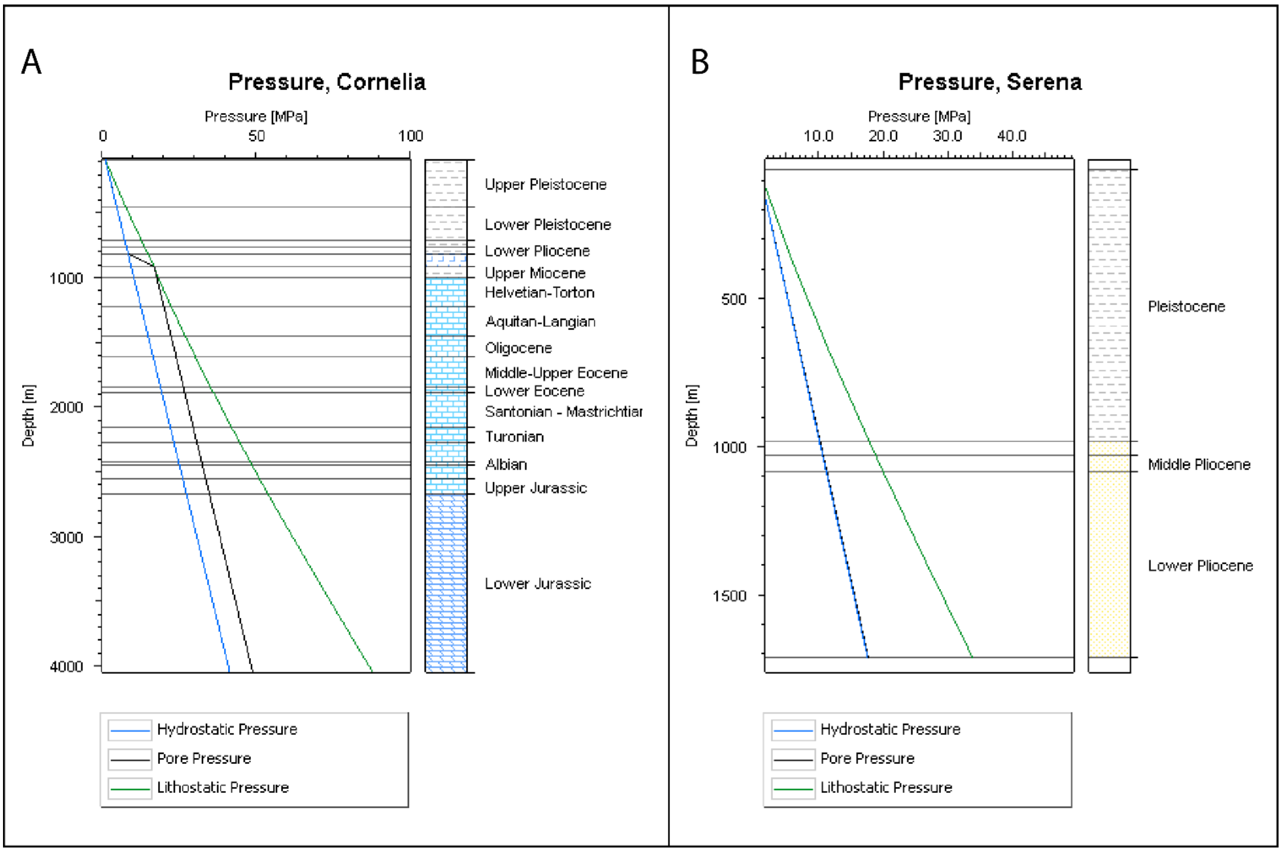

Fig. 6. a) Salt and **b)** non-salt pressure modeling scenarios. In the salt scenario the presence of the Messinian evaporites generates an abrupt increase of the pore pressure (black line) inside this interval, respect to the linear increase of the hydrostatic pressure. In the non-salt scenario, the behaviour of the pore pressure is the same of the hydrostatic pressure for the absence of a low-permeability interval that acts as a seal and considerably increase the pore pressure. This mean that in the salt scenario the pore pressure is higher than the hydrostatic pressure, while in the non-salt scenario the pressures have the same value.

The PetroMod modelling shows a clear difference between the linear increase of lithostatic and hydrostatic pressure and the non-linear increase of pore pressure. Overpressure build-up zones in some of the wells analysed is generated by the hindering of the normal compaction process due to the low permeability of the Messinian evaporites levels in the upper part of the well (Bertoni and Cartwright, 2015). In fact, this high efficiency evaporitic seal acts as a barrier to fluids and generates an abrupt increase in the pressure of the pores in the intervals beneath it (Nashaat, 1998) (Fig. 6). This leads to the presence of a salt-scenario and a non-salt scenario in wells analysed resulting in different pore pressure distribution. The consequence is a different calculation of the resulting effective pressure of the saline aquifer as a function of Eq. (2).

In a salt-scenario (Fig. 6a), as in the case of the Cornelia well, the pore pressure increase is greater than the hydrostatic pressure increases due to the presence of salt, so the resulting effective pressure is in accordance with Eq. (2), because the pore pressure value is different from the hydrostatic pressure value. In a non-salt-scenario, as in the case of the Serena well (Fig. 6b) the increase in pore pressure will be equal to the increase in hydrostatic pressure, so the values are the same and the resulting effective pressure is the difference between lithostatic pressure and hydrostatic pressure.

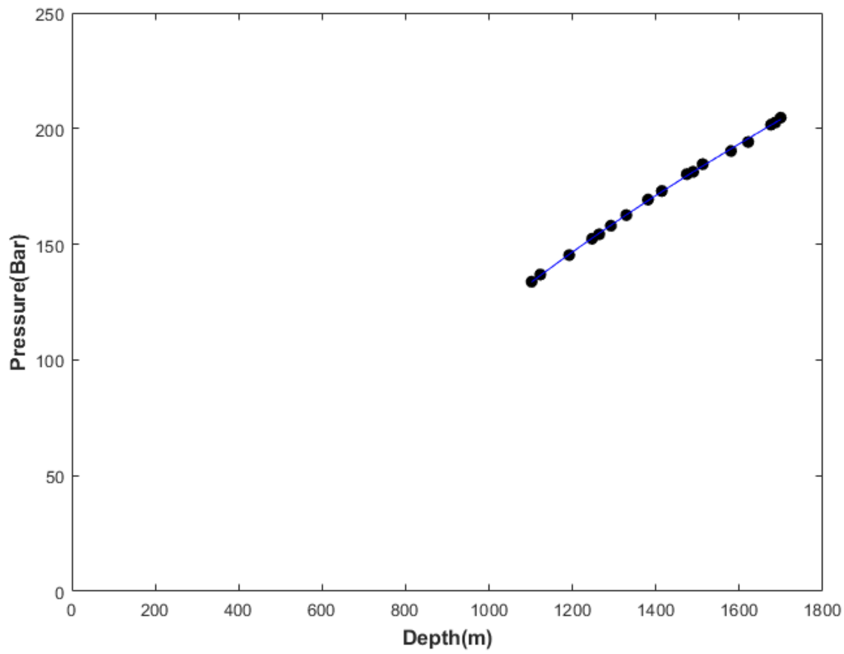

Fig. 7. Graphical plot showing the measured pressure data (from the DSTs) and depth in the Serena well.

In the Patrizia well, the interval analysed is from 1558 m to 1648 m, the well bottom. The well pressure data are drawn from formation testing, and the pressures noted in the interval were 180.9 kg/cm^2 (177.4 bar). This indicates slight overpressure, even more in shallower layers, whereas in the target interval from 2080 to 2350 m of depth in the Elga well, the pore pressure is near hydrostatic, ranging from 208 to 234 Bar (212-238 kg/cm^2). Although this well, too, had salt intervals in the Messinian formation in the upper part, the pressure in the bottom layers is still hydrostatic, suggesting the occurrence of a large aquifer, which is favourable for CO_2 storage. The effective saline aquifer pressure together with the temperature were used to calculate the CO_2 density conditions in the reservoir (Table 1). The Serena well crosses the saline aquifer interval from 1084 m to 1748 m. At 1102 m the pressure is 131.2 bar and at 1676 m it is 197.8 bar, so the pressure gradient factor is from 1.3 to 1.203. The interval of interest in the Cornelia well is from 2500 to 2700 m; due to the Messinian evaporites the pressure modelling shows a slight overpressure with gradient of 1.2 (Fig. 6, Table1). Temperatures of the saline aquifers were taken from the portal of the Geothopica Project (http://geothopica.igg.cnr.it/), a public national database that incorporates the subsurface data, the hot springs, gas, geothermal points, wells, isotherms, and the heat flow in Italy. In our case, for the

Cornelia, Elga and Patrizia wells, available temperatures of 341.15 K, 339.15 K and 313.15 K respectively were measured in the well during drilling. For Serena, the Geothopica database indicates the target depth temperature of 313, 15 K, derived from the geothermal gradient.

With pressure and temperature values it is possible to calculate the density of the CO_2 for the injection in reservoir conditions. This calculation is very important because it will also serve for guidance in many of the decisions that will be made during injection. For the estimation of CO_2 density in this work the calculator of the Penn State Energy Institute - College of Earth and Mineral Sciences was used (http://www.energy.psu.edu/tools/CO2- EOS/; Span and Wagner, 2006).

Structures	Reservoir Volume (m^3)	Pore Volume (m^3)	Effective Pressure (Bar)	Effective Temperature (K)	CO_2 density (kg/m^3)	Storage efficiency factor (%)	CO2 storage capacity (Mtons)
Serena	3476 x 10^6	1082 x 10^6	206,13	313,15	864,06	13	119
Cornelia	3308 x 10^6	337 x 10^6	368,27	341,15	845,4	10	28
Elga	10331 x 10^6	659 x 10^6	302,37	339,15	807,02	7	37
Patrizia	10880 x 10^6	914 x 10^6	178,7	313,15	818,16	7	56

Table 1. Results of static capacity estimations for the identified reservoirs in the Mid Adriatic Sea.

Results

Table 1 shows the results relating to the estimation of the storage capacity for the potential structures identified. All the parameters used for this calculation are indicated for each structure, including the total volume of the saline aquifer, the porosity, and the effective pressure in the conditions of the reservoir, obtained by the difference between the lithostatic and pore pressure, the temperature from the well data and the information relating to the density of CO_2 in the injection conditions. The storage efficiency factors, adopted for each structure are in accordance with Vangkilde-Pedersen et al. (2009a) and Knopf and May (2017). Serena structure shows a potential storage capacity of 120 Mt, whereas the dolomitized saline aquifer of Cornelia, shows a potential exploitable volume of about 30 Mt; the pelagic limestones of the Elga and Patrizia structures have a storage capacity value of 43 and 103 Mt, respectively.

Several studies have been conducted on macro-areas and on a regional scale to evaluate the storage capacity of the Italian territory (Buttinelli et al., 2011; Donda et al., 2011; Moia et al., 2012; Civile et al., 2013; Volpi et al., 2015). Although the database used by these Authors is essentially the same as used in this work, the capacity presented in these studies has values considerably higher than those obtained by this work. These differences are mainly due to decisions adopted during calculation procedure and to the values of the efficiency factors. In fact, previous works calculated volumes without a 3D reconstruction, using structural maps and formation thickness, and adopting average porosity and permeability values, instead of the upscaling approach used in this work thanks to the SGS simulation. One of the main factors was the definition of the bottom of the reservoir, that has been identified by using a flat 'artificial' surface to represent the base of the aquifer controlled by the structural traps represented by the geometry of the anticline. In Cornelia and Patrizia this flat surface represents the base of the limb of the anticline, while in Elga the base derives from the 'artificial' flat surface and the top of the 'Marne a Fucoidi' Formation, immediately below the 'Scaglia' Formation, since the 'artificial' surface cuts through the underlying formation. In Serena it is not necessary to define this surface because from the seismic interpretation it was possible to reconstruct three-dimensionally the base surface of the structure, located within the established depth range.

The efficiency factors used in this work are very conservative and greatly affect the results obtained; this can be deduced from the values of the theoretical capacity- which are more comparable with those of the previous works. The next step will be dynamic simulation of CO2 injection into the saline aquifer; in this way a more comprehensive description of saline aquifer behaviour can be defined, and the matched capacity can be calculated.

Discussion

In this work, we focus on the offshore of the Adriatic Sea, one of the areas in the Mediterranean domain considered suitable for CO2 storage; oil and gas exploration has been conducted there, mainly during the 1970s and 1980s. Evaluating the capacity of an area already extensively studied by oil/gas exploration has several advantages. The information already acquired on the geometric and petrophysical characteristics, together with the pre-existing infrastructure, and the proven fact that the geological formations targeted have already hosted fluids, all suggest that they will be able also to trap CO_2. Once a saline aquifer has been considered a good candidate for geological storage, the next step and one of the most important is the estimation of the geological storage capacity, or the physical limit of CO_2 that the saline aquifer can host. This value must be established to determine the maximal volume of CO_2 that theoretically can be used in the injection phase. The 3D modelling approach is used to obtain more accurate storage capacity estimates for the potential structures identified; in this way we can arrive at more realistic definition of the potential for the studied area.

The effective storage capacity of four potential reservoirs for geological storage in the Adriatic Sea has been estimated. Two of these saline aquifers have been identified in the member of fractured limestones of the 'Scaglia' formation, and in the anticlines of the Patrizia 001 and Elga 001 wells. A reservoir has been identified in the formation of the dolomitized platform limestones of the 'Calcare Massiccio' Formation in the Cornelia anticline, while further to the North, a saline aquifer in the Plio-Quaternary siliciclastic sequence has been identified through the analysis carried out in the structure crossed by the Serena 001 well. Finally, the storage capacities are estimated using different storage efficiency factors, applying the more realistic E value for the identified saline aquifers, based on depth, facies, and exploration level.

The methodology explained here has been applied to a public database obtained from the oil and gas exploration in the area. Certainly, this dataset allowed us the definition of the range of values of the main parameters and obtain the potential for the theoretical and effective capacity estimates for almost every structure that has already been drilled, which is important for estimation of the CO_2 geological storage as a novel national resource. On the other hand, regional seismic grids, and vintage well data are frequently insufficient to reach more detailed evaluations, which in any case would require more complete and dedicated studies. In this way the results from studies like the present one can help in drafting the targeted exploration projects that will catalyse the developments, i.e. attract investments.

CO_2 injection in carbonate successions has been extensively studied in the literature and experimentally, and it is well known that this type of injection has many positive aspects. The carbonate formations provide favourable conditions of confinement because the fracture networks developed can be exploited both as networks for diffusion of the plume and as a volume itself. Furthermore, the carbonate facies, through the dissolution processes linked to the pH variation, can generate a greater volume for the storage of carbon dioxide (Luquot and Gouze, 2009). Some studies also focus on the possible negative effects that could result from brine acidification (Deng et al., 2015; Peng et al., 2016), but these studies conclude that acidification has very little effect in saline aquifer conditions and one of the major effects is improved permeability, a positive factor in the CO_2 storage process.

In the geological storage of CO_2, certain aspects need particular consideration, since the aim of this technology is to inject the largest possible amount of fluid without compromising the integrity of the saline aquifer. For this reason, the most constraining limit chosen in this work is the depth of the reservoirs. A storage site should usually be at a depth between 800 m and 2500 m, to have a balance between the volume of the CO_2 injected and the storage costs, i.e. for the operation to be economically viable. This depth reaches 2700 m in favourable conditions, such as the presence of the already existing infrastructure that can be used to reduce the capital investment, and also if the saline aquifer facies is prone to the storage or has a high level of fracture intensity, which would significantly increase injectivity.

Conclusions

For characterization of the storage sites, the first phase is seismic interpretation of the structures chosen as possible storage targets. With the combination of public (ViDEPi) and confidential (ENI) data, a solid seismic interpretation framework of four structures (Cornelia, Elga, Patrizia and Serena) was constructed, and served as the basis of 3D modelling in Petrel. All these structures are anticlines, trending mainly NW-SE, located in the northern and central Adriatic Sea. The total volumes obtained populated with the distribution of porosity values derived from sonic log analysis, and the total pore volume arrived were combined with the CO2 density achieved using temperatures and pressure in reservoir conditions. Theoretical and effective capacity values were then calculated using eq. (2). The obtained values, showed in table 1, are more conservative than those previously published, although the datasets used are essentially the same. This is due to the constraints defined specifically from each structure, and the use of the 3D model, which allows for more precise definition of the available volumes.

The saline aquifers analysed in this work are strategically located and have enough storage capacity to be considered in hypothetical CCS projects. Moreover, the occurrence of numerous sources of CO_2 along the Adriatic Sea coastline and in the Po Plain (Fig. 2), identified in the final report of the GeoCapacity project (Vangkilde-Pedersen et al., 2009b) makes these saline aquifers attractive storage option, due to the proximity to CO_2 emission points that reach up to 10 Mt/year.

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