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CO_2 storage potential of deep saline aquifers: The case of Italy

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ABSTRACT

CO_2 Capture and Storage techniques (CCS), along with improvements in energy efficiency and a wider use of renewable resources, can represent a key instrument for the reduction of CO_2 emissions to the atmosphere. Deep saline aquifers offer the largest storage potential of all the geological CO_2 storage options and are widely distributed throughout the Earth. This study proposes that CO_2 geological storage is a viable option in Italy and provides the first systematic evaluation of the potential reservoirs in the country. An estimation of the potential CO_2 storage capacity of the selected Italian deep saline aquifers is presented. Most of the 14 identified areas lie in the major Italian sedimentary basins, i.e. the Apennine foredeep and the Adriatic foreland, which are characterized by thick accumulations of sediments. The potential reservoirs mainly comprise permeable terrigenous deep saline formations, whose capacity ranges from 30 to more than 1300 Mt. Based on very conservative estimates these areas would be able to contain the entire volume of CO_2 emitted in Italy for at least the next fifty years. Although these evaluations have not been considered as definitive, this study highlights the great potential of such formations in terms of application of the CCS techniques, even in very complex tectonic settings such as those found in Italy.

1. Introduction

It is widely accepted that the main reason why the temperature is rising is due to a very fast increment of greenhouse gases in the atmosphere. Among them, the amount of the carbon dioxide (CO_2) has risen exponentially since the Industrial Era. A long term record of CO_2 and other natural greenhouse gases come from analysis of the composition of air bubbles trapped in ice cores from Greenland and Antarctica (Berner et al., 1980; Neftel et al., 1982; Petit et al., 1999). In the last 420,000 years before 1750 (i.e. the beginning of the Industrial Era), CO_2 concentrations in the atmosphere remained within 280 parts per million (ppm) (Etheridge et al., 1996; Indermühle et al., 1999; Petit et al., 1999). Carbon dioxide abundance rose roughly exponentially to 367 ppm in 1999 (IPCC, 2001) and to 379 ppm in 2005 (IPCC, 2005). This increase is attributed to anthropogenic causes, primarily related to the combustion of fossil fuels (Le Treut et al., 2007). At present, global anthropogenic emissions are close to 26 Gt annually (Herzog and Golomb, 2004). In Italy CO_2 emissions from the major, stationary point sources (i.e. power plants, Fig. 1A) amount to about 220 Mt, placing our country in the fifth position among the major emitting European countries (http://www.geocapacity.eu).

While energy efficiency and renewable sources are in the long term the most sustainable solutions for the climate, global greenhouse gas emissions cannot be reduced by at least 50% by 2050, as they need to be, if other options are not used. The CO_2 Capture and Storage techniques (CCS) would then represent a key instrument for the reduction of the CO_2 emissions in the atmosphere. CCS is a suite of technological processes which consists of capturing the CO_2 emitted by the major industrial plants, transporting and injecting it into suitable geological formations, such as deep saline aquifers, depleted oil and gas fields and unmineable coal seams, for significant periods of time (thousands to millions of years) (IPCC, 2005). The CO_2 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 CO_2 and a total storage potential of at least 1000 Gt of CO_2 has been estimated globally (Benson and Cook, 2005). In fact, thanks to their large storage capacity and their almost worldwide presence, deep saline aquifers can play a major role in the CO_2 emission reduction. The Sleipner Project in the North Sea is the most famous and the first commercial-scale project dedicated to CCS. At Sleipner about 1 Mt of CO_2 has been stored annually since 1996. This is one of the best examples of large-scale CO_2 storage in a saline formation and clearly demonstrates the technical feasibility of the CCS methods. Deep saline CO_2 storage is also taking place on a commercial scale in Norway. In the Barents Sea Snohvit field, 0.7 Mt of CO_2 are injected annually into the Tubaen formation, a saline

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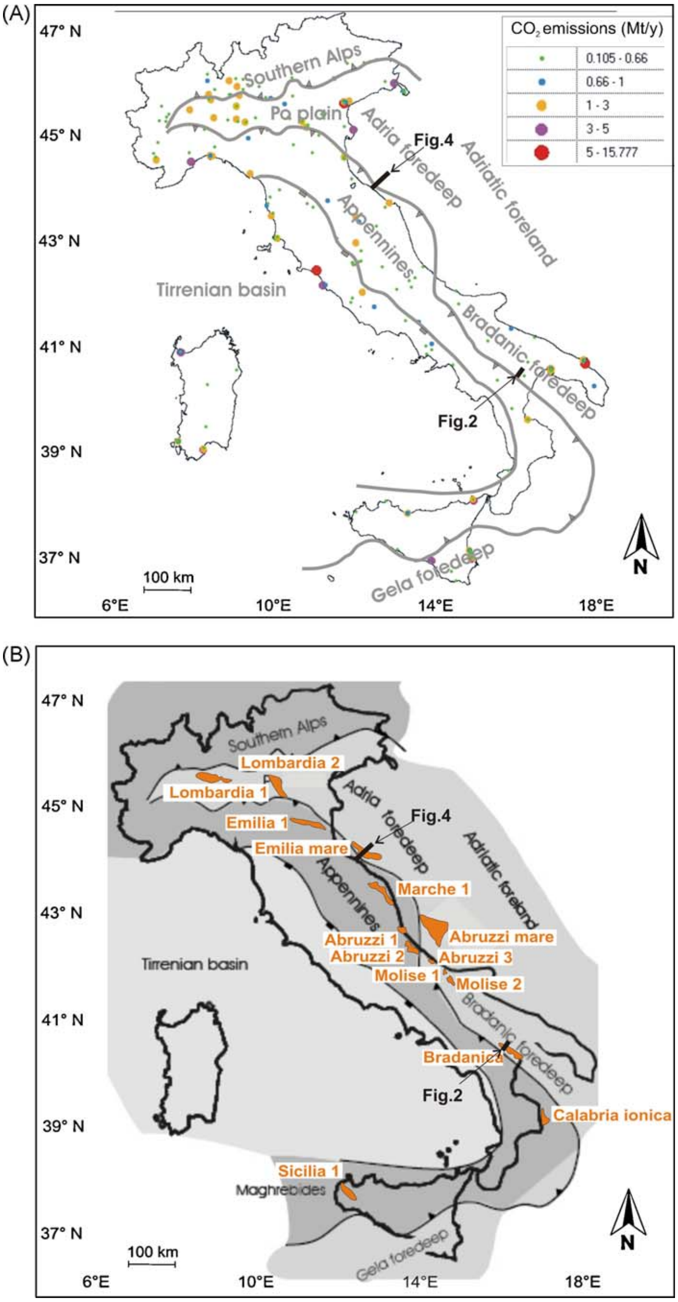

Fig. 1. Simplified geological map of Italy (from Bertello et al., 2008) showing: (A) the location of the major CO_2 point sources (emissions > 0.1 Mt/year); values are provided by Institute for Environmental Protection and Research; (B) the location of the 14 potential areas, suitable for the CO_2 geological storage.

sandstone aquifer. In addition, the Gorgon Project (Australia) will become one of the largest geological CO_2 sequestration projects in the world, where about 3.5 Mt of CO_2 will be injected annually into the Dupuy saline formation.

Here we present the latest results obtained through the analysis of the Italian deep saline, terrigenous formations performed within the framework of the EU GeoCapacity project, that led to the mapping and the evaluation of the storage capacity of potential areas and sites in the European countries (http://www.geocapacity.eu). Once the suitable sedimentary basins at the country-scale have been outlined, the next step has been focused on the potential reservoir and sealing units for CO_2 storage and characterization of their geological and physical properties. At this point regional, i.e. basin scale, CO_2 storage estimates based on the bulk volume of aquifers has been calculated.

This study represents the first, comprehensive evaluation of the Italian storage potential in deep saline aquifers and highlights the great potential of such formations in terms of application of the CCS techniques.

2. Geological setting of Italy

The occurrence of suitable saline formations in Italy for CO_2 geological storage is influenced by Italy's complex active tectonic setting, which has been dominated by the convergence of African and European plates since the Early Cretaceous (Coward et al., 1989). Some of the sedimentary successions deposited on the most distal margin of the Africa Plate (i.e. the Apulian Plate) were thrust over on to the southern edge of the European Plate, obliterating all traces of the Mesozoic Tethys. The major part of the sedimentary cover of the African plate margin and the Tethyan ocean deposits were folded and thrusted on to the Apulian Plate, thus forming the Apennine and Southalpine-Dinaric chains (Fig. 1). Around the end of the Paleogene, important rollback processes began to develop along the subducting western margin of the Apulian plate. During subduction, deep-seated lithospheric tear faults allowed slab segmentation and accommodation of different amounts of slab sinking across adjacent segments of the same plate margin. The present structural configuration of the Apennine system into two main orogenic arcs (Northern Apenninic Arc and Southern Apenninic Arc) has been interpreted as the final result of a differential passive sinking of the foreland lithosphere during the Africa-Europa convergence in Neogene and Quaternary times (Patacca and Scandone, 1989). Apennines and Alps and their southern and eastern sectors constitute a thrust belt–foredeep–foreland system (Fig. 1; Finetti, 1982; Vai and Martini, 2001; Marton et al., 2003) whose evolution was very complex and led to the creation of a wide range of geological scenarios (Bertello et al., 2008). Foreland and foredeep areas represent the major Italian sedimentary basins. The Apennine foreland evolved through a number of several tectonic phases, which led to a step-wise outward migration of the thrust and fold belt (Ghielmi et al., 2009). It consists of an Upper Triassic-Upper Cretaceous carbonate platform, overlain by a terrigenous Plio-Pleistocene sedimentary cover (Argnani and Frugoni, 1997; Marton et al., 2003; Casero, 2004).

The Apennine foredeep, which developed at the end of the Oligocene after the closure of the Tethyan Ocean is limited by the foreland ramp and the outermost submerged Apennine thrust front. The foredeep is a large and elongated, slightly deformed basin stretching parallel to the local structural axes of the Apennines. Its sedimentary infill is constituted of a succession of Messinian to Pleistocene turbidite deposits, whose thickness can vary from several tens to hundred meters (Ghielmi et al., 2009).

The seismicity map of Italy (Castello et al., 2004) shows that between 1981 and 2002 most of the earthquakes have magnitude lower than 4.0 and are located within the Earth's crust, in the upper 12 km. Subcrustal and deep earthquakes occur in the Tyrrhenian Sea, where the Ionian lithosphere subducts beneath the Calabrian arc. A close relationship between seismicity and topography in the Apennines is also recognizable (Castello et al., 2004).

Heat flow values are generally low (30–40 mW/m^{-2}) throughout the Mesozoic carbonate permeable units of the Alpine chain, central-southern Apennines and the Apulia platform (Della Vedova et al., 2001). Higher values (60–70 mW/m^{-2}) are present in some areas of the Alps and in the transition between the Alpine mountain belt and the Po Plain, where, locally anomalies of up to 100 mW/m^{-2} are encountered. Similar values characterize also

Table 1
Main characteristics of the Italian potential reservoirs for the CO_2 geological storage.

Site name	Stratigraphic unit	Formation	Geothermal gradient (°C/km)	Lithology
Abruzzi 1	Early Pliocene	Carassai sands	35	Sandy clay
Abruzzi 2	Late Plioc.	Carassai sands	35	Sand and clayey sand
Abruzzi 3	Mid to Late Plioc.	Carassai sands	35	Quartz-carbonate sandbanks
Abruzzi mare	Late Plioc.	Carassai sands	35	Fine to medium quartz sand
Lombardia 1	Messinian	Sergnano gravel	20	Gravel and sand
Marche 1	Early Plioc.	Teramo	20	Sand, sandstone and clay
Molise 1	Mid to Late Plioc.	Carassai sands		Sandstone
Molise 2	Mid to Late Plioc.	N.D.		Sand and clayey sand
Emilia 1	Early to Mid Plioc.	N.D.	35	Marl and medium to coarse sand
Lombardia 2	Mid to Late Plioc.	Porto Garibaldi	35	Fine to coarse sand
Sicilia 1	Tortonian	Terravecchia	20	Sand and clayey sand
Bradanica	Late Pliocene	N.D.	20	Sand and silty sand with conglomeratic layers
Emilia mare	Early Plioc.	Porto Corsini/Canopo	17	Fine to medium sand
Calabria ionica	Mid-Late Mioc.	S. Nicola		Polygenic conglomerate

N.D., not determined.
Geothermal gradients taken from Della Vedova et al. (2001) and Geothermal Map of Italy (2004).

some areas of the Southern Apennines. The Adriatic foredeep belt underwent a very fast Plio-Quaternary sedimentation that caused a drop in the heat flow values (Della Vedova et al., 2001). The highest values are found along the western Apennines and the central-southern Tyrrhenian Sea (200–250 mW/m^{-2}).

3. Evaluation of the Italian reservoir formations suitable for CO_2 geological storage

Geological formations suitable for CO_2 storage have to lie at depths below 800–1000 m, where the injected CO_2 remains in a supercritical state and has a liquid-like density (about 500–800 kg m^{-3}) that provides the potential for efficient utilization of underground storage space. However, this density allows the buoyant forces to drive CO_2 upwards. Consequently, a well-sealed caprock above the selected storage reservoir is important to ensure that CO_2 remains trapped underground (IPCC, 2005).

In order to verify the location of geological formations having these characteristics in the Italian subsurface, a comprehensive analysis of about 1650 well data and about 55,000 km of 2D multichannel seismic profiles has been performed. This dataset has been acquired since 1957 by several oil companies for hydrocarbon exploration and 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)". In fact, current regulations establish that operating oil companies shall provide the Ministry with progressive technical reports on the activities carried out on their permits and concessions; the reports include several kinds of documents, such as geologic maps, structural maps, final well logs, and seismic lines. Before the implementation of the ViDEPI project, the data were available only as hardcopies, which have been then scanned, geo-referenced and loaded on the ViDEPI web site (http://www.videpi.com). Then, both well and seismic data analysed in the framework of the present study are available at the moment only as raster files.

Well data consist of composite logs that contain the following information: (1) lithology derived from cuttings; (2) geological formation name; (3) formation age; (4) depth; (5) litho-stratigraphy; (6) fluid occurrence; (7) formation depositional environment; (8) bio-stratigraphy; (9) geophysical logs (commonly resistivity, spontaneous potential, sonic, gamma ray). Pressure and temperature values are also reported in places.

After the identification of reservoir and caprock formations based on well data analyses, the areal extent of the reservoir–caprock systems has been evaluated through the seismo-stratigraphic analysis of the 2D seismic data set. Particular attention has been paid also to the structural setting, in order to reveal the occurrence of structural features, i.e. faults, at the level of the reservoir–caprock system, which could represent preferential conduits for potential CO_2 leakage.

Overall estimates of the number of potential reservoirs in deep saline aquifers vary widely and generally involve a high degree of uncertainty, mainly due to the fact that the knowledge of saline formations is quite limited in most parts of the world.

One of the methods used in the calculation of CO_2 storage capacity involves the concept of "total affected space" which is the total space influenced by the injection of CO_2 (van der Meer and Egberts, 2008). In fact, the storage potential of a selected site is a function not only of its capacity but also of the injectivity, which depends on rock permeability and fluid viscosity (Bachu et al., 2007; van der Meer and Egberts, 2008). Other theoretical methodologies for estimating the CO_2 stored in deep saline aquifers require a comprehensive knowledge of the location and geometry of the potential structural and stratigraphical traps (Bachu et al., 2007; Bradshaw et al., 2007). These methods consider specific information regarding the reservoir and require a detailed, but often unavailable, knowledge of the reservoir itself.

In the evaluation of the CO_2 storage potential in the Italian deep saline aquifers, we have adopted the method used in the EU GeoCapacity project (Vangkilde-Pedersen et al., 2008) concerning the CO_2 structural and stratigraphical trapping at a basin scale. The same procedure has been also used for estimating the CO_2 storage potential of saline formations in the United States and Canada (U.S. Department of Energy, 2008). This method provides a regional estimate based on bulk volume of the aquifers referred to as the "effective storage capacity" (i.e. the reservoir capacity evaluated considering technical cutoff limits and technically viable estimate) (Bachu et al., 2007) and is calculated as follows:

$$MCO_2e = Ah\phi\rho_{CO_2r}S_{eff} \tag{1}$$

where MCO_2e is the effective storage capacity (tonnes), A is the area that defines the basin or the region occupied by the aquifer (m^2), h is the effective thickness, i.e. average thickness of aquifer × average net to gross ratio (m), ϕ is the average reservoir porosity (%), ρ_{CO_2r} is the density of carbon dioxide at reservoir conditions (kg m^{-3}), and S_{eff} is the storage efficiency factor.

The area occupied by the Italian deep aquifers has been evaluated through the correlation between the borehole information and the available seismic lines, which led to the mapping of the reservoir and caprock depth. All available velocity information was used to provide maximum confidence in the well to seismic ties.

The effective thickness has been calculated by considering the sum of thicknesses of each permeable coarse-grained, sandy-gravelly layer within the potential reservoir. The Gamma Ray (GR)

Table 2
Key parameters of the Italian potential reservoirs for the evaluation of the CO_2 storage capacity.

Site name	Average reservoir depth (m)	Area (km^2)	Effective thickness (m)	Porosity (%)	Storage capacity (Mt) $S_{eff} = 1\%$	Storage capacity (Mt) $S_{eff} = 4\%$
Abruzzi 1	1340	175	80	25	23	92
Abruzzi 2	1320	340	75	25	40	160
Abruzzi 3	1360	64	125	30	15	60
Abruzzi mare	1500	1,800	210	30	650	2600
Lombardia 1	1590	740	75	10	38	152
Marche 1	1270	615	255	35	358	1432
Molise 1	1320	45	195	25	16	64
Molise 2	1260	155	270	25	70	280
Emilia 1	1100	560	210	20	246	984
Lombardia 2	1100	615	240	20	178	712
Sicilia 1	1050	465	110	35	103	412
Bradanica	1000	520	480	25	344	1376
Emilia mare	1400	715	470	30	657	2628
Calabria ionica	1280	320	350	30	210	840
Total					2950	11,800

and Spontaneous Potential (SP) logs provided a measure of the thickness of any clay interbeds.

The porosity of the potential reservoirs was estimated from P-wave velocity measurements from sonic logs and empirical functions (Schlumberger, 2000).

The CO_2 density at the mean reservoir depth was calculated by assuming a temperature and pressure at surface of 15 °C and 1 atm, respectively. Particular attention has been paid to the geothermal gradient. In fact, the geothermal regime is one of the most important sedimentary basin characteristics, to be considered for the CO_2 geological storage, since the temperature determines the CO_2 density, which in turn affects the basin storage capacity (Bachu, 2003). Table 1 provides the geothermal gradients for each area. Where not available, a value of 25 °C km^{-1} has been chosen, according to the "site selection criteria" proposed in the framework of the GeoCapacity project (Vangkilde-Pedersen et al., 2008).

The storage efficiency factor for aquifers is currently under debate. It accounts for several parameters such as net-to-effective porosity, areal and vertical displacement efficiency, and gravity effects. It reflects a fraction of the total pore volume that may be filled by CO_2, that is defined by the aquifer's compressibility and the pressure increase due to CO_2 storage (van der Meer and Egberts, 2008) and ranges between 1% and 4% (U.S. Department of Energy, 2008). In the EU GeoCapacity project a value of 2% has been suggested for a very conservative estimate of the CO_2 storage capacity within regional saline aquifers (Vangkilde-Pedersen et al., 2008).

4. Results

Our analysis has identified 14 suitable areas, represented by laterally semi-confined to confined deep saline aquifers (Fig. 1B). This analysis was mainly focused on the geological (structural and

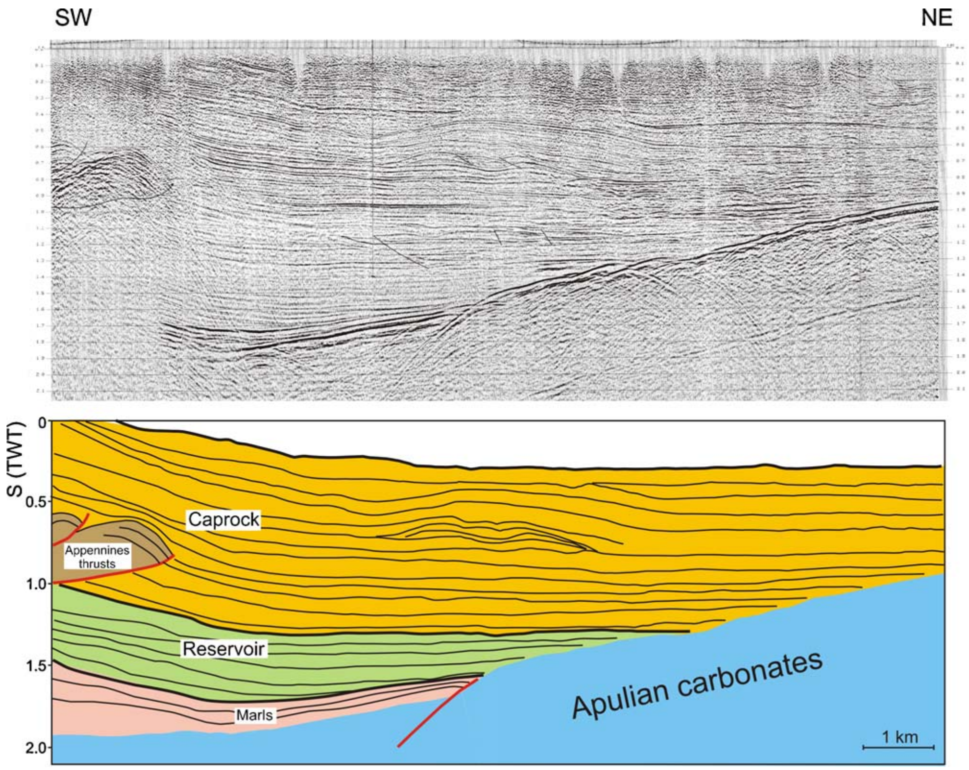

Fig. 2. Example of multi-channel seismic line collected across the "Bradanica" and its interpretation.

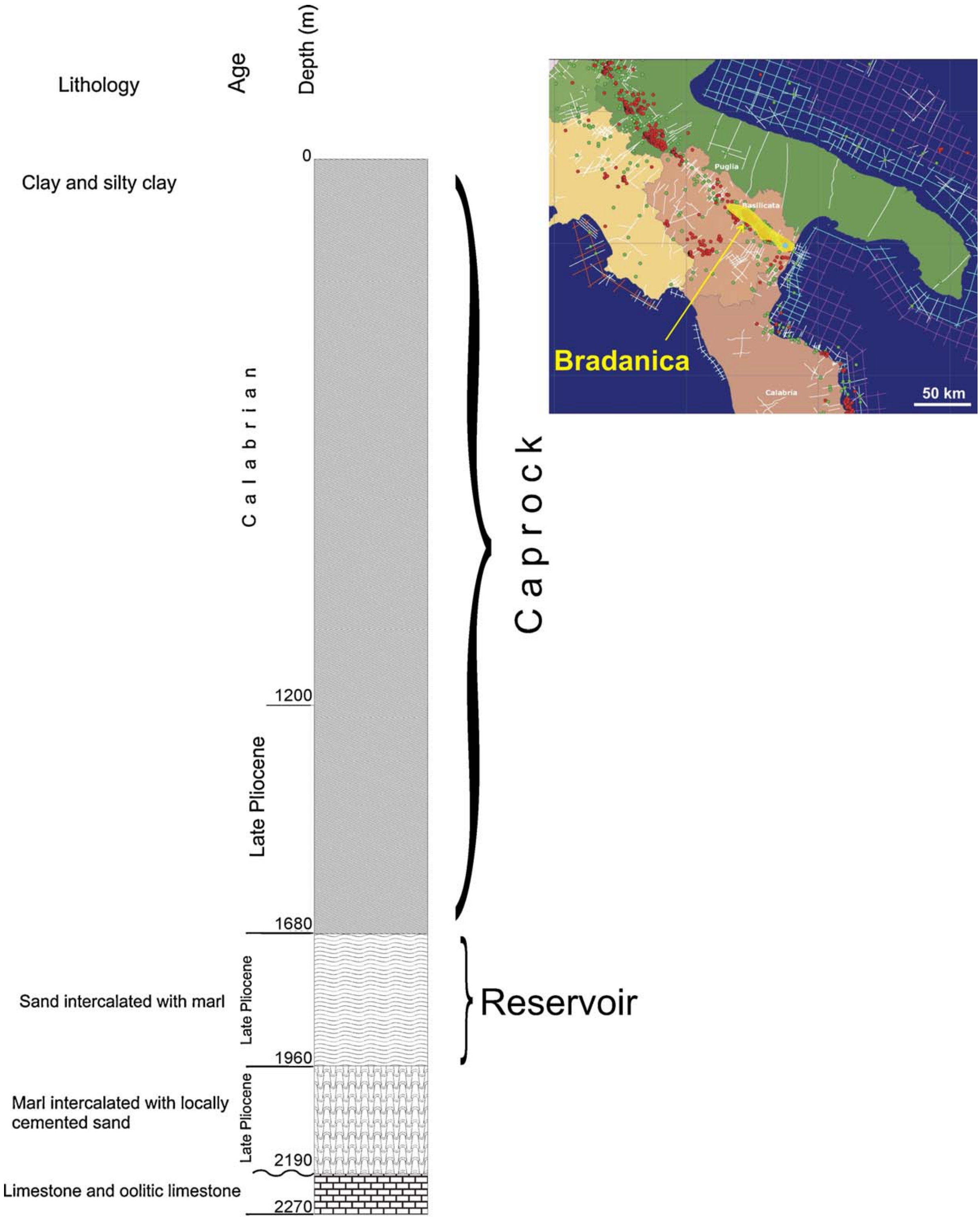

Fig. 3. Schematic representation of the so called "composite log" of one of the boreholes drilled in the "Bradanica", i.e. Salandra 1 (blue dot in the inserted map). Green and red dots represent the location of public (i.e. available) and confidential (i.e. not available) borehole information, respectively. Coloured areas represent the Italian administrative provinces. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

stratigraphical) characterization of the potential reservoir–caprock systems.

The selected areas reveal thick accumulations of sediments, permeable rock formations saturated with saline water and extensive covers of low porosity rocks (acting as seals). The main characteristics of these potential areas are summarized in Tables 1 and 2. All of them lie at mean depths usually greater than 1100 m, where pressures and temperatures guarantee the supercritical state of injected CO_2. Based on the geothermal gradients, the 14 potential areas can then be considered as "cold" basins, according to Bachu (2003), and thus temperature would not affect the CO_2 storage capacity.

Most of the Italian deep saline aquifers, suitable for the CO_2 storage, are Pliocene in age and consist mainly of fine to coarse sands,

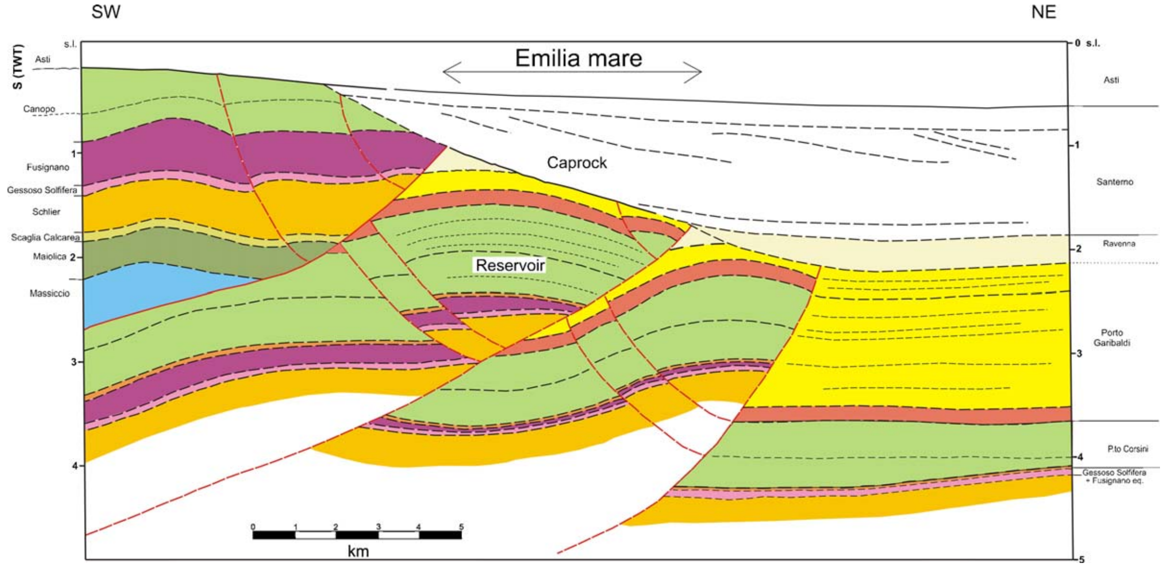

Fig. 4. Schematic geological section across "Emilia mare", showing the main geological formations identified in this area, based on a correlation between seismic lines and borehole information, and the location of the potential reservoir and caprock.

deposited as one-dozen-meter-thick banks or as one-meter-thick layers, intercalated with silty-to-clayey zones. The sealing formations (caprock) are at least 100 m thick and generally consist of clays, late Pliocene–Pleistocene in age.

An attempt to evaluate the potential CO_2 storage capacity of the selected areas has been performed. This is the first time the potential storage capacity of the Italian deep saline aquifers has been estimated.

The sensitivity of Eq. (1) is mainly related to the storage efficiency factor (S_{eff}). As highlighted above, computations of the potential storage capacity were made assuming that 1% or 4% of the total pore volume can be filled by CO_2 (US DOE, 2008). Our calculation yields a very conservative estimate of the effective capacity of the selected areas, equal to about 3 Gt or about 14.7 Gt ($S_{\mathrm{eff}} = 1\%$ or 5%, respectively).

Below we present the main characteristics of two of the most promising areas for the application of the CCS techniques in Italy. They are located in southernmost Italy and in the offshore Northern Adriatic Sea and have been named "Bradanica" and "Emilia mare", respectively (Fig. 1B).

The "Bradanica" lies onshore in the so called "Bradano foredeep", which represents one of the major structural elements of this area. It formed as a consequence of a flexural deformation which occurred during the Plio-Pleistocene in front of the Southern Apennine chain. The latter is here represented as duplex carbonatic system overlain by a thick series of NE-verging allochtonous units (Patacca and Scandone, 2001; Fig. 2). The outermost domain is represented by the Apulian foreland, constituted by Mesozoic carbonates and Triassic evaporites. The progressive dipping of the Apulian platform beneath the Apenninic thrusts takes place through SW-directed, normal faults, which cut through the entire carbonate sequence but not the overlying sediments (Sella et al., 1990; see also Fig. 2). The potential reservoir formation consists of Late Pliocene sands and silty sands with marl and conglomerate layers in places, pinching out toward the east against the carbonate platform. These deposits have been interpreted as basin floor sandstone lobes (Patacca and Scandone, 2001) and constitute a turbiditic complex, which progressively thins from the outermost Apenninic front, onlapping against the foreland platform. The reservoir is locally more than 800 m thick, with an effective thickness exceeding 650 m, as recorded by several boreholes drilled in the area (Fig. 3). The sandy layers are commonly saturated with salt water, as evidenced by the spontaneous potential and resistivity logs. Any borehole drilled in this area contains porosity information; its mean value, 25%, has thus been evaluated through the Sonic Log. From the seismo-stratigraphic point of view, these deposits are represented by low amplitude, sub-parallel and continuous reflectors. The outermost front of the Southern Apennine thrust system, which appears as a prominent frontal ramp, can be also recognized in places (Fig. 2). Below, the reservoir formation is separated from the Apulian carbonates by a predominantly marly sequence, Late Pliocene in age. The associated seismic sequence is clearly recognizable due to its high amplitude reflectors, onlapping onto the Apulian carbonates (Fig. 2). The turbidite sequence is overlain by a very thick (more than 1500 m in places) caprock formation. It consists of Late Pliocene–Pleistocene clays and silty clays (Fig. 3), representing deposits constituting a prograding slope fan (Patacca and Scandone, 2001). The seismic facies associated with these deposits is represented by low-medium amplitude reflectors.

The "Emilia mare" lies in the offshore northern Adriatic Sea (Fig. 1A), in the so called "Po Plain-Adriatic Foredeep" (Ghielmi et al., 2009), where the major Italian gas fields are also located (Pieri and Mattavelli, 1986; Casero, 2004). This basin was a deep-marine depression with water depth usually exceeding 1000 m. Its sedimentary infill is represented by several hundred meter-thick turbiditic successions, almost entirely composed of thick-bedded sand/sandstone that grade into basin plain deposits, made of mud/mudstones with thin-bedded fine-grained sands and sandstones (Ghielmi et al., 2009). The sedimentation in the Po Plain-Adriatic Foredeep was controlled by an intense synsedimentary compressional Apennine tectonics, which has initiated in the Pliocene and led to the formation of fold-and-thrust belts, leading to the formation of anticline folds, commonly hosting natural gas fields (Fig. 4; Casero, 2004). Nine large-scale sequences have been identified in Messinian to Pleistocene sedimentary succession in the Po Plain-Adriatic Foredeep (Ghielmi et al., 2009). Due to the fact that "Emilia mare" lies in one of the Italian most productive areas in terms of hydrocarbon exploration, the available seismic dataset is here quite limited. However, a clear picture of the compressional deformation, involving the several-km-thick Pliocene to Quaternary sedimentary sequences is recognizable (Fig. 4). Such

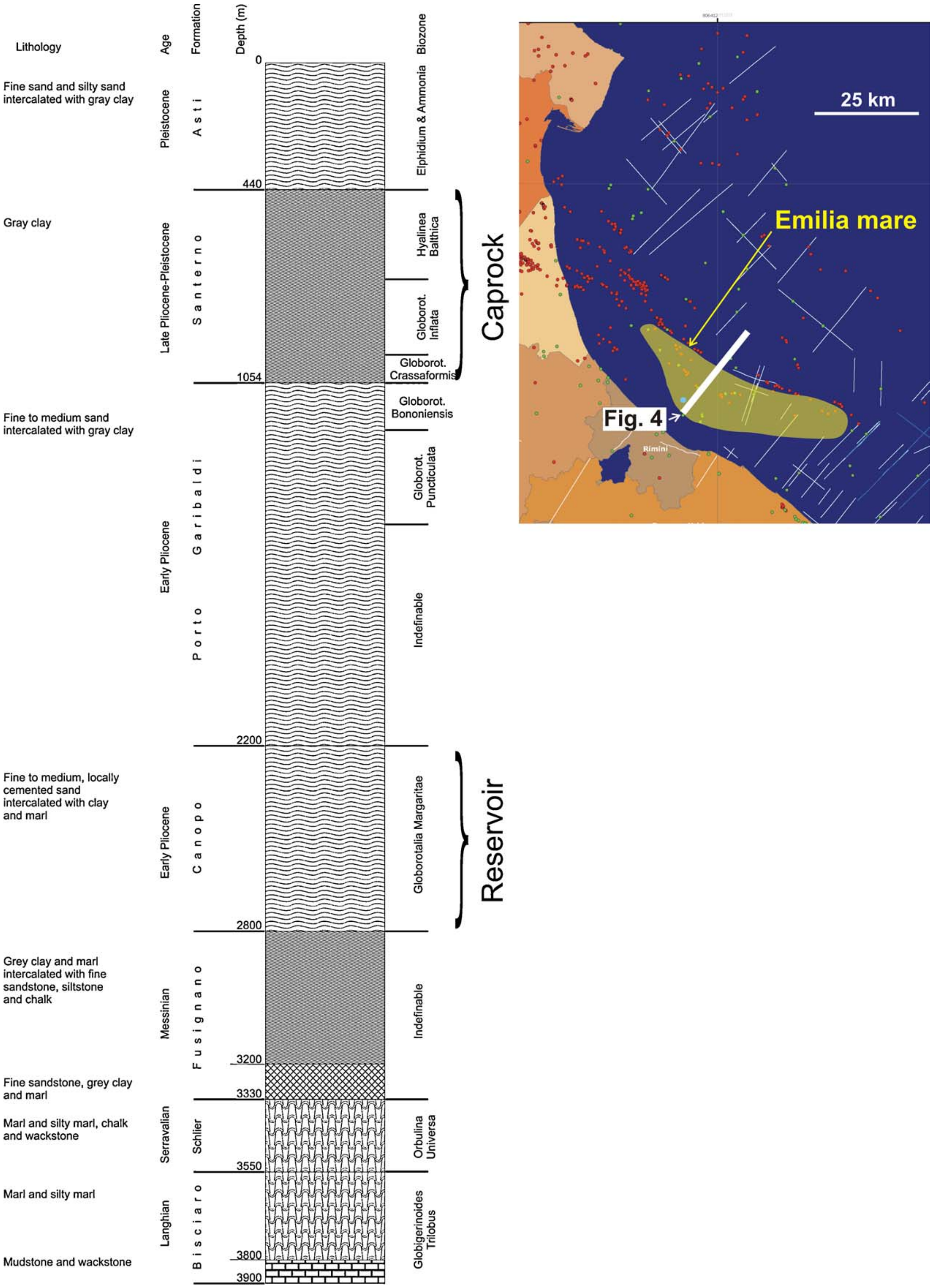

Fig. 5. Schematic representation of the so called "composite log" of one of the boreholes drilled in the "Emilia mare", i.e. Antinea 1 (blue dot in the inserted map). Green and red dots represent the location of public (i.e. available) and confidential (i.e. not available) borehole information, respectively. Coloured areas represent the Italian administrative provinces. The white line marks the location of the cross section shown in Fig. 4. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

features are well imaged on the SW-NE seismic profiles becoming progressively gentler from the coast toward to the East (offshore) (see also Plate 3 of Casero, 2004) Strike-slip faulting has been also recognized in places.

The reservoir formations suitable for the CO_2 geological storage are Early Pliocene in age and are represented by the “Canopo” and “Porto Corsini” formations (Figs. 4 and 5). They deposited in concomitance of a flexural deformation of the continental margin, which advanced at least 15 km toward East and of a change in the depositional regime. In areas more proximal to the coast, an arenaceous-pelitic succession of shallow coastal plan, 350 up to 700 m thick and ascribed to the *Globorotalia margaritae* Zone deposited (the so called “Canopo Domain”). In the external areas a coeval sequence of flexural accommodation, i.e. the Porto Corsini formation, constituted by arenaceous-pelitic turbidites of variable thickness deposited (Fig. 4). The sedimentation of stacked sand lobes about 2000 m thick took place in the central portion of the foredeep; these sediments then grade into muddier basin plain facies (Ghielmi et al., 2009). Meanwhile, the foreland basin underwent a phase of active flexural subsidence. The Porto Corsini deposits consist of fine to coarse-grained sands intercalated with clayey layers, as highlighted by frequent positive peaks in the SP log curves. These fine-grained layers have thicknesses ranging from a few-up-to 30 m. Commonly the sandy layers thicken toward the bottom of the formation. The formation has been deposited in a bathial to neritic environment and is characterized by typical fossil assemblages represented by *Globorotalia Margaritae*, *Globorotalia Puncticulata* and *Globorotalia Bononiensis* (Fig. 5). The potential reservoir formations are generally mineralized by salt water and, in places, with gaseous hydrocarbons. In fact, the Porto Corsini formation contain a high amount of methane pools, which are at present major productive layers in the offshore of Northern Adriatic Sea (Casero, 2004). Mean porosities are 30% (they can reach 35–40% in the sandy layers). No information about permeability values are at the moment available, except for those related to two clay layers, drilled in Serena Nord 1 borehole and mineralized with methane, where permeabilities are 1 and 6.5 mD.

During the Late Pliocene–Early Pleistocene the turbidite systems were fed from the Po river delta, which formed a prograding complex, represented by the Ravenna formation, rapidly advancing along the foredeep axis (Ghielmi et al., 2009; Figs. 4 and 5). During the Pleistocene, strong eustatic variations controlled the deposition of a thick prograding sequence, commonly known as “Santerno” formation. It represents the potential caprock formation and consists of clays and silty clays, whose thickness is up to 600 m in places, containing representative fossils such as *Globorotalia Inflata* and *Globorotalia Crassaformis* (Fig. 5). The SP and resistivity log curves clearly demonstrate the homogeneity of this clayey formation, which is also unaffected by any tectonic feature, such as the main and back thrusts deforming the underlying sequences (Fig. 4). The latest stages of the Neogene evolution of this area are dominated by a marine ingression which led to the deposition of transgressive sand deposits belonging to the “Asti” formation (Figs. 4 and 5).

Other geological formations that characterize the stratigraphy of this area could represent suitable reservoirs for the CO_2 geological storage. This is the case of the Porto Garibaldi formation, which is constituted by fine to medium sands (Fig. 5) and appears to be very similar to the Porto Corsini formation. Its paleogeographic domain lies to the NE of the study area, where it shows the greatest thickness (Fig. 4). However, only a few available boreholes drilled this formation and thus the information we have are at the moment too limited to evaluate the suitability of this formation in terms of the application of the CCS techniques.

5. Discussion and conclusions

Based on our evaluation of the total CO_2 potential storage capacity, the 14 saline reservoirs we have identified could potentially store Italy’s annual CO_2 emissions for the next 50 years. This value represents a very conservative estimate of the Italian potential for the CO_2 geological storage in deep saline aquifers because other potential promising reservoirs could lie in areas where data are not available at present. Moreover, carbonate formations have not been included in the overall estimate.

In our capacity estimation some uncertainties arise from the unavailability of specific data, such as the occurrence of local heterogeneities, that can affect CO_2 distribution and migration within the reservoir, although, at this stage, no evidence of relevant leakage features is detected. However, additional, site-specific investigations accompanied by further data are needed to a more detailed evaluation of the potential CO_2 storage areas. In fact, more precise estimates could be provided if stratigraphic or structural traps with suitable reservoir and sealing properties are identified within the selected areas and the storage potential of the individual trap is calculated. Regional estimates could then be calculated as the sum of storage potential of all the traps identified (Vangkilde-Pedersen et al., 2008).

Despite the uncertainties, this is the first time the potential storage capacity of the Italian deep saline aquifers has been estimated. This study demonstrates that, just as in other countries, CO_2 storage in deep saline aquifers is a viable option in Italy too. It represents the first comprehensive analysis of the whole public data set and highlights the location and the effective capacity of sites having suitable characteristics for the application of CCS techniques. However, due to uncertainties arisen from the unavailability of several kind of data (such as physical properties of the reservoir–caprock sediments) our evaluation on the total storage capacity of the Italian deep saline aquifers is far from being definitive and that it represents the “starting point” for future, more detailed analyses.

Our study would also underline that all the countries geologically characterized by the occurrence of deep saline formations could potentially contain reservoirs suitable for the application of the CCS techniques, even if the geological and structural setting appears to be very complex as in Italy.

These considerations are of particular interest considering the targets established by the international agreements, i.e. the Kyoto protocol, to cut CO_2 emissions by 8% and even more (20%) as envisaged by the European Parliament within 2012. A wide use of the CCS techniques will be then necessary not only in the developed countries but also, and especially in those countries characterized by a rapidly growing energy demand.

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