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Detailed petrophysical and geophysical characterization of core samples from the potential caprock-reservoir system in the Sulcis Coal Basin (southwestern Sardinia - Italy)

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Abstract

In this work we present a methodology suitable to identify a caprock-reservoir system for the CO_2 storage in the Sulcis Coal Basin (SW Sardinia – Italy). The petrophysical and geophysical characterizations indicate that the potential carbonate reservoir ("Miliolitico" Fm. *Auct.*) located at the base of the Eocene stratigraphic sequence in the mining district of the Sulcis Coal Basin, southwestern Sardinia, is heterogeneous but presents suitable reservoir zones for the storage of the CO_2. The GPS data analysis indicates that the study area is stable, since it is characterized by a surface crustal deformation smaller than 1 mm/y.

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Keywords: GPS; petrophysics; CO_2 storage

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1. Introduction

Nowadays the need to minimize the amount of CO_2 in the atmosphere is becoming greater and greater and consequently sequestration of industrial emissions in adequate geologic formations is a current necessity. As is well known, CO_2 cannot be injected anywhere in the subsurface, geological formations with the suitable requisites must be identified. The evaluation of a CO_2 geologic storage site requires a robust experimental database especially regarding the spatial petrophysical heterogeneities. This requires specific investigations by means of a detailed characterisation of the rocks that make up the possible caprock-reservoir system in order to build a reliable model, whose CO_2 storage capacity can be planned in advance and can guarantee an efficient use of the reservoir.

The integrated analysis of minero-petrographical, physical and geophysical parameters of the rocks that make up a caprock-reservoir system can substantially reduce the geologic uncertainty in the storage site characterization and in the geological and numerical modelling for the evaluation of CO_2 storage capacity. In this study the Middle Eocene - Lower Oligocene Cixerri Fm. made up of terrigenous continental rocks and the Upper Thanetian - Lower Ypresian Miliolitico Carbonate Complex in the Sulcis coal basin (southwestern Sardinia - Italy) [1, 2, 3, 4] have been identified respectively as potential caprock and reservoir for CO_2 storage in the Sulcis coal basin (southwestern Sardinia - Italy) (Fig. 1 a, b). The Sulcis coal basin represents one of the most important Italian carbon reserves characterized by a great mining potential. Deep carbon layers and minable coal are present in this area. In this study the experimental data deduced from the petrophysical and geophysical characterization has also given an important contribution to the numerical modelling aimed to simulate CO_2 behaviour in the short, medium and long term after its injection in single or multiple wells [5, 6].

Moreover to control the stability of the investigated area a geodetic study was carried out using the GPS permanent stations located around and inside the study area. The Basin shows a very little surface crustal deformation rate (less than 1 mm/y) when measured by GPS permanent stations.

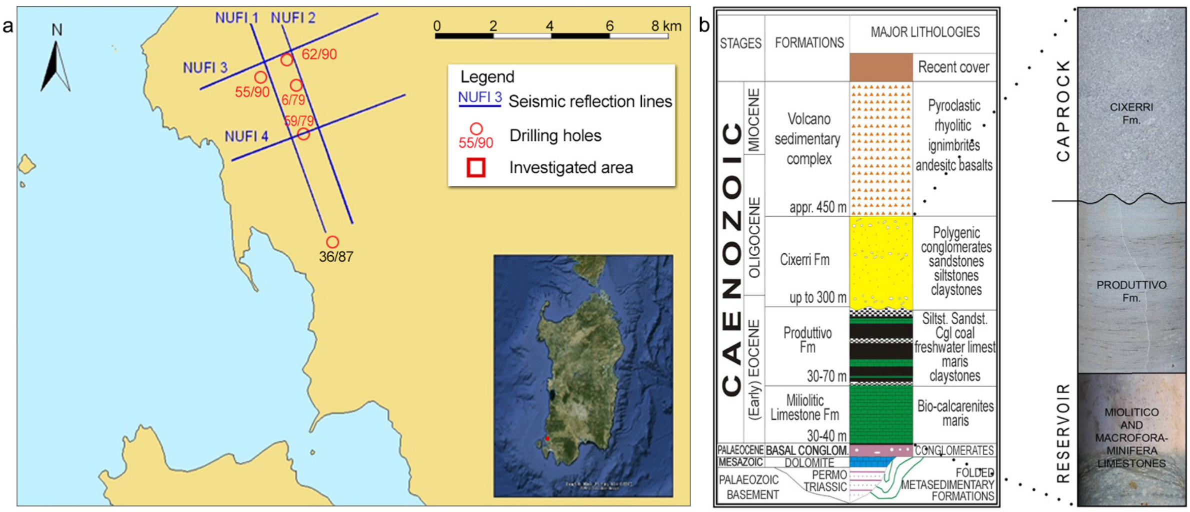


Fig. 1. (a) Location of the investigated area; (b) Left: Stratigraphic scheme of the Tertiary succession of the Sulcis Coal Basin (SW Sardinia – Italy), *courtesy from* Beretta et al., 2012; right: schematic set up of the caprock-reservoir system.

2. GPS monitoring

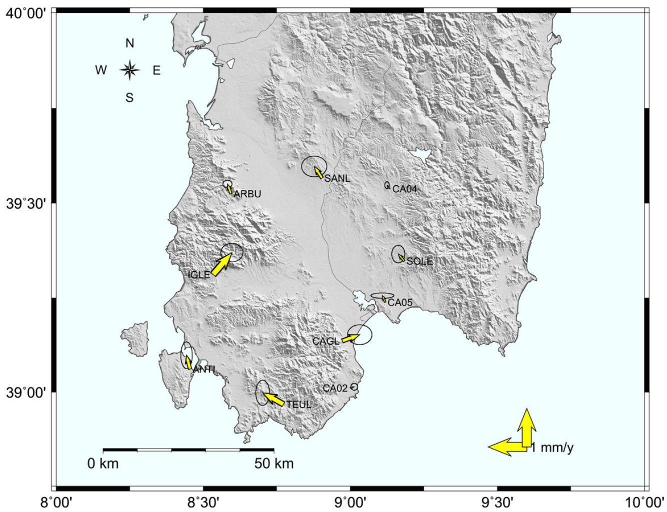
To verify the stability of the area of interest we have processed a GPS array of permanent stations maintained by 4 different private and public companies.

We gathered data from 12 permanent GPS stations located around and inside the area of interest (Cixerri, Sulcis, Sardinia, Italy) comprised in the time span January 2008 – April 2015. The GPS data belong to four permanent GPS networks, in particular the sites: CAGL and CAGZ to *geodaf* GPS network maintained by ASI (Italian Spatial

Agency). ANTI, ARBU, CA02, CA04, CA05, IGLE belonging to the *italpos* GPS network maintained by Leica-Geosystems Italy and INGV, and SANL, SOLE, and TEUL to *NetGEO* maintained by Topcon, Sokkia. For the robust combination of solutions we added the *EUREF* (European Reference Network) stations of AJAC, MATE, NOT1, PADO, GENO, GRAZ, POTS, and WTZR.

Data have been processed using Gamit/Globk 10.5 GPS analysis software [7, 8] a package for analyzing GPS measurements and for crustal deformation studies. The software is maintained by MIT, Scripps Institution of Oceanography, and Harvard University and is partly funded by the NSF (National Science Foundation).

We used IGS (International GNSS (Global Navigation Satellite System) service for geodynamics) precise orbits, absolute phase center corrections, and EOP (Earth Orientation Parameters). We used FEM2004 for oceanic loading corrections, and the EDM08 gravitational model, and IERS03 for the tidal corrections [9]. Data have been processed using a multiple step approach based on the distributed sessions methodology, in particular, in the first step all the data, organized in an archive, are processed using Gamit processor in order to compute solution (*h-files*) containing coordinates, covariance and bias models [9, 10, 11, 12]. In a second step, solution *h-files* called quasi-observations are combined with global SOPAC (http://garner.ucsd.edu) *h-files* to form the observations. In a third step, the formed observations are stabilized in the IGB08 reference frame using coordinates and velocities of a set of fiducial stations belonging to the IGS core boundary to loose constrain the models. Finally the inherently rigid rotation of the Eurasian plate is removed using the definition of Eurasian rotation pole given by Altamimi for the ITRF2008 reference frame [13]. Time series of position coordinates are computed for all the sites of the network analyzed, and intra-plate velocities with error ellipses. Position time series of all the network have been edited using Matlab tools [14] in order to correct for outliers, and offsets (Fig. 2).



Site Name	Residual Horizontal Velocity (mm/y)
ANTI	0.371
ARBU	0.266
CA02	0.104
CA04	0.114
CA05	0.184
CAGL	0.478
CAGZ	0.577
IGLE	0.764
SANL	0.361
SOLE	0.234
TEUL	0.702

Fig. 2. Horizontal intraplate velocities of the Cixerri GPS array, values are well below 1 mm/y.

As can be observed with the time series of sites coordinates and residual intra-plate velocities of the investigated area we can expect movements smaller than 0.7 mm/y in the Cixerri, and Sulcis area, testifying the great stability of this region (Fig. 2, 3). All the ellipsoidal heights computed show a positive trend in the range 0-2 mm/y. Therefore the area does not seem to be affected by subsidence phenomena. Cross-correlated images of the descending track of the ERS1-2 (European Remote Sensing) SAR (Synthetic Aperture Radar) satellites processed by the “geo-portale nazionale” (national geo-portal) of the Italian Ministry of the Environment (http://www.pcn.minambiente.it/GN/) were used to compute the surface strain of this area (Cixerri) with the technique of the permanent scatterers, and a mean value of the surface strain comprised between +/- 1.5 mm/y is computed in the period from 1992 to 2000, validating the results obtained with the GPS technique.

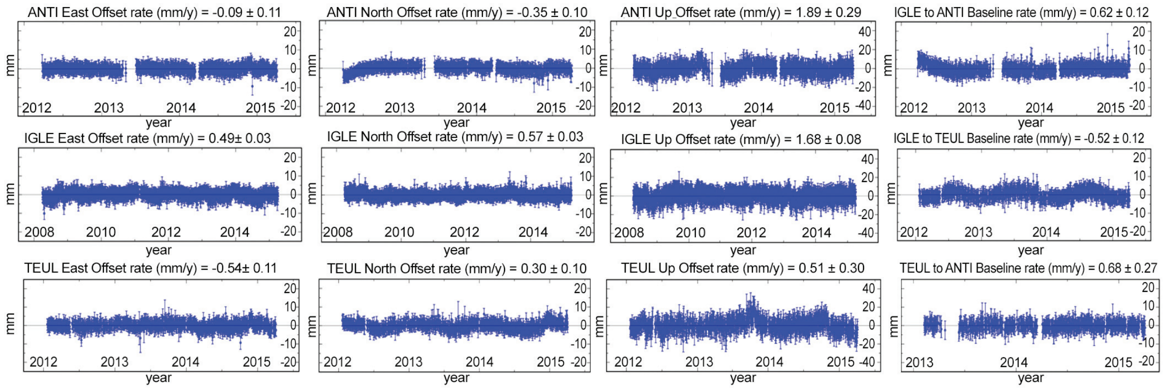


Fig. 3. First three columns from left to right: de-trended position time series of East, North and Up components of the permanent GPS stations of ANTI (Sant'Antioco), IGLE (Iglesias), and TEUL (Teulada) respectively. Right side, last column, baselines: IGLE-ANTI, IGLE-TEUL, and TEUL-ANTI. Both baselines, and residual velocities range in the 0-0.7 mm/y interval.

3. Data analysis

The Sulcis coal basin region is characterized by very little crustal, and non-significant residual velocities [15] as stated by the GPS data analysis performed at the beginning of our procedure. In the following we briefly describe the petrophysical and geophysical analyses carried out to classify the lithological types composing the potential caprock-reservoir system, respectively the Middle Eocene - Lower Oligocene Cixerri Fm. made up of terrigenous continental unit of siltites, sandstones and subordinated conglomerates, and the Upper Thanetian - Lower Ypresian Miliolitico Carbonate Complex for the CO_2 storage in the Sulcis coal basin (SW Sardinia - Italy). The caprock (Cixerri Fm.) and the carbonate reservoir ("Miolitico" Fm., saline aquifer) characterization, carried out mainly by petrophysical and geophysical investigations, was aimed to provide experimental data for the subsequent geological modeling and to give a contribution to estimate the total amount of CO_2 that can be stored in the hypothetical reservoir.

3.1. Petrophysical and geophysical characterization

For the characterization of the rocks that make up the caprock-reservoir system, in our area of interest, we started from a detailed analysis of both the petrographic and physical characteristics of the terrigenous continental rocks of the "Cixerri" Fm. *Auct.* and the carbonate rocks that make up the "Miliolitico" Fm. *Auct.* The physical characteristics of the rocks under study have been analyzed in the light of their petrographic characteristics and in particular of their texture. Knowledge of the texture is important because of its relationship with the primary and secondary porosity, which affects both the permeability and the geomechanical properties of the rocks.

We carried out laboratory tests on 60 cylindrical rock samples of the "Cixerri" Fm. *Auct.* (potential caprock) and of the "Miolitico" Fm. *Auct.* (potential reservoir) provided by Carbosulcis S.p.A. - the society responsible for the maintenance of the coal mine in SW Sardinia. These samples derive from several core wells drilled in the study area for mining exploration purposes.

The petrographic data were determined by optical microscope (OM) analysis of thin sections and a scanning electron microscope (SEM) examination of samples representing the different facies of the caprock-reservoir system. As an example Figs. 4a, b and 5a, b show the results of both optical and electronic microscope analyses, carried out on samples respectively from wells 57-90 and 59-90 located in the northern part of the Sulcis coal basin (Nuraxi Figus mining area). Fig. 4a, b show the thin sections of a lithotype (Sample C8 - well 57-90) belonging to the continental terrigenous Cixerri Fm. Fig. 4a represents an arenaceous siltstone, made up of quartz grains bounded by an oxidized matrix. At the SEM analysis (Fig. 4b), this matrix proved to be made up of clay minerals. The presence of this clay matrix ensures low permeability compatible with the potential caprock role of this formation. Fig. 5a, b shows a lithotype (Sample C17 - well 55-90) from the carbonate "Miliolitico" Fm. As shown in Fig. 5a, the "Miliolitico" Fm. is made up of Miliolidae limestones, where open fractures or fractures filled by pyrite or oxidized material are present. At the SEM observation (Fig. 5b) these carbonate rocks are characterized by microfractures and pyrite crystals, usually gathered in spheroidal aggregates. An interesting element emerged from the electronic microscopy analyses on the study carbonate rocks, ie in many cases where dolomitization of the calcite occurred, leading to dissolution and replacement of the calcite with the dolomite in the micritic matrix, diffuse microporosity formed and consequently lead to a significant increase in the rock porosity.

Thanks to the optical microscopy analysis on all the samples from the "Miliolitico" Fm., it has been possible to identify different types of porosity. These have been classified according Coquette and Pray (1970) [16]. This is the most widely used classification in the characterization of carbonate reservoirs. Some porosities are of the primary type, ie a porosity linked to depositional processes such as inter-particle porosity, while others are of the secondary type, mostly related to tectonic and diagenetic processes, for example fracture type or channel type porosity, which are the result of processes of limestone dissolution and collapse. In most samples we observed a channel type porosity, which is particularly interesting because it favours the movement of fluids within the rock. We found that the secondary porosity of the potential carbonate reservoir, both at the micro- and meso-scale, and at the macro-scale is mainly related to tectonic events that have affected the area, and caused faults or fractures that represent the main drainage paths of fluids which produced changes in the geometry of the porous system.

The observation carried out under optical and SEM microscopy analyses were integrated with the Mercury intrusion porosimetry (MIP) technique to obtain information such as pore size distribution, total pore volume, bulk and skeletal densities of the study rocks. Besides this information, other important parameters (permeability and tortuosity) were deduced from the MIP analyses. As an example in Table 1 we report the results for six samples relating to well 57-90, respectively three from the caprock and three from the reservoir.

Table 1. Results of the MIP analyses obtained for three samples of the Cixerri Fm. and three samples of the "Miliolitico" Fm.

Well 57-90	Sample	Porosity (%)	Permeability (mD)	Tortuosity
Caprock (Cixerri *Fm.*)	**C2**	4.7	2.3	1.5
	C3	2.2	2.5	1.3
	C8	7.3	< 0.1	50.7
Reservoir (Miliolitico *Fm.*)	**C5**	4.6	2.3	1.3
	C6	20.7	< 0.1	6.8
	C14	5.8	< 0.1	42.4

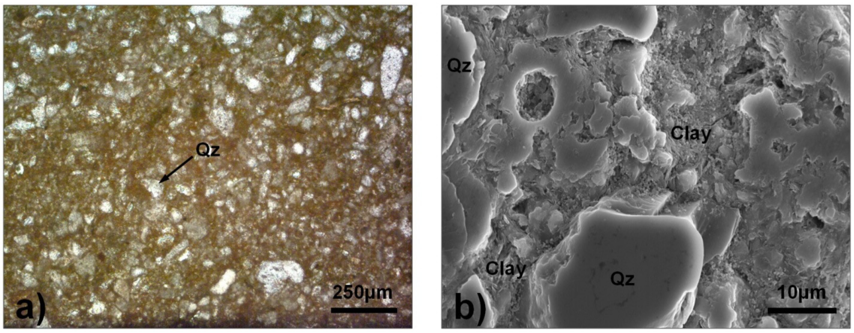


Fig. 4. Arenaceous siltstone belonging to the Cixerri Fm. (a) optical microscope analysis (thin section treated with blue dye); (b) SEM analysis, Qz (quartz).

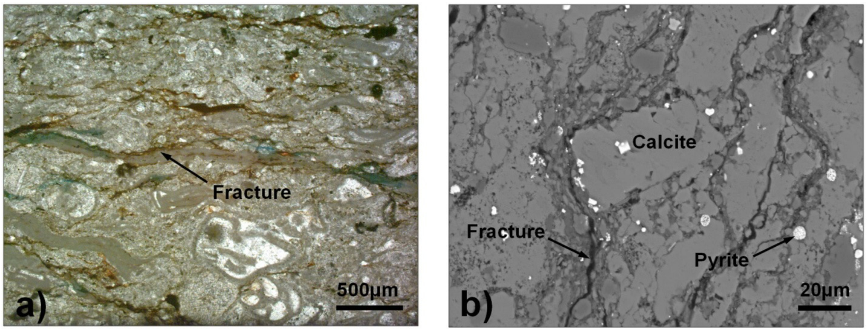


Fig. 5. Miliolidae limestone belonging to the Miliolitico Fm. (a) optical microscope analysis (thin section treated with blue dye); (b) SEM analysis.

It is observed that all samples show low porosity (except C6) and permeability values. Tortuosity is low except in two samples (C8 and C14) that show very high values. The high values of this parameter can be related to the intrinsic features (texture, size, shape and arrangement of the grains or crystals) of the study rocks. These features control the pore-system geometry (i.e. pore connectivity, pore system shapes). Further physical properties, such as dry and saturated density and porosity, and water absorption were determined on the above mentioned cylindrical rock samples using the caliper and saturation method [17]. The analysis of the petrophysical and acoustic properties of the rocks as well as that of their relationships were considered of paramount importance in defining the characteristics of the potential geological reservoir. Therefore, in this study we carried out measurements of the propagation velocities of longitudinal and transverse waves in the rocks making up the reservoir both in the laboratory and *in situ* in the main reflux gallery of the Nuraxi Figus mine. The propagation velocity of longitudinal (Vp) and transversal (Vs) waves on the core samples of the caprock-reservoir rocks was determined in laboratory by a portable ultrasonic non-destructive digital indicating tester (P.U.N.D.I.T.), and combined P and S wave transducers manufactured by C.N.S. Electronics Ltd (London, U.K.) were used to acquire useful data for velocity measurements [18]. As an example in Fig. 6 we report the results of some discriminant analyses (OM, SEM, MIP, ultrasonic waveforms and longitudinal velocity) performed on core samples from a well representative of the stratigraphical sequence in the Sulcis coal basin.

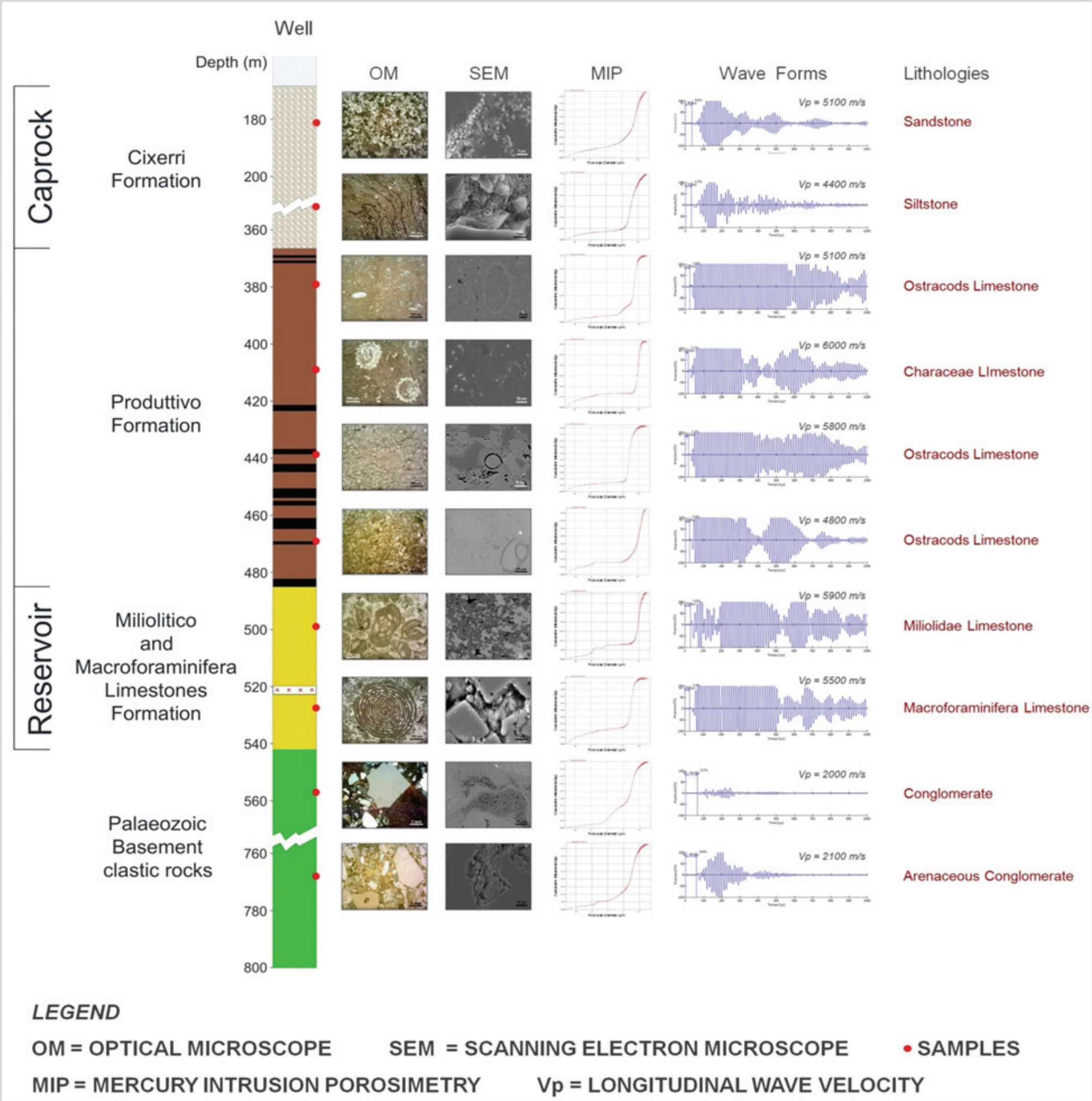


Fig. 6. Example of a typical stratigraphical sequence of the study area with discriminate analyses.

Starting from the experimental laboratory values of the P and S wave velocities we computed the dynamic elastic modulus of Young, Poisson's ratio, and finally bulk modulus using the well-known relationship linking the longitudinal (Vp) and shear wave (Vs) velocity and the rock bulk density (ρ).

The acoustic velocity data and other physical properties obtained from laboratory measurements on the samples of the caprock-reservoir system (Cixerri Fm. and Miliolitico Fm.) have provided a useful reference during the analysis of the reflection seismic data and the evaluation of the *in situ* conditions of the rocks.

4. Conclusion

The analysis of all the experimental data acquired during this study has provided an essential contribution to the characterization of the caprock-reservoir system respectively made up of the continental terrigenous Cixerri Fm. and carbonate Miliolitico Fm. in the Sulcis coal basin (SW Sardinia). The stability of the area was studied by computing the GPS intra-plate velocities of a few continuous stations in this region. Moreover we analyzed the position time series and baselines of these GPS sites to show that site movements are less than 1 mm/y. All the ellipsoidal GPS heights of the analyzed permanent stations show a positive trend ranging mainly in the 0-2 mm/y interval, which also proves the vertical stability of the studied region.

By the petrographic and petrophysical analyses a number of important properties of the caprock-reservoir system were determined. These include texture, type of porosity, shape and size of the pores, permeability and tortuosity of the porous system. As is known, these properties affect the hydrogeological characteristics of the rocks and therefore their ability to act as a potential natural reservoir more or less effectively. The primary porosity of the potential carbonate reservoir is not very high. Therefore this formation takes on characteristics of reservoir for the purpose of geological storage of CO_2 particularly in light of the locally high dolomitization and widespread fracturing.

Some important elastic properties (Vp, Vs, elastic moduli) and their correlation with physical properties such as porosity and density have also been analyzed. The poor correlation found between longitudinal velocity and porosity in the tested samples of the potential carbonate reservoir (Miliolitico Fm.) suggests that the texture of the carbonate rocks under study determines the shape and size of the pores in a way that can improve or worsen their elastic properties. The different experimental data acquired in the laboratory, supplemented with data from the surface geology and wells available in the area, will provided a major contribution to the analysis of reflection seismic data and their seismostratigraphic interpretation.

All the experimental data deduced from this study are being used to improve the geological model aimed at verifying the geological CO_2 storage capacity within the carbonate reservoir rocks, to guarantee an efficient use of the reservoir, and to improve the numerical simulation of CO_2 behaviour in the short, medium and long term after its injection in single or multiple wells.

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References

[1] Murru M, Salvadori A. Ricerche stratigrafiche sul bacino del Sulcis (Sardegna sudoccidentale). I depositi continentali paleocenici della Sardegna meridionale ed il loro significato paleoclimatico. Geologica Rom 1987; 26:149–165.

[2] Barca S, Costamagna LG. Il Bacino palogenico del Sulcis-Iglesiente (Sardegna SW): nuovi dati stratigrafico-strutturali per un modello geodinamico nell'ambito dell'orogenesi pirenaica. Boll Soc Geol It 2000; 119:497–515.

[3] Murru M, Matteucci R. Early Tertiary of Sardinia, Italy. *Rend Soc Pal It* 2002; 1:269–273.

[4] Barca S, Costamagna LG. New stratigraphic and sedimentological investigations on the Middle Eocene–Early Miocene continental successions in southwestern Sardinia (Italy): Paleogeographic and geodynamic implications. CR Geosci 2010; 342:116–125.

[5] Beretta S, Cappelletti F, Fais S, Guandalini R, Moia F. Confinamento geologico della CO2 nel Bacino del Sulcis in Sardegna. Deliverable RSE 12001251 2012; p. 93.

[6] Fais S, Ligas P, Moia F, Pisanu F, Sardu G. Characterization of CO_2 storage reservoir - a case study from south western Sardinia, Italy. In: European Association of Geoscientists and Engineers (EAGE) editor, EAGE Europec Proc, Amsterdam: EAGE; 2013, p.1–5. ISBN:9789073834484 doi:10.3997/2214-4609.20130628

[7] Herring TA, King RW, McClusky SC. GPS Analysis at MIT, GAMIT Reference Manual, Release 10.4. (2010) (Department of Earth, Atmospheric, and Planetary Sciences Massachusetts Institute of Technology, Cambridge MA 2010, available on line at http://www-gpsg.mit.edu/~simon/gtgk/GAMIT_Ref.pdf, accessed 28 May 2015).

[8] Herring TA, King RW, McClusky SC. Global Kalman filter VLBI and GPS analysis program, GLOBK Reference Manual, Release 10.4. (2010) Department of Earth, Atmospheric, and Planetary Sciences Massachusetts Institute of Technology, Cambridge MA 2010b, available on line at (http://chandler.mit.edu/~simon/gtgk/GLOBK_Ref.pdf, accessed 28 May 2015).

[9] Dubbini M, Cianfarra P, Casula G, Capra A, and Salvini F. Active tectonics in northern Victoria Land (Antarctica) inferred from the integration of GPS data and geologic setting, J. Geophys. Res. 2010; 115, B12421, doi:10.1029/2009JB007123.
[10] Pesci A, Teza G, Casula G, Cenni N, Loddo F. Non-permanent GPS data for regional-scale kinematics: reliable deformation rate before the 6 April, 2009, earthquake in the L'Aquila area. Ann Geophys 2010; 53:55–68. doi: 10.4401/ag-4740
[11] Pesci A, Teza G, Casula G. Improving strain rate estimation from velocity data of non-permanent GPS stations: the Central Apennine study case (Italy). GPS Solut 2009; 13:249–261. doi: 10.1007/s10291-009-0118-3
[12] Teza G, Pesci A, Casula G. Strain rate computation in Northern Victoria Land (Antarctica) from episodic GPS surveys. Geophys. J. Int. 2012; 189:851–862. doi: 10.1111/j.1365-246X.2012.05403.x
[13] Altamimi Z, Collilieux X, Métivier L. ITRF2008: an improved solution of the international terrestrial reference frame. Journal of Geodesy, 2011; 85, 8, 457-473. doi: 10.1007/s00190-011-0444-4.
[14] King RW, Bock Y. Documentation for the GAMIT GPS analysis software, release 10.1. 2011; Cambridge: Mass. Inst. of Technol.
[15] Devoti R, Riguzzi F, Cuffaro M, Doglioni C. New GPS constraints on the kinematics of the Apennines subduction. Earth and Planetary Science Letters 2008; 273:163–174. doi:10.1016/j.epsl.2008.06.031
[16] Coquette PW, Pray LC. Geologic nomenclature and classification of porosity in sedimentary carbonates. Am Assoc Petrol Geol Bull 1970; 66:207–250.
[17] ISRM (International Society for Rock Mechanics). Suggested Method for Determining Water Content, Porosity, Density, Absorption and Related Properties and Swelling and Slake-Durability Index Properties. International Society for Rock Mechanics, Commission on Standardisation of Laboratory and Field Tests. Int J Rock Mech Min Sci 1979; 16:141–156.
[18] ISRM (International Society for Rock Mechanics). Suggested Method for Determining Sound Velocity. Int J Rock Mech Min Sci 1978; 15:53–58.
[19] Wessel P, Smith WHF. New Improved version of Generic Mapping Tools Released, EOS Trans. AGU 1998; 79:47-579.