14th International Conference on Greenhouse Gas Control Technologies, GHGT-14

21st -25th October 2018, Melbourne, Australia

Characterization of fractured rocks for the design of a pilot-scale CO_2 injection site in the Sulcis Basin, Italy

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Abstract

The naturally fractured carbonates have a great potential for Carbon Capture and Storage (CCS) purpose because they could offer the possibility for CO_2 storage in areas where no suitable sandy reservoirs are available, as for example in the Mediterranean area, where most of the stratigraphic succession is composed by carbonate rocks. The Sulcis basin, located in the south-western part of Sardinia island (Italy), is an ideal site for technology development. Although the site is not feasible for commercial-scale geological storage (mainly due to the lack of stationary CO_2 sources), it represents an optimal location for pilot-scale experiments. Thanks to data available from several national and international projects, as well as from the mining activities, it has been possible to recognize a potential reservoir-caprock system, suitable for pilot-scale CCS development. A sequence of well bedded, about 50 m thick, mudstones and grainstones ("*Miliolitico* Fm.") has been identified as a potential reservoir; the caprock is represented by a thick succession of siltstones, sandstones and conglomerates ("*Cixerri* Fm.") and up to 900 m of Oligo-Miocene volcanic rock, ranging from basaltic to rhyolitic composition. In this work we present the results of several geophysical and geological surveys, including reflection seismic profiles, and geo-structural analysis. All the data were combined in a 3D model, defining the volumes of each formation. The evaluation of the storage capacity and the existence of a thick and impermeable caprock are essential to consider the site suitable for the experimental tests. With this aim, we measured primary porosity and permeability, whereas the fracture network was studied using scan lines and scan areas techniques on outcropping analogue of reservoir and seals. The measured linear parameters were used to build several Discrete Fracture Model (DFN) both of reservoir and caprock formations. In particular, DFN were constructed varying length and aperture values to evaluate their influence on the total secondary porosity.
Keywords: CO_2 Geological Sequestration; Site characterization; Fractured carbonate reservoir; Fracture analysis; Petro-physical modelling.

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1. Introduction

The current process of global warming, driven by the constant and increasing emission of greenhouse gases, such as carbon dioxide and methane, is one of the most discussed topics both in science and at government level [1, 2]. With around two-thirds of current greenhouse gas emissions coming from the energy sector and with 82% of world energy supply (in 2014) coming from fossil fuels [3], the transition to low-carbon energy systems is consequently an urgent priority [4]. With the Paris Agreement, the international community proposed to keep the increase in global average temperature to "well below 2°C" above pre-industrial levels. The achievement of this objective will require rapid and extensive deployment of all low-emissions technologies, including carbon capture and storage (CCS) [5]. Currently, only a few large-scale CCS projects exist in Europe, and all of them are offshore and storing CO_2 in deep geological formations. In order to reach the EU commitment, it is needed to widely deploy CCS to power plants and industries, incrementing the storage capacity, using also onshore storage sites.

The Eocene Sulcis basin, located in the south-western corner of Sardinia (Italy), hosts extensive sub-bituminous coal deposits. Here it has been identified a potential reservoir in fractured carbonate deposits at a variable depth between 1000 and 1500 meters. Fractured reservoirs are widespread in sedimentary basins across the world, but have received little attention as potential candidates for CO_2 storage. The primary reason is related to the dual porosity and permeability of matrix and the fracture network, that could affect significantly the calculation of storage capacity [6]. In addition, carbonate minerals are very reactive and usually form very heterogeneous reservoirs, and therefore are very likely to suffer significant alterations with CO_2 injection.

In the recent years, several research institutions (Sotacarbo, Sapienza – University of Rome, INGV, OGS, University of Cagliari and RSE) are working on the geological characterization of the Sulcis basin, as it has been identified as a suitable site for the development of CO_2 storage technologies, through different pilot-scale experiments [7,8]. In this work, we present some of the results from the site characterization of the Sulcis basin.

2. Site description

The study area is located in the coastal region of south-western Sardinia (Italy), in an area where a research permit has been grant by Sotacarbo S.p.A. to conduct CCS-related research. The geology at the outcrop mainly consists of Pleistocene and Holocene marine, lacustrine, fluvial, and alluvial unconsolidated sediments, while Cenozoic volcanic and sedimentary rocks outcrop at the surrounding hills. The sub-surface geology is well known in the Northern part of the basin, where several coal mines occur, whereas there are more uncertainties to the South. The data presented in this work are an improvement of the knowledge of the area.

The basement of the Sulcis basin is mainly composed of metamorphites (from terrigenous, volcanic and carbonate succession of Cambrian to Carboniferous age) and large volumes of granitoids relating to the Hercynian orogeny [9], which is covered locally by a Permo-Carboniferous terrigenous and volcanic complex. These successions are overlaid by Mesozoic carbonate successions of platform and basin environment [10].

During the Paleogene, a transgressive-regressive sedimentary cycle occurred. The base of this succession consists of macroforaminifera limestones, evolving in wackestone and mudstone with an oligotypical miliolid fauna, named "*Miliolitico Fm*.". This carbonate unit, proposed as the CO_2 injection reservoir, is 30-40 thick and has limited primary porosity [11], but the extensive secondary fracturing and paleo-karstic features contribute to its overall storage capacity [12]. A rhythmic succession of siliciclastic to carbonate deposits with interbedded lignite (*Produttivo Fm*.) occur at the top of *Miliolitico Fm*.. Due to the adsorption processes of CO_2 on the coal beds, the *Produttivo* could be considered a secondary reservoir.

The caprock above the proposed reservoir consists of a 300 m thick continental succession composed of siltstones, sandstones and conglomerates [13,14], known as "*Cixerri Fm*.", and up to 900 meters of Oligo-Miocene volcanic rocks, ranging from basaltic to rhyolitic composition.

The southern sector of the Sulcis basin is tilted southwestward, and is dissected by E-W, N-S and NE-SW high angle normal faults generated during the Miocene extensional phases, which produced half-graben/tilted block system [7,12].

3. Site characterization and preliminary results

In general, the identification of a suitable site to store CO_2 is a complex and long process, in which data from different disciplines merge together in order to give a model. The characterization of a geological storage site has the objective of identify the principal features of the reservoir-caprock system, such as depth, permeability, porosity, storage capacity, injectivity, containment, trapping mechanisms [15]. In this section we present a summary of the principal results of the site characterization at the Sulcis basin.

3.1. Petrophysical characterization

The petrophysical and elasto-mechanical characterization was started using data from previously drilled wells located in the northern part of the Sulcis basin (Nuraxi Figus area), where crucial geologic data had been recovered from core samples provided by Carbosulcis S.p.A. (the local mining company) and from mining galleries [16].

The petrographical characteristics of the caprock-reservoir rocks were determined by optical and SEM analyses of samples representing the different facies of the *Cixerri* and *Miliolitico* formations. Porosity analysis was completed by mercury porosimetry (MIP), carried out by MICROMERITICS AutoPore IV 9500, which also provided quantitative information on the permeability of the rocks and on the tortuosity of their pore system. Further physical properties, such as dry and saturated density and porosity, and water absorption were determined on the cylindrical core samples of intact rocks [17]. The propagation velocity of longitudinal (Vp) and transversal (Vs) waves on the same samples were carried out by a portable ultrasonic non-destructive digital indicating tester (P.U.N.D.I.T. plus) [18]. The transit time for each sample was recorded as the average of five independent measurements. The analysis of the complex relationship between acoustic velocities with other petrophysical parameters suggests that the acoustic properties of the investigated rocks are mostly influenced by their textural characteristics. The results of the petrophysical characterization could allow to deduce the rock texture from acoustic data and contribute efficiently in aiding the recognition of the different rock types from reflection seismic data.

3.2. Seismic survey

The geology of the Sulcis basin was reconstructed by means the seismo-stratigraphic and structural interpretation of a seismic dataset acquired and processed by OGS from 2008 to 2016. It consists of several multichannel seismic reflection profiles with different resolution. The seismic profiles were processed with the scope of obtaining good image of the buried structures and faults. The stratigraphic data of several available exploration wells were used to calibrate the Paleogene-Miocene succession on the seismic profiles. The investigated area can be subdivided in a northern and southern sectors characterized by different stratigraphic successions. The Miocene vulcanites shows a thickness between 750 and 800 m, which locally may reach 1000 m, in the southern sector, while in the northern area they are between 450 and 500 m. The thickness of the potential caprock, the *Cixerry Fm*., is about 300 m in the northern area compared to the 500 m on average observed in the southern sector. The top of the *Produttivo-Miliolitico* succession, showing a general dipping to SSW, has been identified at a depth ranging between 500 and 600 m in the northern sector, and between 650 and 1800 m in the southern one. Two main normal faults have been identified in the investigated area: the WNW to ESE-trending Conca de Monserrato Fault, which separates the northern and southern sectors of the Sulcis basin, and the NW-trending Matzaccara Fault, showing a maximum offset of about 300 m, that cut the previous structure and affects the alluvial Quaternary deposits. The northern portion of the Matzaccara Fault has been analyzed by means of three high resolution profiles in order to investigate the possibility that this structure is an ideal target for the study of the behaviour of the faults in relation with the migration of fluids as a consequence of CO_2 injection.

3.3. Structural analysis

In the study area, the analysis of brittle deformation was carried out both on caprock and reservoir formations, collecting data of fault architecture and fracture network. In the fault zones at the outcrop were measured the fracture density close the fault plane, the type of fractures and the evidence of fluid circulation associated with deformation. These observations were used to define the fault zone architecture and the permeability structure that control the fluid flow, defining a conduit or barrier behaviour [19]. The deformation is strongly controlled by lithology, both in sedimentary and volcanic formations. In particular, faults observed in the *Miliolitico Fm*. in the coal mine are often affected by karst phenomena, with active circulation of fluids. The fault zones in the *Cixerri Fm*. show a wide damage zone and a poorly developed core zone, while in the volcanic units the deformation is localized along the fault plane, along which a clay-rich core zone develop.

In order to investigate the parameters related to the fracture network, we measured several scan lines at the outcrop. The scanline method consists in the systematic measurement of all the fractures along a given direction in the outcrop. The observations include spacing of fractures, orientation (dip and dip azimuth), length termination style (abutting, blind, or through-going), aperture and filling [20].

The fracture dataset measured by scan lines were used for the construction of Discrete Fracture Network (DFN). DFNs allow to distribute properties, such as spacing, orientation, fracture geometry, in a volume, allowing to calculate the secondary porosity and permeability within the defined volume.

3.4. Reconstruction of 3D volume and fracture modelling

The construction of a geological model describing lateral and vertical variations of petrophysical properties (porosity and permeability) is of primary importance for the estimation of storage capacity due to fracture network, to verify the sealing of the caprocks and to identify potential leakage pathways in the fault zones [16,21,22,23 among others]. For this purpose, it is necessary to recognize fractures and faults within the reservoir and describe their characteristics, such as geometries (orientation, length, opening), spacing, distribution and connectivity, both qualitatively and quantitatively.

In this work, the stratigraphic succession of the Southern part of the Sulcis basin was built from seismic and boreholes data, using Petrel® (Schlumberger) to reconstruct the volumes and to calculate the petrophysical properties. In the figure 1 the volumes represent the alluvial deposits, the Miocene ignimbritic sequence (Upper vulcanites), andesites (Lower volcanites), *Cixerri Fm*., *Produttivo Fm*., *Miliolitico Fm*. and the basement.

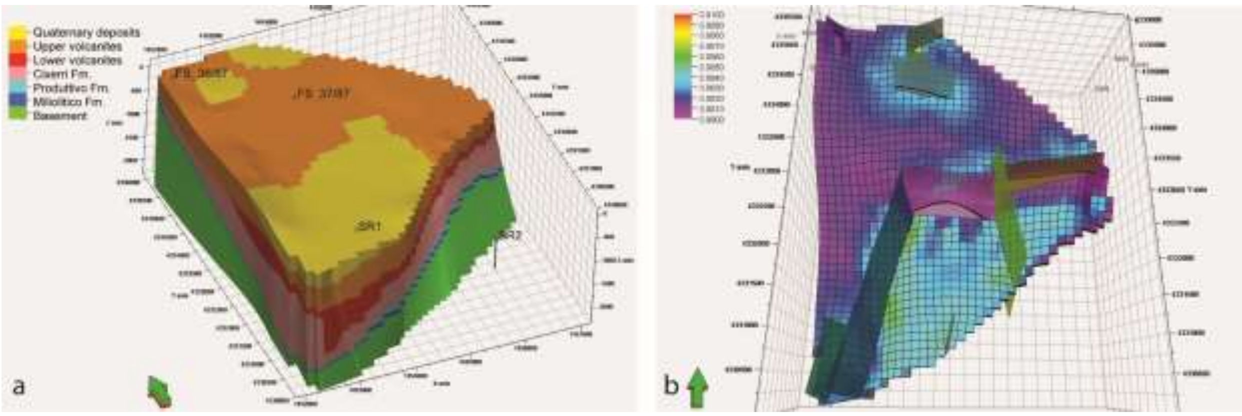

Fig. 1. (a) 3D model of Sulcis basin; (b) distribution of secondary porosity in Miliolitico Fm. The sub-vertical planes are the main faults identified in the area.

In table 1, some of the results of the properties calculation performed the petrophysical module in Petrel are summarized. The Cixerri Fm. shows a very low secondary porosity and permeability, which is more than two orders of magnitude lower than that calculated in the Miliolitico Fm., and this is mainly due to the lithology control on fracture distribution, that do not propagate in the clay and silty layers. The distribution of the petrophysical properties inside the vulcanites (both in the ignimbrites and andesites) is quite homogeneous. This could be attributed to the fracture spacing, which in the absence of tectonic elements have a constant distribution as for the most part is associated with cooling process.

The Miliolitico Fm., on the other hand, shows an increase in porosity and permeability near the fault planes and in the hanging wall of the main faults.

Table 1 – Summary of porosity and permeability tensor for each formation, calculated with the petrophysical modelling.

Lithology	Mean Porosity (%)	Mean K_i (mD)	Mean K_j (mD)	Mean K_k (mD)
Upper volcanites	0.08	2920.4229	9514.9789	9146.9885
Lower volcanites	0.03	1597.1018	3086.3238	4003.2293
Cixerri Fm.	0.005	402.3944	358.8230	639.4110
Miliolitico Fm.	0.30	21660.8908	21985.6851	36102.8819

4. Conclusions

The site characterization of the Sulcis basin has been carried oud by integrating different techniques, on rock samples, at the outcrop and using geophysical data. All these data were combined to reconstruct the 3D model of a part of the basin, and to calculate the petrophysical properties of the whole caprock-reservoir system. The evaluation of the storage capacity and injectivity will complete the geological characterization of the basin, which represent an optimal location to test and develop CCS technologies at pilot-scale. Here will be possible to study the carbonate behavior during injection and the caprock sealing, as well as to improve knowledge on capture at Sotacarbo laboratories.

Acknowledgements

This work has been performed within the “Centre of Excellence on Clean Energy” (CUP D83C1700037002) funded by the Regional Government of Sardinia (FSC 2014-2020) and the "Research on Electric System" funded by the Italian Ministry of Economic Development.

References

[1] Hulme M. Why we disagree about climate change: Understanding controversy, inaction and opportunity. Cambridge University Press; 2009.

[2] Stocker T. (Ed.). Climate change 2013: the physical science basis: Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press; 2014.

[3] IEA. CO_2 emissions from fuel combustion – 2016 edition. Key CO_2 emissions trends. International Energy Agency (IEA), Paris; 2016.

[4] Ringrose PS. Principles of sustainability and physics as a basis for the low-carbon energy transition. Petroleum Geoscience 2017;23(3):287-297.

[5] IEA. 20 years of Carbon Capture and Storage. Accelerating future development. International Energy Agency (IEA), Paris; (2016).

[6] Siqueira TA, Iglesias RS, Ketzer JM. Carbon dioxide injection in carbonate reservoirs - a review of CO_2-water-rock interaction studies. Greenhouse Gases: Science and Technology 2017; 7(5):802-816.

[7] Tartarello MC, Plaisant A, Bigi S, Beaubien SE, Graziani S, Lombardi S, Ruggiero L, De Angelis D, Sacco P, Maggio E. Preliminary results of geological characterization and geochemical monitoring of Sulcis Basin (Sardinia), as a potential CCS site. Energy Procedia 2017; 125: 549-555.

[8] Plaisant A, Maiu A, Maggio E, Pettinau A. Pilot-scale CO_2 sequestration test site in the Sulcis Basin (SW Sardinia): preliminary site characterization and research program. Energy Procedia 2017; 114:4508-4517.

[9] Carmignani L, Pertusati PC, Barca S, Carosi R, Di Pisa A, Gattiglio M, Musumeci G, Oggiano G. Struttura della catena ercinica della Sardegna. Guida all’escursione del Gruppo Inf. Geol. Strutt., Siena, 1992:1-177. [Italian].

[10] Costamagna L, Barca S. The “Germanic” Triassic of Sardinia (Italy): a stratigraphic, depositional and palaeogeographic review. Rivista Italiana di Paleontologia e Stratigrafia 2002; 108:67-100.

[11] Fais S, Ligas P, Cuccuru F, Maggio E, Plaisant A, Pettinau A, Casula G, Bianchi MG. Detailed petrophysical and geophysical characterization of core samples from the potential caprock-reservoir system in the Sulcis Coal Basin (southwestern Sardinia - Italy). Energy Procedia 2015; 76: 503-511.

[12] Bigi S, Tartarello MC, Ruggiero L, Graziani S, Beaubien SE, Lombardi S. On-going and future research at the Sulcis Site in Sardinia, Italy– Characterization and experimentation at a possible future CCS pilot. Energy Procedia 2017; 114:2742-2747.

[13] Costamagna LG, Barca S. Stratigraphy and depositional architecture of the continental Middle Eocene–Early Miocene successions of Southwestern Sardinia: changing tectostratigraphic significance of the ‘‘Cixerri Fm.’’Auct. along times. Rendiconti online Soc. Geol. It. 2008; 2: 1-2.

[14] 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. Comptes Rendus Geoscience 2010; 342(2):116-125.

[15] Raza A, Rezaee R, Gholami R, Bing CH, Nagarajan R, Hamid MA. A screening criterion for selection of suitable CO_2 storage sites. Journal of Natural Gas Science and Engineering 2016; 28:317-327.

[16] 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; 2013:1–5.

[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. 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] Caine JS, Evans JP, Forster CB. Fault zone architecture and permeability structure. Geology 1996; 24(11):1025-1028.

[20] Bigi S, Marchese M, Meda M, Nardon S, Franceschi M. Discrete fracture network of the Latemar carbonate platform. Italian Journal of Geosciences 2015; 134(3): 474-494.

[21] Rutqvist J. The geomechanics of CO_2 storage in deep sedimentary formations. Geotechnical and Geological Engineering 2012; 30(3): 525-551.

[22] Aydin A. Fractures, faults, and hydrocarbon entrapment, migration and flow. Marine and petroleum geology 2000; 17(7): 797-814.

[23] Van Dijk JP, Bello M, Toscano C, Bersani A, Nardon S. Tectonic model and three-dimensional fracture network analysis of Monte Alpi (Southern Apennines). Tectonophysics 2000; 324(4): 203-237.