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Geomechanical evaluation of analogs of reservoirs for geological storage of CO_2

Évaluation géomécanique d'analogues de réservoirs pour le stockage géologique du CO_2

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ABSTRACT: Anthropic activities significantly contribute to the release of CO_2 into the atmosphere, which worsens global warming and accelerates climate change. To address these issues, geological storage in depleted oil reservoirs is seen as a potential solution to mitigate these effects. However, there is a lack of information on the application of this technique in the Golfo San Jorge Basin in Argentina, as well as geomechanical studies on its rocks. This study aims to characterize the geomechanical properties of rocks from the Salamanca, Castillo and Pozo D-129, formations under the influence of supercritical carbon dioxide injection. The studied samples were obtained from reservoir analogues exposed at the outcrop. Core plugs were used to assess the variation in the rock's mechanical behaviour when exposed to a CO_2-rich environment during 30-day periods, by performing Uniaxial Compressive Tests in both pristine and carbonated states. Additional analyses including X-ray diffraction (DRX) and mercury intrusion porosimetry (MIP) were conducted to evaluate the modifications produced in the microstructure. Notably, significant variations in mechanical parameters and porosity were observed in the studied formations. This article discusses the interaction between rock and supercritical CO_2, considering its chemical composition, to contribute to a better understanding of the potential for geological storage in the Golfo San Jorge Basin.

RÉSUMÉ: Les activités anthropiques contribuent de manière significative à la libération de CO_2 dans l'atmosphère, ce qui aggrave le réchauffement de la planète et accélère le changement climatique. Le stockage géologique dans des réservoirs de pétrole épuisés est considéré comme une solution potentielle pour atténuer ces effets. Cependant, on manque d'informations sur l'application de cette technique dans le bassin du Golfo San Jorge en Argentine, ainsi que d'études géomécaniques sur ses roches. Cette étude vise à caractériser les propriétés géomécaniques des roches des formations de Salamanca, Pozo D-129 et Castillo sous l'influence de l'injection de dioxyde de carbone supercritique. Les échantillons étudiés ont été obtenus à partir d'analogues de réservoirs exposés à l'affleurement. Des carottes ont été utilisées pour évaluer la variation du comportement mécanique de la roche lorsqu'elle est exposée à un environnement riche en CO_2 pendant des périodes de 30 jours, en effectuant des essais de compression uniaxiale à l'état vierge et à l'état carbonaté. Des analyses supplémentaires, notamment la diffraction des rayons X (DRX) et la porosimétrie par intrusion de mercure (MIP), ont été effectuées pour évaluer les modifications produites dans la microstructure. Notamment, des variations significatives des paramètres mécaniques et de la porosité ont été observées dans les formations étudiées. Cet article traite de l'interaction entre la roche et le CO_2 supercritique, compte tenu de sa composition chimique, dans le but de contribuer à une meilleure compréhension du potentiel de stockage géologique dans le bassin du Golfo San Jorge.

Keywords: Carbon dioxide geological storage; supercritical CO_2; Golfo San Jorge Basin; depleted oil and gas reservoirs; geomechanical property evolution.

1 INTRODUCTION

According to the Intergovernmental Pannel on Climate Change, during the past 100 years, an increase of 1.1ºC has been produced in the World's mean temperature (IPCC, 2023). Bearing in mind that climate change is produced due to the increase in the emission of greenhouse effect gases (GHG), and that at least 75% of them are represented by carbon dioxide (CO_2), it would be reasonable to think that by reducing the emissions of CO_2, this phenomenon would be mitigated. Among the available alternatives, capturing and storing CO_2 in the subsurface, is being considered as a way of reducing the concentration of this GHG in the atmosphere, while replacements for fossil fuels are developed.

CO_2 underground storage consists of capturing the CO_2 directly from its emission source (industries) for its further injection into an underground rock stratum. The formation chosen as reservoir, must be studied deeply enough to assure it is adequate. The feasibility of using a certain stratum as a CO_2 reservoir is determined by the evolution of the rock's geomechanical and hydro-chemical properties when exposed to a supercritical CO_2 ($scCO_2$) rich environment. The final objective is to ensure the reservoir's integrity in both short and long terms. Among the properties looked after in a possible CO_2 store, porosity, permeability, composition, and strength are of special interest (Bradshaw et al., 2007, and Hawkes et al., 2004).

In Argentina, there are several underground formations considered as possible CO_2 stores. Some of the potential underground reservoirs are Neuquina Basin, Claromecó Basin and Golfo San Jorge Basin (GSJB) (Grasetti et al., 2022, Laskowski et al., 2023). The three of them are characterized for being oil and gas reservoirs, being of particular interest for this study the Golfo San Jorge Basin (GSJB), since it stands out for containing reservoir rocks in different formations such as Salamanca, Castillo and Pozo D-129.

The main aim of the presented research is to fill the lack of information available in terms of geomechanical and chemical characterization of some GSB Basin formations and to technically consider their potential as possible CO_2 reservoirs. In this context, the results obtained from developing a series of laboratory tests on both pristine and carbonated rocks are presented, showing the evolution produced in their properties after the 30-day and 60-day aging.

2 MATERIALS AND METHODS

2.1 Geological context

The three different groups of rocks studied correspond to Salamanca, Castillo, and Pozo D-129 formations, which are all part of the Golfo San Jorge Basin (GSJB). Figure 1 shows a resume of the geological context of GSJB. The Pozo D-129 Fm. is the basal unit of the Chubut Group, which contains some tight reservoirs that serves as a source of oil and gas (Paredes et al. 2022). The depositional environment is associated with lacustrine and deltaic systems (Allard et al., 2018). The overliying Castillo Fm. represents traditional reservoirs of the petroleum system associated to the Chubut Group, consisting mainly of fluvial and paleosoils deposits (Paredes et al. 2015). A common feature of both rocks is the presence of varying amounts of tuffaceous material, associated with resedimented volcanic ash. The main lithologies are tuffaceous sandstone and tuff. (Cortes et al., 2024). On the other hand, the Salamanca Fm. is the shallowest oil reservoir of the basin, depleted at present and formed of marine sediments. The analyzed rock is a well-sorted glauconitic sandstone (Foix 2009).

These reservoir rocks are proposed as possible CO_2 stores as they meet the properties mentioned by Bachu (2000), presenting high porosity and permeability values (Cortés et al. 2024). Besides, the contrasting geological framework allows for the evaluation of different controls like the lithological composition and the diagenetic evolution.

2.2 Pristine and carbonated cores

To analyse the evolution produced in the properties of the different rocks due to their exposure to a CO_2-rich environment, it is necessary to obtain a group of representative specimens. Even when it would be ideal to obtain reservoir depth samples, this was economically not feasible, so it was proposed as a first approach, to obtain outcrop samples. Once in the laboratory, from these samples, cores with a 38 mm diameter and 76 mm height were obtained following the ASTM D 4543 – 01 specifications. From the samples obtained, half of them were separated and stored as pristine samples, and the other half were selected to expose them to $scCO_2$. Having completed the separation of the cores, the ageing process began.

Firstly, the cores were saturated in water by submerging them for 24 hours. This is an important step since water inside the rock facilitates the diffusion of CO_2. Secondly, they were disposed of in a tray holder, and introduced in the carbonation cell (Figure 2), where the CO_2-aging procedure was meant to be completed. Thirdly, the gas inlet was allowed until the carbonation cell was filled, a moment in which the temperature and pressure conditions were established to ensure the supercritical state of the CO_2 (60ºC temperature and 10 MPa pressure). The cell's conditions were maintained constant for 30 days. Finally, both the temperature and pressure were taken to environmental conditions carefully, to avoid the cracking or even fracture of the carbonated cores due to abrupt changes. The extracted cores were stored in a constant temperature and humidity chamber, covered in 40 μm polyethylene film, to maintain their properties invariant in time.

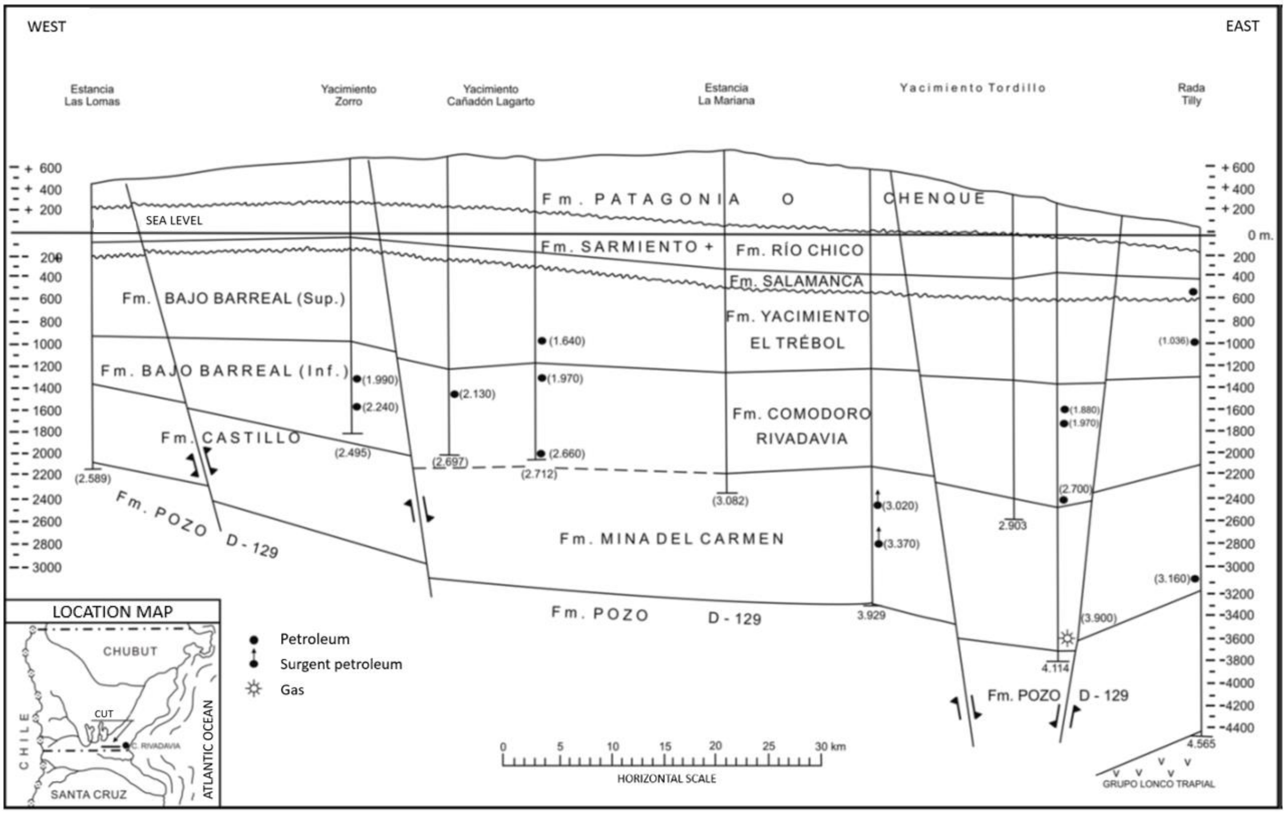

Figure 1. Golfo San Jorge Basin distribution of studied Formations (Sciutto et al., 2008).

Figure 2. Specimens in tray holder and carbonation cell.

2.3 Mechanical properties determination

The importance of analysing the evolution produced in the mechanical behaviour of the reservoir rock proposed as CO_2 underground storage, lies in verifying its long-term integrity. It is in this context, that a series of Uniaxial Compressive Tests, following the ASTM D 3148 – 02 specifications, were performed in both pristine and carbonated rock cores corresponding to the three formations. The results obtained from these tests were tenso-deformational curves which allowed making a complete comparison between the mechanical and elastic properties of the rocks before and after their exposure to $scCO_2$.

2.4 Microstructural properties determination

To reach a better understanding of the results obtained from performing the Uniaxial Compressive Tests, the variation produced in the microstructural properties due to CO_2 injection was analysed. The tests chosen for this research were the Mercury Intrusion Porosimetry (MIP) and the X-Ray Diffraction (XRD). With the results derived from the first group of tests, the available pore volume for CO_2 storage would be estimated, giving this a first approach to determine if the rock is a good reservoir alternative or not. On the other hand, the results obtained from the XRD, would allow to understand the trapping mechanisms being developed in each rock.

3 RESULTS AND DISCUSSION

3.1 Uniaxial compressive strength

The stress–strain curve obtained from performing Uniaxial Compressive Tests on Salamanca Fm. shows a significant reduction of Uniaxial Compressive Strength in carbonated cores at 30 days as is shown in Figure 1. Also is observed that the sample becomes more ductile after the $scCO_2$-aging.

Figure 3 shows the comparison for all lithologies, and formations, showcasing the evolution of Uniaxial Compressive Strength (UCS) for both pristine and carbonated cores. After subjecting the Sandstone from the Salamanca Fm. to ageing with supercritical carbon dioxide for 30 days, a notable decrease of approximately 40% in Uniaxial Compressive Strength (UCS) is evident. However, in the Tuffaceous Sandstone samples and the Tuff from Castillo and D-129 Fms., this reduction is less pronounced, ranging from 20 to 22%. The trend of UCS reduction persists in rock samples aged for 60 days, though the results remain inconclusive due to the limited number of tests conducted. Various authors have highlighted variations in strength, which depend upon the composition of the rocks. Typically, carbonates exhibit more significant alterations, while results for carbonate-cemented sandstone appear ambiguous, and silica-cemented sandstone tends to undergo minor changes (Vilarrasa et al., 2019). The predominance of carbonate cement within the Salamanca Fm. (Laskowski et al., 2024) and the identification of zeolitic cement in the D-129 Fm. (Olazabal, pers. com.) and samples from the Castillo Fm. (Tunik et al., 2015), explains the variations in strength observed, both before and after $scCO_2$ carbonation, between the studied formations.

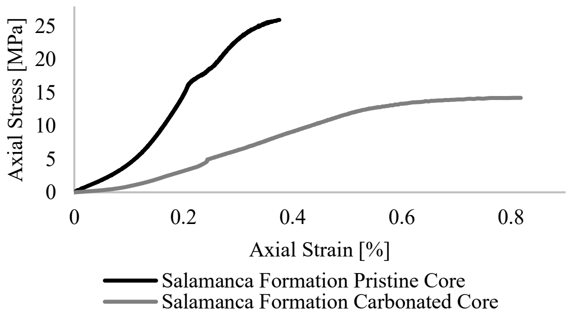

Figure 2. Example of results of stress – strain curve obtained from performing Uniaxial Compressive Tests on Salamanca, in both pristine and carbonated cores at 30 days.

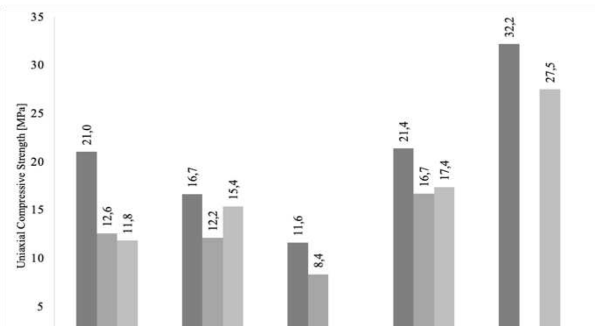

Figure 3. UCS on Salamanca, Castilla and Pozo D-129 Fms, in both pristine and carbonated cores at 30 and 60 days.

3.2 Porosity variations after $scCO_2$-exposure

Mercury Intrusion Porosimetry (MIP) tests were carried out to examine the porosity changes in the chosen reservoir rock induced by supercritical carbon dioxide ($scCO_2$). In general, the sandstone demonstrated a reduction in porosity following exposure to a CO_2-rich environment as is shown in Table 1. MIP porosity of sandstone from Salamanca Fm. is approximately 10.66%, while post-aging porosity is 9.65%. The tuffaceous sandstone from the Castillo Formation and the Tuff of the D-129 Formation exhibit mean values of MIP porosity of approximately 19%, with post-aging porosity measuring 17%.

A detailed examination of Figure 4 revealed changes in the pore size distribution of sandstone from Salamanca Fm. The Differential Intrusion-Pore Diameter curves indicated a notable increase in the volume of smaller pores (40-90 nm), rising from 30% to 45%, alongside a decrease in the larger pores (800-4000 nm) from 30% to 10%.

Table 1. Porosities were obtained for the different rocks studied.

Specimen Characterization		CO_2 exposure time [days]	
		0	30
Formation	Lithology	Porosity [%]	
Fm. Salamanca	Sandstone	10,66	9,65
Fm. Castillo	Tuffaceous Sandstone	19,79	17,05
Fm. Pozo D-129	Tuff	19,30	17,05

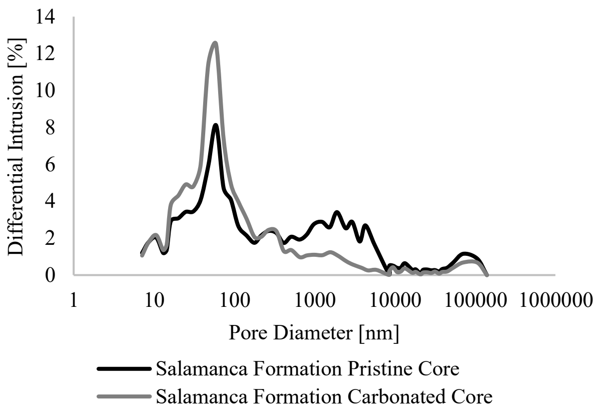

Figure 4. Results of Differential Intrusion-Pore Diameter obtained from performing MIP tests on Sandstone from Salamanca Fm. in both pristine and carbonated cores.

3.3 X-Ray diffraction

XRD analysis demonstrated that the rocks from Castillo and D-129 Fm. generally contain variable amounts of quartz, potassic feldspar, plagioclase, and clays such as kaolinite and illite. Small amounts of jarosite and analcime are also present in some of the samples.

The treated samples exhibited insignificant changes in potassic feldspar, kaolinite, and illite, except for a 2% reduction in illite observed only in the tuffaceous sandstone of the Castillo Fm. Similarly, analcime displayed minimal changes, but the variation was almost 7%.

The most significant alterations were observed in quartz and plagioclase. In most cases, quartz content decreased, while plagioclase increased in the treated samples. This trend aligns with the measurements of silica and aluminium obtained by portable XRF (Cortés et al., 2024). The reduction in silica and quartz content in the carbonated samples, as determined by XRF and XRD measurements, respectively, may be attributed to the corrosion of quartz crystals (Rathnaweera et al., 2015) or the dissolution of clay minerals (Rathnaweera et al., 2015). However, it is more conventional for feldspars to react before quartz.

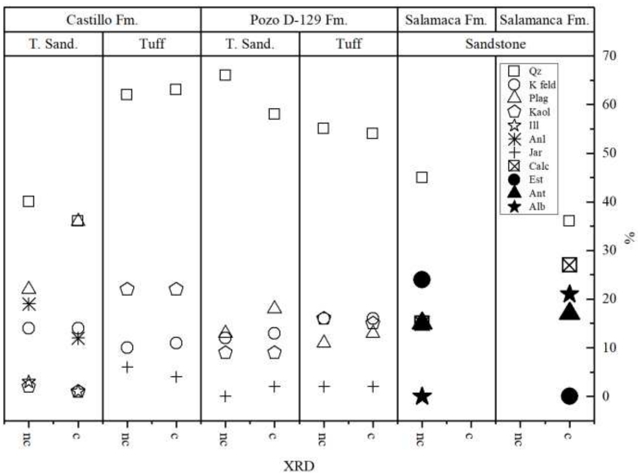

Figure 5. Mineral composition of carbonated and non-carbonated samples determined by XRD. Qz= Quartz, K feld= Potassium feldspar, Plag= Plagioclase, Kaol=Kaolinite, Ill=Illite, Anl=Analcine, Jar=Jarosite. Cal = magnesic calcite, Est = sodic estilbita, Ant = anorthite, Alb=albite.

Remarkably, the quantity of potassic feldspar remained relatively stable, while the amount of plagioclase increased. Both observations pose geological inconsistencies due to the inert nature of quartz and the exclusive magmatic genesis of plagioclase. This increase is attributed to the dissolution of minerals more soluble than plagioclase, leading to an increase in its relative content as stated by Yang et al. (2022). This also could be attributed to the sampling process, which may be influenced by the potential heterogeneity of the formation. Another aspect to remark on is the high quartz content which is inconsistent with previous petrographic studies as stated by Cortés et al. (2024).

The treated samples of Sandstone from Salamanca Fm. exibihit changes in magnesic calcite, sodic estilbita and albite. The effects of glauconite reaction to CO_2 may be a major control in the associated geochemical process (Fu et al. 2015). These changes are affecting the porous matrix and its strength. Further clarity on this uncertainty will be obtained through in-depth analyses, such as thin sections or Scanning Electron Microscope images.

4 CONCLUSIONS

The research emphasizes findings across mechanical, petrophysical, and chemical evolution of the glauconitic sandstone of Salamanca Fm. and tuff and tuffaceous sandstone Castillo and Pozo D-129 Fms for pristine and supercritical CO_2-aged samples at 30 and 60 days.

The evident alteration in the chemical composition of the treated specimens indicates a consequential influence on both mechanical strength and porosity. The drop in mechanical strength is evident across all three analyzed lithologies following CO_2-aging. However, despite the impact on mechanical strength, the samples exhibit a decrease in porosity. Further examination, particularly through thin sections and Scanning Electron Microscopy (SEM), is imperative to elucidate the underlying geochemical reactions and mineralogical changes. The scope of tests is being broadened, encompassing triaxial tests, to delve deeper into the mechanical behaviour and explore the evolution of microstructures under conditions mimicking CO_2 underground storage.

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