CHAPTER 7

THE INFLUENCE OF FLOW UNITS ON CO_2 STORAGE WITHIN THE SHALE AND CARBONATE RESERVOIRS OF THE IRATI FORMATION, PARANA BASIN, SOUTHWEST OF SÃO PAULO

Richardson M Abraham
Colombo Celso Gaeta Tassinari

ABSTRACT

CO_2 injection and storage within the potential reservoirs depend on the geological/geochemical trapping mechanisms and the reservoir quality involving porosity (Φ), permeability (K) and other flow unit factors. Core samples are not available for petrophysical evaluation of the rock units. Therefore, the reconceived expressions aided to predict the hydraulic unit in the shale and carbonate reservoirs concerning the CO_2 storage capacity of the Irati Formation. The study presents the average values of flow units in shale and carbonate units and their influences on the injection and storage of CO_2. Low flow units may restrict the CO_2 storage potential in shale, while water saturation (S_w) may affect the carbonate reservoirs. However, there are potentials for CO_2 storage in the shale and carbonate rocks based on the abundance of the rock units within the study location, higher reservoir depths and proximity to CO_2 emitting sources. The Irati Formation can also serve as a shale-carbonate hybrid geological reservoir for CO_2 storage. The presented parameters (Φ, K, reservoir quality index-RQI and flow zone indicator-FZI) may be applied in future studies involving hydrocarbon exploration, thereby expanding the CO_2 storage potentials of the targeted reservoirs.

Keywords: Atmospheric CO_2 Reduction; Petrophysical characterisation; Flow Units; Hybrid Reservoir; Irati Formation

1. INTRODUCTION

The need for carbon capture and storage (CCS) in São Paulo stems from global warming mitigation and the presence of CO_2 emission sources. São Paulo has CO_2 emission sources (mainly from the energy and biomass sectors) with capacities ranging from 20Kt/yr to 6400 Kt/yr (Ketzer et al., 2014). 25.8% of the domestic CO_2 production and 31.4% of CO_2 acquisition via importation activities in Brazil come from São Paulo (Imori and Guilhoto, 2016). References have been made to the geological reservoirs within the Parna Basin concerning CO_2 storage potentials (Ketzer et al., 2015; Richardson and Tassinari, 2019). The Irati Formation of the Parana basin consists of shale, carbonate and siltstone lithologies intruded by basalt sills at some intervals. The petrophysical characterisation based on the rock units is of pertinent interest in predicting the CO_2 storage potentials of the geological reservoirs. It aids to evaluate the storage efficiency factors such as reservoir thicknesses and porosity (Φ) for volume estimation. The shale and carbonate rock of the Irati Formation could provide the required efficiency to aid CO_2 repositioning within the Parana Basin. Depleted and already enhanced reservoirs for hydrocarbon recovery have been on the target for CO_2 storage (Steven et al., 2010; Pearce et al., 2011; Gabriela et al., 2013). This idea does not disregard the possibility of CO_2 storage in geological Formations without hydrocarbon production history. Wireline logs are engaged to estimate the flow units, reservoir thicknesses/depths and water saturation (S_w) in shale and carbonate reservoirs. The wireline logs consist of density and sonic logs to aid the estimation of the porosity (Φ), permeability (K), Reservoir Quality Index (RQI) and Flow zone indicator (FZI). These parameters (Φ, K, RQI and FZI) are essential to predict the reservoir characteristics such as pore-throats, pore sizes, distribution of pores, grain sizes, grain sorting, textures and structures of grains and pores in the reservoirs. The injection, movement, storage and security of fluid within geological structures depend on the above-stated parameters, geological/geochemical trapping mechanisms and overburden integrity.

Brazil has existing CO_2 injection wells and storage sites monitoring, measuring and verification (MMV) related projects (Moreira et al., 2014; Ketzer et al., 2014). The MMV project is an advantage for CCS in the country, and São Paulo via the collaboration of related institutions [e. g. Research Centre for Gas Innovation (RCGI) of the University of Sao Paulo (USP)] should be able to benefit from this programme to foster CO_2 storage within its environs. CCS is possible in São Paulo, considering the shale and carbonate units of the Irati Formation as potential repositories. However, the best reservoir option could be the shale-carbonate hybrid geological reservoir to minimise CO_2 storage uncertainties involving thin-bedded factors and overburden integrity.

2. SHALES

Shales are naturally fine-grained clastic sedimentary rocks consisting of mud/clay minerals with tiny particles of other materials (quartz, calcite and others) depending on the area's geology. Based on the depositional environment, there are different types of shales. There are calcareous shales, carbonaceous and black shales. There are also siliceous shales, ferruginous shales and sandy/silty shales. Black and carbonaceous shales exist within the Parana basin, and they could serve as a reservoir for CO_2 storage in the Formation of Irati. Free gas occurs in shales within dispersed organic matter, adsorbed by these organic matter or other related minerals. The organic matter rich lamina is also a factor related to the injection and storage of CO_2 in shales. K, in shales, is directly related to the degree of natural cracks/fractures that allow fluid passage. Therefore, K depends on fractured paths, fracture patterns, organic matter content and cementation. Other factors include relative configuration of the building grains of the rock, pore/grain sizes, thermal maturity, and volume of organic matter per unit area/organic matter distribution and mineral composition. In shales, the intra-particle of organic pores and inter-particle of organic and inorganic pores hold the gas (Loucks et al., 2009; Loucks et al., 2012; Yang et al., 2015). The abundance and the distribution of cracks and fractures aid the movement and positioning of fluid in shale reservoirs. It is uncertain at this point whether or not fracturing to increase the storage potential in shales will be an option because hydraulic units of the shale reservoir rock in situ may not encourage high CO_2 storage. Shale fracturing to increase permeability (K) enhances injection rate and transmissibility of fluid. Further exploration activities within the region may reveal significant gas in the shale units to call for fracturing for gas production and increase the CO_2 storage potential of the shale afterwards.

3. CARBONATES

Limestone and dolomite are found in the Irati Formation and could also offer units for CO2 storage. In the carbonate reservoirs category, dolomites will present better reservoirs in terms of porosity and permeability distribution. Dolomitisation is a process that involves the substitution of some Ca^{2+} ions in limestone $(CaCO_3)$ by Mg ions to form dolomite $[Ca.\ Mg\ (CO_3)_2]$. It includes the dissolution of pre-existing carbonate rocks with subsequent precipitation of dolomite. The balance between dissolution and precipitation rates brings about changes in porosity (Tucker and Wright, 1990; Purser et al., 1994; Warren, 2000; Wang et al., 2015). Dolomitisation produces new crystals due to the dissolution of the less stable parent rock (limestone). The repeated occurrence without complete pore cementation leads to inter-crystalline separations and porosity enhancement. Intercrystalline porosity is a highly interconnected porosity style that gives dolomite reservoirs significant fluid storage capacity and efficient drainage (Warren, 2000). Therefore, dolomitisation increases the crystal sizes; pore sizes and thus enhances porosity (Φ) and permeability (K) (David et al., 2008; Ritesh et al., 2014). Furthermore, dolomites are less reactive and less ductile compared to limestone, as such; they are less likely to lose porosity with depth due to dissolution or re-precipitation (Grammer & Harrison., 2003; Davis et al., 2008; Grammer and Harrison, 2013; Sharma et al., 2014; Chao et al., 2016). A dolomite bed can retain or create porosity and permeability to much greater burial depths and into higher temperature realms than a limestone counterpart (Warren, 2000). However, the injection of CO_2 into the geological structures activates physicochemical changes over time (Gaus, 2010; Ketzer et al., 2012; Siqueira et al., 2017). Injected carbon dioxide within the carbonate reservoir brings about geochemical alterations, imbalances in pore pressures, mineral dissolution, and alteration of porosity and permeability (Andreani et al., 2009; Bacci et al., 2011; Kampman et al., 2014). The presence of water in the reservoirs activates the CO_2-carbonate reaction. Therefore, the choice of carbonate reservoirs for CO_2 storage depends on the need for storage, geochemical composition of other surrounding rocks and water saturation (S_w).

4. THEORETICAL ESTIMATION OF HYDRAULIC UNITS

A couple of basic parameters are essential in the estimation of flow units. Cementation exponent (***m***) and factor of tortuosity (***a***) vary from one rock unit to another. A recapitulation of the use of these parameters reveals ranges of approximated values for shale and carbonate rocks. Such that, the tortuosity factor ranges from 0.59 to 1.00 in carbonates and up to 1.65 in shales. In the same vein, the cementation exponent could be up to 2 in carbonates and above 2.5 in clay minerals/shale depending on the type of clay minerals (Carothers, 1968; Asquith and Gibson, 1982; Schlumberger, 1989; Hilmi and George, 1999). The theoretical estimation of flow units based on wireline logs (Richardson and Taioli, 2017) shows the possibility of maximising porosity to estimate the reservoir quality and predict transmissibility. In the absence of core data, the interdependency among porosity (Φ), permeability (K), reservoir quality index [RQI] and flow zone indicator [FZI] is engaged in the prediction of the reservoirs flow units with the aid of wireline logs (Tiab and Donaldson 2012; Richardson and Tassinari, 2019). This study presents a combination of expressions based on reviewing the concerned intrinsic parameters (Φ, K, RQI and FZI) defined for the carbonate and shale reservoirs of the Irati Formation. Based on Equations (1) to (8), these parameters are engaged to predict the flow units and their implications on CO_2 storage.

$$\Phi_{S-D} = \frac{\Phi_S + \Phi_D}{2} \quad (1)$$

K may be expressed in carbonate as Equation (2) and in shales as Equation (3).

$$K = (4472\Phi_e{}^{3.25})^2 \quad (2)$$

$$K = \frac{(20000000\Phi_e{}^{6.7})}{1.65} \quad (3)$$

RQI is defined for carbonates by Equation (4) and shales by Equation (5).

$$RQI_{(e)} = \frac{140.4\Phi_e{}^{3.25}}{\Phi_e{}^{0.5}} \quad (4)$$

$$RQI_{(e)} = \frac{0.0314*\left(2\times10^7\Phi_e{}^{6.7}\right)^{0.5}}{1.65\Phi_e{}^{0.5}} \quad (5)$$

FZI is estimated based on Equations (6) in carbonates and Equation (7) in shales.

$$FZI = \frac{140.4\Phi_e{}^{3.25}}{\Phi_e{}^{0.5}*\Phi_R} \quad (6)$$

$$FZI = \frac{0.0314*\left(2\times10^7\Phi_e{}^{6.7}\right)^{0.5}}{1.65\Phi_e{}^{0.5}*\Phi_R} \quad (7)$$

Where Φ_R takes the form of Equation (8) (Tiab and Donaldson, 2012)

$$\Phi_R = \frac{\Phi_e}{1-\Phi_e} \quad (8)$$

5. CO_2 STORAGE EFFICIENCY FACTORS

In qualitative and quantitative reservoir evaluations, porosity (Φ) is a dependent factor used for the prediction of other parameters such as permeability (K), reservoir quality index (RQI) and flow zone indicator (FZI). RQI is a factor that describes the distribution of pore sizes, grain sizes and pore-throats, while FZI predicts the grain sizes, grain sorting, textures and structures of grains/pores (Tiab and Donaldson, 2012). Fluid mobility and storage within the reservoir depend on these parameters. During volumes estimations, among the considered factors are thickness (h) and Φ, which are derivable from wireline logs. Figures 1, 2, 3 and 4 show the delineated rock units and depths in the Irati Formation, southwest of São Paulo.

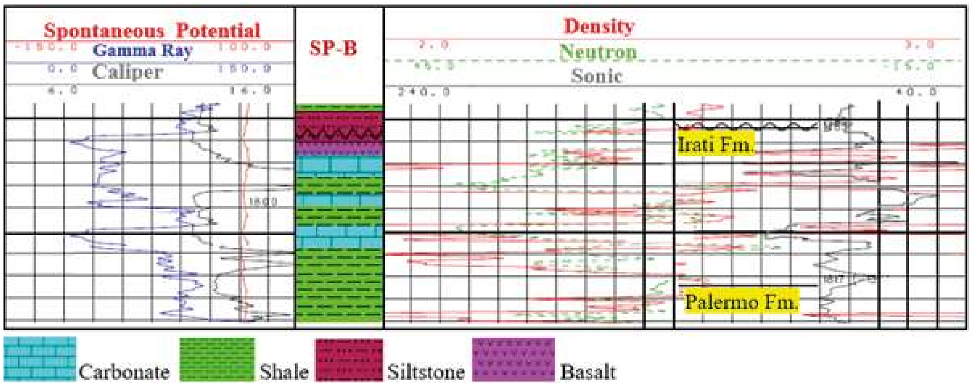

Figure 1: Showing the thicknesses of the rock units below 1780m

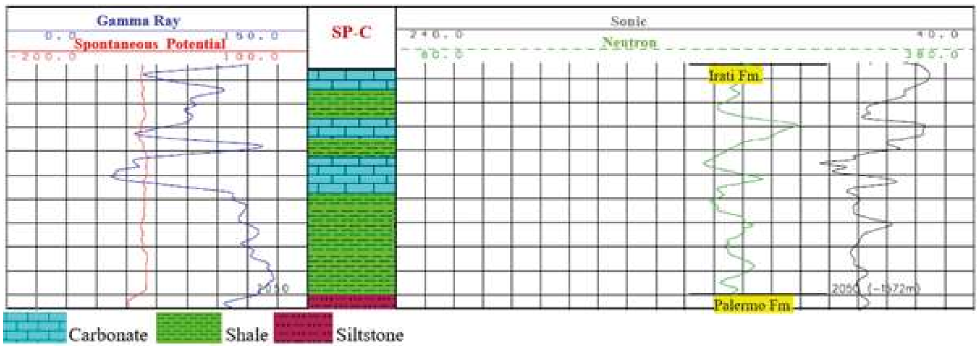

Figure 2: Showing the thicknesses of the rock units below 2000m.

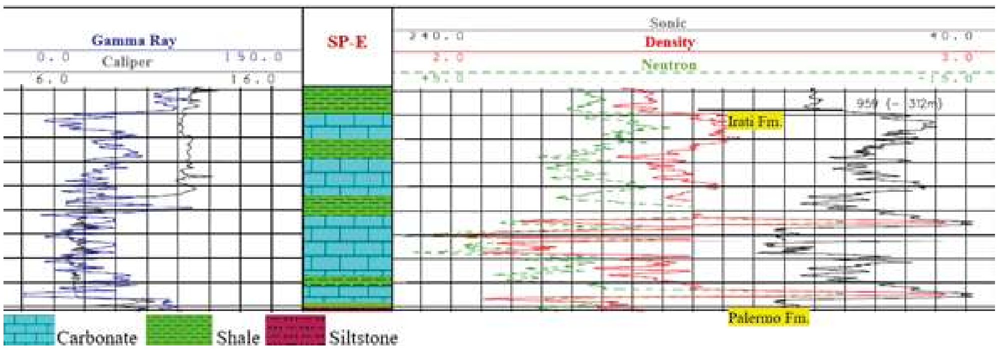

Figure 3: Showing the thicknesses of the rock units below 960m.

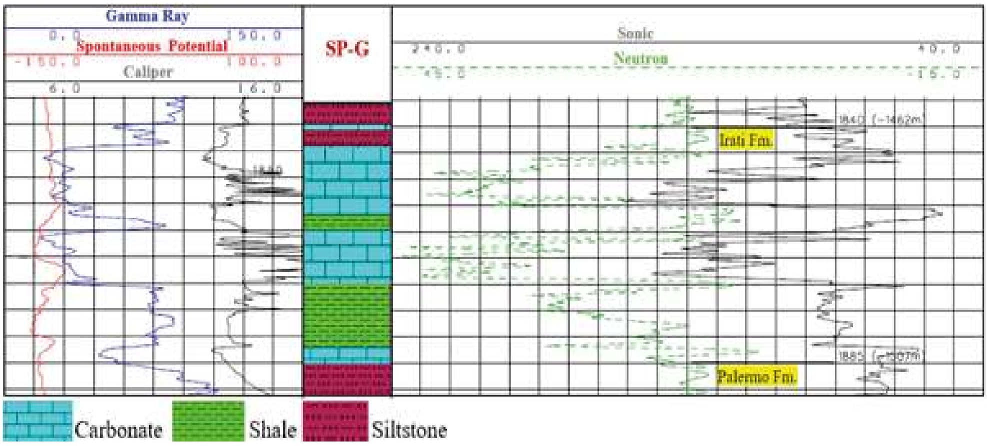

Figure 4: Showing the thicknesses of the rock units below 1840m.

The thicknesses of the rock units range from ≤2m to ≤33m, such that the average value for shale is about 17.1m and carbonate is about 17.5m. The shale and carbonate reservoirs consist of thin-bedded layers, and this factor may limit the CO_2 storage potentials within the Irati Formation. Other factors may include low permeability in shale units and overburden integrity. Therefore, the algorithm for volume estimation based on CO_2 storage for the Irati Formation will be affected by the fractional reductions in reservoir thickness, porosity and storage area. Hence, the associated volume efficiency factor (E_{av}) takes the form of Equation 9.

$$E_{av} = E_h \times E_a \times E_\Phi \qquad (9)$$

Where; E_h = fractional reduction in reservoir thickness, E_a = fractional reduction in the storage area, and E_Φ = fractional reduction in reservoir porosity.

The combination of seismic images with the wireline logs for further study is imperative. This way, the storage area (A) and the area-based efficiency factor (E_a) are predicted. Relevant seismic interpretations are required to confirm the seal and trap mechanisms at higher depths. It is also imperative to consider the influence of tectonic activities on the Irati Formation during the selection of depths for CO_2 storage. Seismic images will aid to delineate the surface area of the selected storage sites and reservoir geometries considering faults distribution/ orientations, seals/traps integrity and reservoir thicknesses.

According to the Intergovernmental Panel on Climate Change (IPCC, 2005) special report, the recommended depths for CO_2 storage are 800m and above. However, considering the buoyancy of supercritical CO_2 concerning the reservoir rocks, temperatures and pressures, fluid can migrate to the surface even at these depths (Matter and Kelemen, 2009). The buoyancy of CO_2 threatens the long-time storage of CO_2 within geologic structures except for the high integrity of traps and seals mechanisms. However, to overcome issues related to buoyancy, CO_2 may be dissolved in water by releasing it as bubbles of gas within the injection well at some intervals of depths as the water flows down (Galison et al., 2014). Another factor that may affect CO_2 storage (especially in the carbonate units) is water saturation (Sw). However, based on the spontaneous potential (self-potential) log and the charts [modified from Asquith and Gibson (1982) and Allied-Horizontal Wireline Services (2015)], water saturations are low at higher depths in the Irati Formation at the southwestern region of Saõ Paulo. Reservoir depths higher than 900m show Sw of <14%, while those below 800m indicate ≥40%. Therefore, CO_2/S_w ratios may determine the choice of the carbonate units for CO_2 storage.

6. PREDICTION OF FLOW UNITS

Figure 5 shows the average limits of porosity (Φ) and permeability K defined for the shale and carbonate reservoir units within the Irati Formation. The reservoir quality index (RQI) and flow zone indicator (FZI) (Figures 6 and 7) are essential to provide the theoretical estimation of the distribution of the reservoirs pore integrity, grains and pore-throats, grain sizes and sorting, textures and structures of grains. These parameters define the porosity and pore spaces interconnectivity within a given reservoir unit. The injection rate and transmissibility of fluid within the reservoirs also depend on these factors.

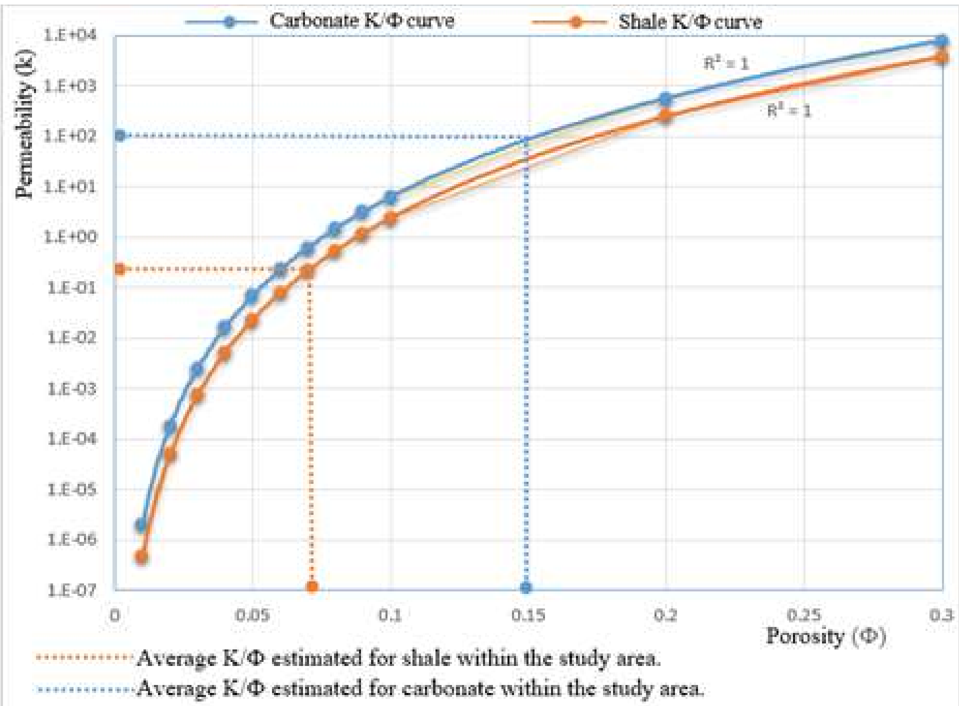

Figure 5. Showing the average values K based on shale and carbonate rocks

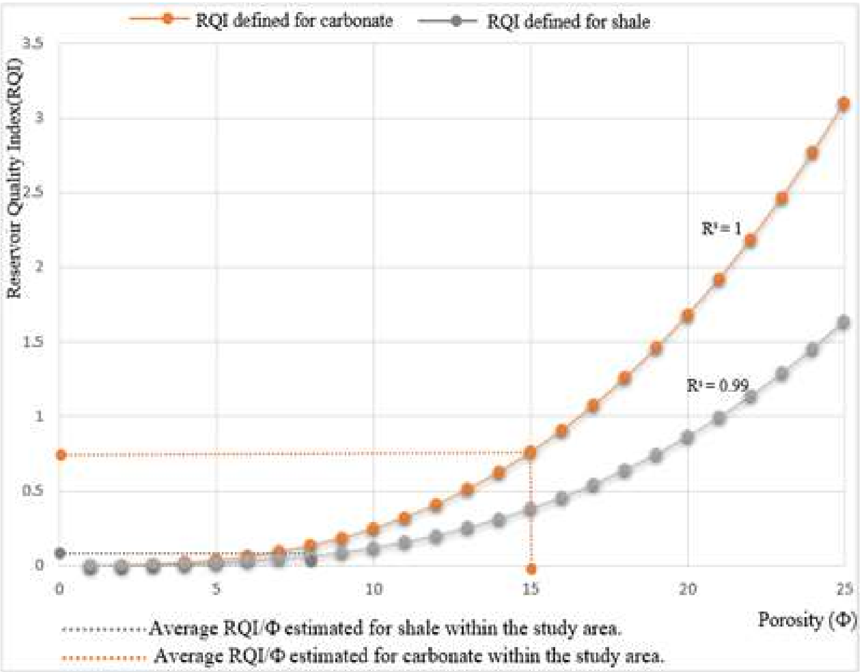

Figure 6. Showing the average RQI predicted for shale and carbonate rocks

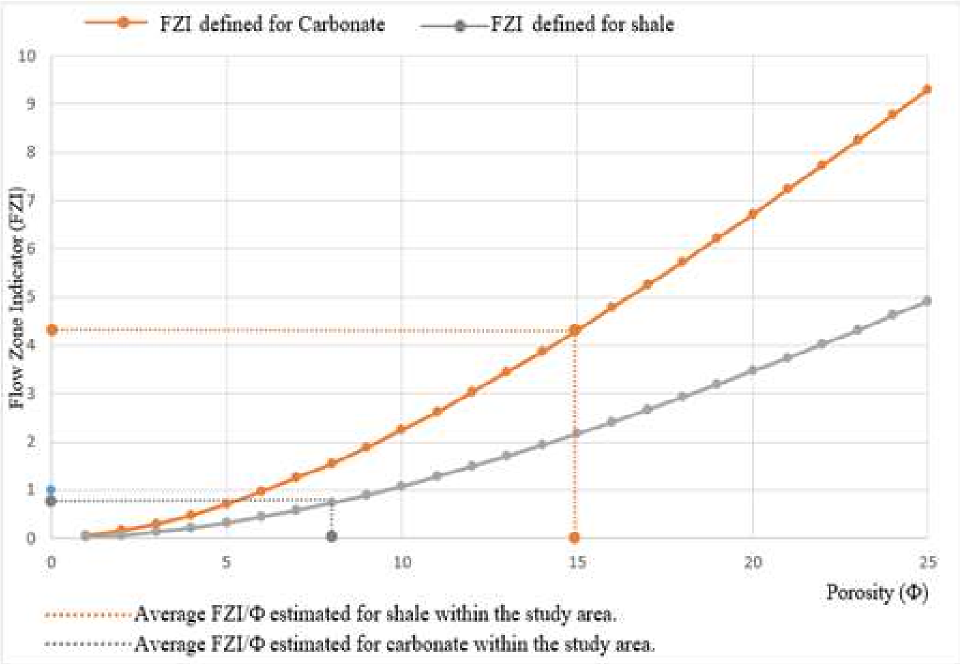

Figure 7. Showing average FZI estimated for shale and carbonate rocks

7. INJECTION, STORAGE AND SECURITY OF CO_2 WITHIN THE IRATI FORMATION

Geologically, the injection, storage, and security of fluids depend on the targeted reservoirs' flow units and geological/geochemical trapping mechanisms. The flow unit factors in the rock units in-situ are not as significant in shale reservoirs as presented by the carbonate rocks. Regardless, on a large scale, based on the flow units and the need for carbon capture and storage (CCS), the shale and carbonate reservoirs in the Irati Formation are recommendable for CO_2 storage. The flow units represent the intrinsic elements that define some of the storage efficiency factors.

Fault orientations and the integrity of seals/traps are factors that define the geometry of reservoirs and the security of the fluids in them. Therefore, they are crucial concerning CO_2 storage in geological structures. Evaluating these parameters is essential to predict the CO_2 storage potentials of the reservoirs within the Irati Formation. The security of CO_2 within the geological reservoirs will depend on the prevalent structural styles within the Parana Basin (Rostirolla et al., 2003). While the pore spaces in the reservoir rocks provide the largest capacity for CO_2 storage, rock surfaces will adsorb some quantities of the fluid depending on the total organic content (TOC) of the rock units (especially shales) and reservoir pressure. Therefore, geological and geochemical trapping mechanisms will secure the injected CO_2 within the reservoir units of the Irati Formation of the Parana Basin. Geochemical trapping mechanisms contributing to the CO_2 storage potentials of the reservoirs include hydrodynamic trapping, residual trapping, solubility trapping and mineral trapping (Rosenbauer and Thomas, 2010; Zhang and Song, 2014). The effectiveness of some of these geochemical trappings (e. g., solubility and residual trappings) depends on the presence of brine (salt-water) within the Formation. Therefore, in the absence of brine within the Irati Formation, hydrodynamic and mineral trappings are likely to be more active.

Other factors concerning CO_2 injection, storage and security are gross thicknesses (h) and depths of the reservoir units. The wireline logs show that the Irati Formation thickness ranges from ≥ 20m to ≤ 80m across the study location (southwest of São Paulo). Therefore, considering that the shale and carbonate units are predominant within the Irati Formation, the shale-carbonate hybrid geological reservoir will provide sufficient thicknesses for CO_2 storage in agreement with existing standards and proven atlases. The depths of occurrence of the Irati Formation across the study location is higher than the recommended depth (above 800m) (IPCC, 2005; Chadwick et al. 2008; IEA-GHG, 2009; Smith et al., 2011). The wireline logs also reveal that towards the southwestern region of São Paulo, the Irati Formation depths are above 800m (more than 2500m in some cases); therefore, they meet the recommended depth of reservoirs for CO_2 injection and storage.

The average values presented for the evaluated flow units suggest that the Irati Formation should support the injection (probably considering higher pressure in shale because of low flow units) and storage of CO_2. The flow unit factors are significant in carbonates when compared with the shale. Carbonates-CO_2 chemical interaction is imperative in the storage potential evaluation. The carbonate-CO_2 reaction may not constitute concerns in the Irati Formation, considering the low water saturations with depth increases indications. Therefore, the shales may form the required seals and traps for the carbonate reservoirs to serve as CO_2 storage tanks. Basalt sills are not uncommon within the sedimentary layers of the southwest of São Paulo. Basalt consists mainly of pyroxene (augite), plagioclase and olivine with silica content between 45% and 52%. It has good potentials for CO_2 mineralisation (McGrail et al., 2008; Oelkers et al., 2009; Goldberg and Slagle, 2011). The mineralisation of CO_2 means a chemical reaction between certain minerals and CO_2, leading to the transformation of CO_2 in the rock. Therefore, the associated basalt could contribute to the overburden or seal integrity or present itself as a potential reservoir. Considering the combined shale and carbonate rocks of the Irati Formation as a storage unit such that the overlaying Serra Alta Formation forms the required seal is also a conceivable idea. However, the Serra Alta Formation consists of porous rock units (e. g., carbonate), debunking its possibility as a potential overburden layer for the entire Irati Formation. It is also promising to consider the portions within the Irati Formation overlying by shale and basalt sills for CO_2 storage, provided other factors support the system.

8. FINAL REMARKS

The shale and carbonate reservoir units within the Formation of Irati Formation within the southwest of São Paulo can support storage, especially with a delineated large area, provided other geologic and environmental factors are favourable. The associated basalt sills of the Sera Geral Formation intruding the study location (Irati Formation) and the siltstones of the Irati Formation may contribute to the quality reservoirs concerning |CO_2 storage. However, geology-based limitations exist involving low shale permeability, water saturations in carbonates, thin-bedded layers, overburden integrity/continuity, and fault styles/distributions. The engaged wireline logs for this study dated from the mid-60s to the 80s. Therefore, if further exploration activities based on modern/improved equipment and expertise reveal significant shale gas, fracturing to enhance gas production will increase CO_2 storage potentials in shales. The reduction in the water saturation (Sw) with depth increase may also boost carbonate storage potentials depending on CO2/water ratios. Seismic interpretations involving 2D-4D data to evaluate the geometry of the reservoirs and capacity estimation for storage are pertinent. Further formation evaluations may use the presented hydraulic units as hydrocarbon exploration input data to verify possible oil or gas production, thereby boosting CO_2 storage capacity within the Irati Formation.

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