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Characterizing Flow Paths in Peridotite Formations for CO_2 Sequestration: Hydro-Mechanical Modelling of a Pilot Test in the UAE

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Abstract

CO_2 mineralization in peridotite formations has emerged as a promising method for permanent CO_2 sequestration. Characterization of fracture networks is essential for assessing the success of projects. 44.01 conducted a series of injection tests in peridotites in Oman and United Arab Emirates (UAE) to evaluate their suitability for large-scale CO_2 sequestration. This study uses hydro-mechanical modeling of injection test data from their pilot project in the UAE to calibrate fracture properties. These calibrated models were then compared with time-lapse geophysical surveys to evaluate their ability to predict the distribution of injection fluids. Wireline logging and electromagnetic survey are employed to construct reservoir model, which are then coupled with a geo-mechanical framework that links fracture permeability to pore pressure. The injection test covered a wide range of injection rates, providing critical insights into fracture responses under different stress regimes.

Initial fracture porosity distributions are estimated using electromagnetic surveys, which enables distinguishing between peridotite and serpentinized peridotite. Injection cycles are history-matched sequentially. This approach helps optimize injection test design for estimating stress-dependent fracture properties. Calibration results indicated that a piece-wise power-law correlation was necessary to match the injection test data, which stemmed from the fact that the numerical discretization could lead to lumping multiple fractures into a fracture set in a grid block in dual-porosity models.

This study puts forward a comprehensive understanding of fluid flow through fractures in deep ultramafic formations, offering valuable insights into the potential for large-scale in-situ CO_2 mineralization in this region.

Introduction

In-situ mineralization processes in mafic and ultra-mafic formations involves injection of water with dissolved CO_2 where the dynamic dissolution of the formation and precipitation of carbonates leads to elimination of CO_2 (Kelemen & Matter, 2008). Mafic and ultra-mafic rocks as the main host formations targeted for CO_2 mineralization are naturally fractured exhibiting very low matrix permeabilities (Kelemen, Benson, Pilorge, Psarras, & Wilcox, 2019). Hence, flow of aqueous phase through a network of fractures can determine the efficacy of the mineralization projects. Amongst various pertinent aspects of mineralization processes, formation transmissibility can play a crucial role as it can have commercial implications. Additionally, fractures of ultra-mafic rocks can be sensitive to effective stress imposed on the fracture network (Falcon-Suarez, et al., 2017) and hence, geomechanical effects and stress-dependent properties are needed to robustly investigate how the formation responds to injection scenarios (Mahzari, et al., 2021). In other words, characterization of injectivity and formation permeability requires detailed understanding of fracture distribution and impact of stress variation on fracture permeability.

The Samail ophiolite in the UAE and Oman is partially composed of peridotites and serpentinized peridotites where this ultra-mafic rock has been studied extensively for CO_2 mineralization (Paukert, Matter, Kelemen, Shock, & Havig, 2012). Fractures in peridotites can undergo a range of serpentinization degrees whereby the primary minerals such as olivine and pyroxene are altered into less dense and less electrically resistive minerals called serpentine. The electrical resistivity of serpentines and primary minerals can differ by 2-3 orders of magnitudes (Stesky & Brace, 1973). As the serpentinization reactions occur through fractures, it is conceivable that this contrast in electrical resistivity can be utilized for identifying natural fractures. Peridotites in the UAE are highly fractured exhibiting fractures and cracks in various dimensions and hence, small- and large-scale heterogeneities would necessitate a tailored characterization methodology of fractures.

A pilot injection test was performed in the UAE targeting peridotites at the depth of 600-800 m for CO_2 mineralization. The focus of this work is that the injection profile of the pilot test is used to calibrate the fracture network and stress-dependent properties. In this modelling work, a discrete fracture network (DFN) is developed, which is then coupled with a dual porosity model using CMG-GEM code to solve hydro-mechanical simulations. The injection test was history-matched to obtain permeability distribution of the DFN as well as stress-dependent relationship between the DFN permeability and pore pressure.

Methodology

CO_2 charged water injection was performed at pilot site in the UAE for a month with intermittent stops. The average wellhead injection pressure was 1200 psi. The injection well is cased with three perforation intervals at depths of 610 m, 680 m, and 780 m. A series of wireline well logging measurements were carried out such as formation microresistivity imaging (FMI), sonic, resistivity, density, gamma-ray, and farfield sonic. Also, a background 3D electromagnetic survey was conducted to cover a 300 m × 700 m area on the surface where the survey could record electromagnetic characteristics of the formation down to 1,000 m depth. A monitoring well was drilled 15.2 m north of the injection well. The injection fluid was an aqueous phase with dissolved CO_2. Figure 1 shows the water injection profile along with a section of FMI well logging data. The injection profile indicates a variation of the rate with respect to time, which can be interpreted as how fracture permeability changes as water advances away from the injection well. The FMI well logging data point out that numerous fractures could be detected within 3 meters of the wellbore where the fracture could spread in various dip angles and azimuth, which highlights the substantial heterogeneity and anisotropy in the peridotite formation. Using the well logging data and injection profile, the main scope of this work is the modeling of injection test to calibrate the stress-dependent fracture permeability.

Modelling of injection tests in fractured peridotite formations requires a reservoir model where the flow through small scale fractures and cracks is simulated by a dual porosity model while the major fracture sets are represented by a discrete fracture network (DFN). Our preliminary tests indicated that correlation between injectivity and injection pressure is non-linear, which implies a significant mechanical sensitivity of fracture permeability with respect to pore pressure. Therefore, a hydro-mechanical model is used to simulate water injection into a dual porosity medium with an embedded DFN.

The DFN model was developed based on well logging data such as FMI, nearfield, and farfield sonic logs. The DFN consists of a series of rectangular shaped planes intersecting the injection wellbore, which honor the dip angle and azimuth angles identified by FMI and sonic logging. The size of individual planes is determined by analyzing farfield sonic logging interpretation. The DFN model at the near well bore is then extended in the reservoir model based on a 3D electromagnetic survey whereby sections of the reservoir with very low resistivity are painted with high fracture porosity and permeability and high resistivity regions are treated as very low porosity and permeability fractures. The rationale behind this approach is the considerable contrast in electrical resistivity between fracture fillings (serpentines) and olivine minerals.

A similar method is implemented for the dual porosity grid blocks in which the permeability of fractures in high resistivity regions is very low. Figure 2 depicts the 3D distribution of fracture porosity in the reservoir model, which is estimated using the 3D electromagnetic survey. Based on the fracture porosity distribution, 3 main compartments can be identified: (i) shallow aquifer where a shallow layer with high fracture porosity exists, (ii) sealing layer which has a very high electrical resistivity indicating a very low fracture porosity and permeability, and (iii) storage reservoir where a network of high permeable fractures can accommodate the injection of CO_2-augmented water. This classification is based on fracture propensity to allow the fluid flow rather than the conventional approach of lithological differentiation of different components of a CO_2 storage reservoir.

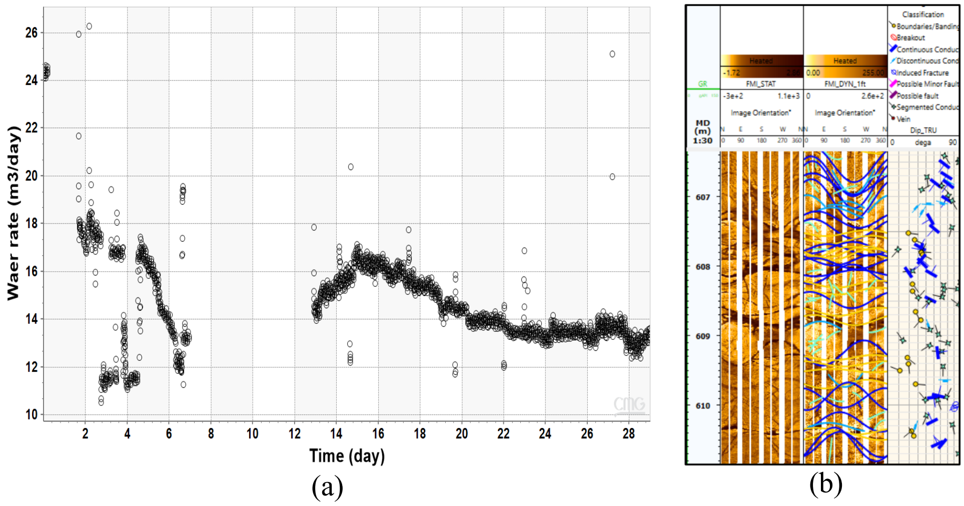


Figure 1: (a) Injection rate of water during the pilot test (b) FMI well logging data for 3 meters of the well highlighting a highly fractured formation.

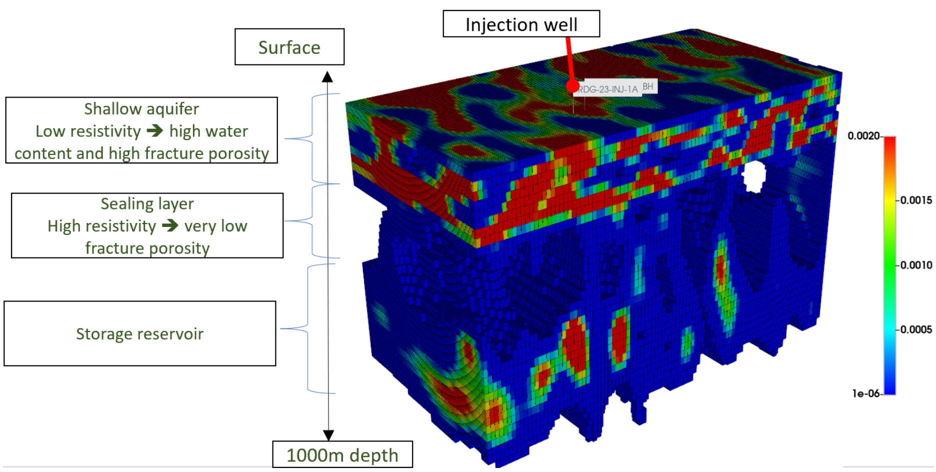


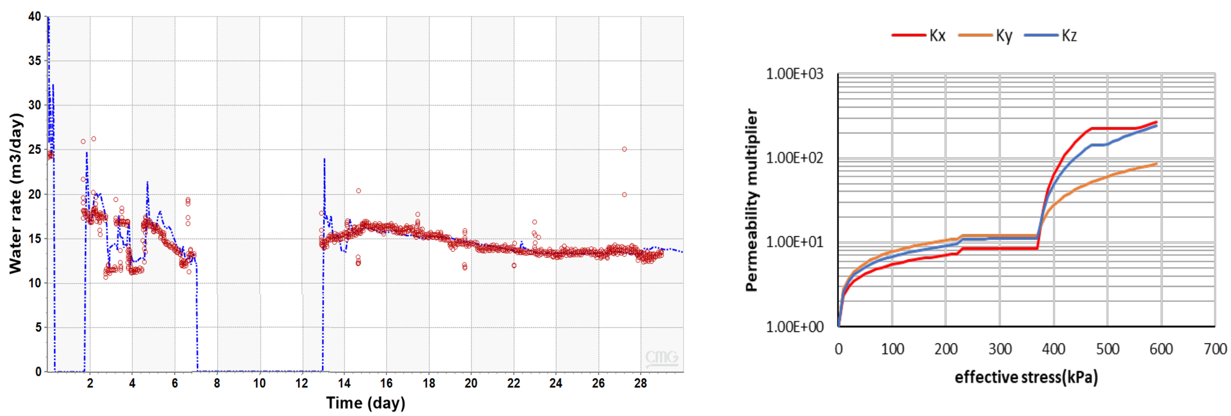
Figure 2: Distribution of fracture porosity in the reservoir model in three areas of interest, i.e. storage reservoir, sealing layer, and shallow aquifer.

Results

Given that the reservoir is not well-developed with data from a single well, history matching of the injection profile can be challenging. To history match the injection rate profile, a number of main tuning parameters are used: a universal multiplier for fracture permeability, a universal multiplier for fracture porosity, a multiplier for fracture permeability for the grid blocks hosting the injection well, a multiplier for fracture porosity of well grid block, a multiplier for DFN permeability and aperture, three exponents of power-law correlations for stress-dependent fracture permeability in x,y, and z directions. The stress-dependent permeability multiplier is a piecewise power-law correlation to have a better control of permeability variations for different ranges of effective stress, which stems from the visual observation of anisotropically distributed fractures and cracks in peridotite rocks in the Samail ophiolites. Figure 3a shows the results of history matched model (blue line) as compared against the field data (red dots). The water rate was intermittently stopped due to operational difficulties at the commissioning and start of the injection in the first week of injection bringing about hysteresis effects, which was assumed to be negligible due to numerical complexities. Conversely, the reservoir model could reproduce the field data in the last two weeks of injection more satisfactorily.

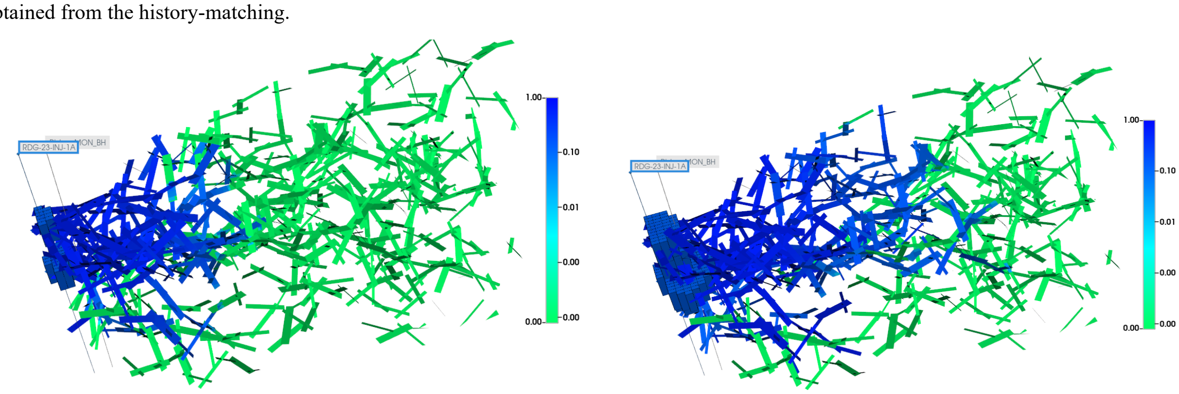
Figure 3b shows the tuned stress-dependent permeability multiplier for the fractures including DFN grid blocks. The resultant stress-dependent multiplier exhibits a strong anisotropic behavior for high effective stress regions. The stress-dependent correlation behaves in a segmented fashion that could not be expressed with a single exponential function.

Figure 4 illustrates the water saturation distribution in the reservoir after 7 and 29 days of injection. The advancement of water after 7 and 29 days of injection is 170m and 310m away from the injection well. The water saturation distribution after 29 days is in agreement with the time-lapse electromagnetic survey carried out at the injection. Therefore, it is conceivable that the plume of the injected water can spread over a relatively large area due to the fact that the main conduit for the flow is the discrete fracture networks.



(a) (b)

Figure 3: (a) results of history-matching (blue line) as compared against the filed data (red markers), (b) tuned stress-dependent permeability obtained from the history-matching.



(a) (b)

Figure 4: water saturation distribution after (a) first 7 days and (b) after 29 days of injection.

Conclusions

A tailored methodology was employed to calibrate the fracture network within the peridotite reservoir in the UAE. DFN model represented the fluid flow through major fractures while the dual porosity model could simulate small scale fractures and cracks. A thermos-hydro-mechanical model was also implemented to simulate stress-dependent fracture process where the increase of pore pressure enhances fracture permeabilities. Moreover, the electromagnetic surveys were used to extend the fracture properties providing a 3D distribution of fracture porosity. The reservoir model was then tuned to match the injection rate profile. The results indicated a significant degree of anisotropy in the stress-dependent properties as well as a segmented permeability correlation with respect to effective stress.

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