Geological Identification and Storage Capacity of Suitable formation for CO₂ disposal in Eastern Zagros (Fars area), Iran

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ABSTRACT

Climate change is one of the major global concerns. Emission of anthropogenic greenhouse gases is the main cause of climate change. One way of reducing the emissions is the application of carbon capture and storage (CCS) in geological formations. In this study, feasibility of CCS was studied in an Iranian gas production area located in the northern Persian Gulf coast in the south of country. There is a close and direct relationship between the number of oil and gas reservoirs and amount of CO₂ emissions in Zagros area in Iran. Therefore, finding an appropriate geological structure, i.e. site selection, in Zagros region is the first priority for the injection. The recognized aquifer at a depth of 1500 meters below the sea level in Fars area in Zagros, which is covered by Nar cap rock, showed a good prospect for CO₂ injection. This aquifer is located in Lower-Dalan with an appropriate reservoir property that was investigated in this paper. Simulation studies indicated that one ordinary reservoir in this area is capable of capturing at least 41.41E9 Sm³ (68 million ton CO₂) over 10 years of injection.

1 INTRODUCTION

In 1980s, scientific observations revealed that human activities released high levels of greenhouse gases into the atmosphere, and consequently global temperature increased (Hitchon et al., 1999; Orr & Franklin, 2004). Thus, reduction and control of these gases especially CO₂ became the most important issue for international environmental agencies. Among several proposed methods for the reduction of these gases, Carbone capture and sequestration (CCS) became more favorable in that it could be implemented in large extents across the world. In CCS technology, CO₂ is captured from the production units and transported to the underground structures (Hitchon et al., 1999; Orr & Franklin, 2004). Depleted oil and gas reservoirs (Holloway, 2001; Kovscek et al., 2005; Kovscek & Wang, 2005), deep unminable coal beds (Sams et al., 2005), and saline aquifers are options for the

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underground storage (Bruant et al., 2002; Pruess & Garcia, 2002; Pruess et al., 2003).

Depleted oil and gas reservoirs and saline aquifers at the depth of 800m and lower are the most important subsurface structures (Bachu, 2008; Lokhorst & Wildenborg, 2005; IPCC, 2005). Compared to saline aquifers, depleted oil and gas reservoirs are well characterized over operation years; therefore, such static and dynamic information as initial pressure, porosity, water saturation, reservoir temperature, fluid and rock compressibility, fluid contacts, reservoir thickness, etc. are available for these structures. Although size and structure of saline aquifers are unreliable compared to depleted oil and gas reservoirs, wide extent and large capacity of these formations make them attractive options for CO\textsubscript{2} disposal (Dooley et al., 2003). So far, CO\textsubscript{2} injection projects have been approved and implemented in some countries.

In 1996, Sleipner project operated by Statoil, injected one million tons of CO\textsubscript{2} per year in North Sea at the depth of 1012m. This project guaranteed the implementation of geological CO\textsubscript{2} storage (Jakobsen et al., 2005). In July 2004, the injection of CO\textsubscript{2} started into a saline formation known as the In Salah project located in Algeria. The operation continued by three horizontal wells and annual rate of 1.2 million ton of CO\textsubscript{2} in 2010. This project proved the possibility of CO\textsubscript{2} storage in non-qualified formations (Riddiford et al., 2003). Also, the Smshvit project commenced commercial storage of CO\textsubscript{2} at a depth of 2500m under sea bed in Norway (Statoil, 2015). In addition, 12 pilot injection sites were gotten grant by US-DOE and their feasibility was proven by 20 injection tests in 2007 (Hosa et al., 2010).

Iran as a large oil and gas producer has a noticeable contribution in the emission of CO\textsubscript{2} into the atmosphere. Fossil fuel power plants and gas flaring in oil and gas operations are among the major sources of CO\textsubscript{2} production in Iran. In the past two decades, CO\textsubscript{2} emission level has increased dramatically because of the drastic dependence of Iran’s economy on the oil revenue and ascending trend of energy consumption to the extent that Iran was ranked as the ninth CO\textsubscript{2} emission country in the world in 2009 (IEA, 2009). Therefore, seeking for the methods of CO\textsubscript{2} emission reduction and implementation of CCS technology is a necessity for sustainable development in Iran.

The aim of this paper was to identify and introduce appropriate CO\textsubscript{2} injection sites in the geological structures of the South Zagros zone located in Iran. In the next sections, the major sources of CO\textsubscript{2} production and emission are assessed. Then, stratigraphy of Zagros Mountains will be analyzed. After that, appropriate saline formation for CO\textsubscript{2} injection will be introduced. The storage capacity for the selected zone will be determined next. Conclusions are presented in the final section of the paper.

2 PRODUCTION OF CO\textsubscript{2} IN IRAN

Although Iran has only 1.7% share of CO\textsubscript{2} emission in the world, the IPCC report (2005) indicates that Iran was the ninth major CO\textsubscript{2} producer in the world with 612 million tons per year. According to the Iran’s second national communication to United Nations Framework Convention on Climate Change (UNFCCC, 2010), 77% of the produced CO\textsubscript{2} in 2000 was due to burning fossil fuel in energy section. This figure amounted to 84% in 2012.

Fig. 1 shows the level of CO\textsubscript{2} production in Iran. According to the chart, power plants and industry are responsible for 28% and 16% of the CO\textsubscript{2} production, totally comprising annual CO\textsubscript{2} emission of 612 million tons in the country.
Fig. 1. CO₂ production in Iran in energy section (Saeed et al., 2010).

<table>
<thead>
<tr>
<th>Power plant</th>
<th>CO₂ production (million ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam</td>
<td>58.11</td>
</tr>
<tr>
<td>Gas</td>
<td>32.25</td>
</tr>
<tr>
<td>Combined cycle</td>
<td>19.68</td>
</tr>
<tr>
<td>Diesel</td>
<td>0.17</td>
</tr>
<tr>
<td>Total</td>
<td>110.21</td>
</tr>
</tbody>
</table>

Table 1
CO₂ production level of different electricity power plants in 2006 (UNFCCC, 2010)

Fifty eight power plants including 27 gas, 19 steam, and 12 combined cycle power plants supply electricity in Iran and produce 110.21 million tons of CO₂ annually (UNFCCC, 2010). Fig. 1 illustrates that electricity power plants are sources for implementing CCS technology in Iran. Table 1 shows power plant with the largest CO₂ production in Iran. Major power plants like Kazeroon, Bandar Abbas, and Hormuzgan in the south of Iran and Bushehr, Shiraz, Kangan, Fars, and Gheshm in the south west account for the total production of 16 million tons CO₂ per year (Saeed et al., 2010).

Industrial CO₂ sources are divided into metal industry, mineral industry (cement factory), and chemical industry (petrochemical and gas refinery). Fig. 2 provides information on industrial CO₂ production in Iran. This section emits approximately 5.5-6.2 million tons of CO₂ per year in south of Iran. Table 2 represents the contribution of each industry in the south.

Table 2
Sources of CO₂ production in the south of Iran (Saeed et al., 2010)

<table>
<thead>
<tr>
<th>Industry</th>
<th>Source</th>
<th>Location</th>
<th>CO₂ purity (Wt%)</th>
<th>CO₂ production level (ton/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petrochemical</td>
<td>Farsa Shimi</td>
<td>Asaluye</td>
<td>93.2</td>
<td>142000</td>
</tr>
<tr>
<td></td>
<td>Jam</td>
<td>Asaluye</td>
<td>6.2</td>
<td>900000</td>
</tr>
<tr>
<td></td>
<td>Morvarid</td>
<td>Asaluye</td>
<td>93.2</td>
<td>178000</td>
</tr>
<tr>
<td></td>
<td>Dalan</td>
<td>Asaluye</td>
<td>98</td>
<td>120000</td>
</tr>
<tr>
<td></td>
<td>South Pars</td>
<td>Asaluye</td>
<td>90</td>
<td>746000</td>
</tr>
<tr>
<td></td>
<td>Fajr Jam</td>
<td>Bushehr</td>
<td>90</td>
<td>1071727</td>
</tr>
<tr>
<td></td>
<td>Fars</td>
<td>Shiraz</td>
<td>14.3</td>
<td>801993</td>
</tr>
<tr>
<td></td>
<td>Darab</td>
<td>Shiraz</td>
<td>14.3</td>
<td>776562</td>
</tr>
<tr>
<td></td>
<td>Estahban</td>
<td>Shiraz</td>
<td>14.3</td>
<td>174044</td>
</tr>
<tr>
<td></td>
<td>Dashtestan</td>
<td>Bushehr</td>
<td>14.3</td>
<td>432716</td>
</tr>
<tr>
<td></td>
<td>Abade</td>
<td>Shiraz</td>
<td>14.3</td>
<td>165962</td>
</tr>
</tbody>
</table>
Annually 2.26 BCM (Billion Cubic Meters) natural gas at standard conditions is produced from the gas fields located in south-southwest of Iran, most of which are among the world supergiant fields, including the South Pars Gas field, the world's largest field.

Gas sweetening and refining produce a large amount of acid gases in the atmosphere. Table 3 summarizes CO$_2$ production from some Iranian gas refineries. According to this table, phases 1-5 of south pars gas complex and other refineries in the south of country produce 4.3-5 million tons of CO$_2$ per year.

By combining the collected information on CO$_2$ production and emission sources with concentration in south and south-west region of the country, shown as grey circles on the map in Fig. 3, it is found that CO$_2$ emission in the south of Iran amount to 26-27 million tons per year over a radius of 200 kilometer. This level is equal to 10% of total production of CO$_2$ in the country that can be reduced by CCS technology. This will justify seeking for the appropriate formations over this area that can be used as sink for CO$_2$ disposal. To find suitable formations for CCS technology, the stratigraphy of this area will be described in the next section.

Generally, selection of a location for CO$_2$ injection is based on injectivity and capacity, cap rock integrity and tectonic activity in order to preserve cap rock continuity integrity. Taking these properties into account, appropriate areas for storage are placed between continents or near the edge of the continent's plates such as Atlantic and Indian oceans or behind mountains that were produced as a result of continental plates collision like Rocky Mountain in America and Zagros in Iran (Esrafili-Dizaji, 2013; Miliaresis, 2001).

### 3 STRATIGRAPHY OF ZAGROS

According to geological studies, Iran is divided into 10 geological zones, including Zagros fold and thrust belt, 1500 km in length that crosses from Taurus Mountains in the South-East in Turkey to near the Strait of Hormuz in Persian Gulf, south of Iran. Based on lateral changes, Zagros sedimentary facies are divided into three Tectonostratigraphic regions, including Western Zagros, Central Zagros, and Eastern Zagros or Fars area (Falcon, 1974; Motiei, 1993; Sherkati and Letouzey, 2004).

![Fig. 3. Concentration of pollutants in south of Iran.](image-url)
Fig. 4. Approximate Fars area in structural zone of Zagros (Motiei, 1993).

Fars area includes western border of Kazeroon Fault, Eastern margin of imaginary line that separates Bandar-Abbas Hinterland from Fars province, thrust belt in the north and Persian Gulf coastline in the south. Anticlines in this area have different orientations in northwest-southeast directions, as well as east-west and northeast-southwest orientations (Motiei, 1993). Fig. 4 shows the approximate boundaries of this area.

Orogenic system in this area is known as the 'Simply Folded Zone' with NW-SE orientation, changing to E-W and NE-SW towards Strait of Hormuz. The results of this orogenic are long anticlines like Halegan, Salamati and Sefidar with a length of 70 km, Kangan with 26 km, Sabz Poshan with 50 km, Ahmadi with 40 km, Sim with 25 km, Nora with 65 km and several other anticlines located in this area. Most of these have been explored by various oil companies for hydrocarbon exploration but lots of them are dry and without any hydrocarbon (Motiei, 1995). Examples of these anticlines along the A-B section are shown in Fig. 5.

One of the identified groups in this area is Dehram group which includes Faraghan, Dalanand Kangan formations formed during Permo-Trias. Dehram group is a vast carbonate platform which extends from eastern part of Saudi Arabia to the entire Persian Gulf and vast areas in the south and south-west in Iran. It covers an area over one million square kilometers (Motiei, 1993; Bordenave, 2008).

From geological viewpoint, Dalan formation is divided into three members, named as Upper Dalan, NAR and Lower Dalan. The NAR member which is composed of thick anhydrites, dolomite-anhydrite, dolomites and oolitic limestone with over 227 meters thickness as the cap rock, separates the Upper and Lower Dalan and cuts their hydraulic communication (Motiei, 1993). Fig. 6 illustrates the NAR member that extends across the Fars area.

Geological structure of the NAR member suggests that the lower Dalan can be used as a suitable sink for CO$_2$ storage, and the impermeable anhydrites can prevent leakage of the injected CO$_2$.

According to the isobaric contours and potentiometric maps, there is a general hydrodynamic flow from Zagros Mountains to the Persian Gulf. This hydrodynamic flow varies with topography, anticline geometry, faults and fracture intensity, porosity and permeability. The isosaline contours follow hydrodynamic flow (Motiei, 1995).

Flow direction in some aquifers of Permo-Triasreservoirs in Fars area is shown in Fig. 7.
Fig. 6. Nar member thickness in A-B section (Bahrami, 2006; Esrafili-Dizaji, 2013).

Fig. 7. Direction of aquifer fluid flow in some reservoirs of Fars area (Nadri, 2013).

Analysis of formation fluid shows that H$_2$O, CO$_2$, and NaCl are main components of the fluid (Fyfe et al., 1978). Other information regarding the type and concentration of ions present in the fluid is necessary to estimate the solubility of CO$_2$ and determine the amount and type of the precipitated minerals (Roedder, 1984), which affect the long-term storage. In the investigation area, 54 samples of saline aquifer were collected from Kangan-Dalan reservoir and analyzed (Nadri, 2013). Results of the analysis showed that the average total dissolved solid (TDS) was between 300000 and 330000 mg/lit; dominant ions included Ca$^{2+}$, Na$^+$, and Cl$^-$ with 10.5%, 23%, and 60.9% respectively. Dominant ions included 10.5% Ca$^{2+}$, 23% Na$^+$, and 60.9% Cl$^-$ with respect to TDS. Compositions of the ions in saline aquifer samples are given in Tables 4 and 5.

Table 4
Main ions of aquifer of Kangan-Dalan reservoir (Nadri, 2013)

<table>
<thead>
<tr>
<th>Sample</th>
<th>HCO$_3$</th>
<th>Mg$^{2+}$</th>
<th>Ca$^{2+}$</th>
<th>SO$_4^{2-}$</th>
<th>Cl$^-$</th>
<th>Na$^+$</th>
<th>K$^+$</th>
<th>TDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>November 2009</td>
<td>542</td>
<td>14579</td>
<td>30650</td>
<td>252</td>
<td>177500</td>
<td>66999</td>
<td>501</td>
<td>333820</td>
</tr>
<tr>
<td>May 2010</td>
<td>427</td>
<td>15140</td>
<td>30000</td>
<td>240</td>
<td>177500</td>
<td>66930</td>
<td>625</td>
<td>333000</td>
</tr>
</tbody>
</table>
Table 5
Secondary ions of aquifer of Kangan-Dalan reservoir (Nadri, 2013)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Sr²⁺</th>
<th>Zn²⁺</th>
<th>Li⁺</th>
<th>Rb⁺</th>
<th>Mn³⁺</th>
<th>Ba²⁺</th>
<th>Pb²⁺</th>
<th>Se²⁻</th>
<th>Cu²⁺</th>
</tr>
</thead>
<tbody>
<tr>
<td>November 2009</td>
<td>1253</td>
<td>357</td>
<td>129</td>
<td>22.9</td>
<td>18.6</td>
<td>16.3</td>
<td>6.7</td>
<td>2.4</td>
<td>0.77</td>
</tr>
<tr>
<td>May 2010</td>
<td>1450</td>
<td>165</td>
<td>152</td>
<td>20.5</td>
<td>19.1</td>
<td>14.2</td>
<td>1.2</td>
<td>0.5</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Fig. 8. Distribution of porosity and permeability in matrix and fracture (Nadri, 2013).

Correlation between vertical permeability of the matrix \(K_{m-V}\) and fracture \(K_{f-V}\) as a function of porosity is based on the analysis of cores equations (1) and (2) respectively. Porosity and permeability distribution in matrix and fracture are presented in Fig. 8.

\[
K_{m-V} = 0.0849 \times \exp(0.1963 \times \Phi)
\]  
\[
K_{f-V} = 1.3312 \times \exp(0.2024 \times \Phi)
\]

Phase diagram of pure CO₂ shows that at pressures and temperatures above 7.38 MPa and 31.1°C, CO₂ is in super-critical state and behaves liquid-like (Yang et al., 2010). The solubility of CO₂ in water depends on its density, which is a function of reservoir pressure and temperature. Therefore, temperature and pressure are two chief factors in the determination of CO₂ storage capacity.

According to the tests during exploration drilling, pressure and temperature profile for Lower Dalan were exploited. The average values are summarized in Table 6. According to this table, the injected CO₂ at formation temperature and pressure will be at supercritical conditions.

Based on the geological description, the area under study for CO₂ injection is approximately 130000 km² with cap rock thickness between 50 and 250 meters. This area is located at the depth of 1500 meter under sea level in the south west of Iran along the northern Persian Gulf coastline. Continuous anticlines under this cap rock that were saturated with brine have large capacities for the deposition of pollutant gases. In the next section, one of the reservoirs in this area will be simulated to estimate the storage capacity.

4 GEOLOGICAL MODEL AND RESERVOIR SIMULATION

A sector model was constructed using the lower Dalan petro-physical data. The model was imported into CMG-GEM software. This section is shown in Fig. 9. Grid modeling was based on the corner point method with 20, 18 and 27 cells in X, Y and Z direction respectively.

Table 6
Temperature and pressure in the target layer (Nadri, 2013)

<table>
<thead>
<tr>
<th>Formation</th>
<th>Sampling depth m.ss (ft.ss)</th>
<th>Pressure Kpa (psia)</th>
<th>Temperature at the sampling depth °C</th>
<th>Temperature slope°C/m(°F/ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Dalan</td>
<td>1650 (5414)</td>
<td>21580 (3130)</td>
<td>77.2</td>
<td>0.01458</td>
</tr>
</tbody>
</table>
The grid size was 175m in the X- and Y-directions, and 11 m in the Z-direction.

The model properties were heterogeneous. Static parameters (like porosity, vertical and horizontal permeability) and aquifer properties are given in Table 7. Gas and liquid relative permeability data is shown in Fig. 10 (Nadri, 2013). Acquiring to this figure $S_L$ and $S_W$ are liquid and water saturation and $k_{rw}$, $k_{ro}$, $k_{rg}$ and $k_{rlg}$ are relative permeability in water, oil, gas or gas in liquid in respectively. Relative permeability is a dimensionless parameter.

### Table 7

<table>
<thead>
<tr>
<th>parameter</th>
<th>Value</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aquifer size</td>
<td>3500×3150×297</td>
<td>Meter</td>
</tr>
<tr>
<td>Grid</td>
<td>20×18×27</td>
<td>-</td>
</tr>
<tr>
<td>Average porosity</td>
<td>0.1</td>
<td>-</td>
</tr>
<tr>
<td>Average vertical permeability</td>
<td>9.87E-14 (10)</td>
<td>$m^2(mD)$</td>
</tr>
<tr>
<td>Average horizontal permeability</td>
<td>9.87E-15 (1)</td>
<td>$m^2(mD)$</td>
</tr>
<tr>
<td>Aquifer’s depth (under sea level)</td>
<td>1650</td>
<td>Meter</td>
</tr>
</tbody>
</table>

![Fig. 9. 3D view of the CO\textsubscript{2} injection reservoir.](image)

![Fig. 10. a) relative permeability of gas ($k_{rg}$) and water-oil in the vicinity of gas versus liquid fluid. b) water ($k_{rw}$) and oil ($k_{ro}$) relative permeability versus water saturation ($s_w$) (Nadri, 2013).](image)
An injection well is drilled and perforated at the lower Dalan formation that is about 300 meters of thickness. Because of the vertical flow of CO$_2$ and meeting fresh water which leads to more CO$_2$ solubility and trapping, the perforation depth is about 1940 meters under the sea level. The injection rate and maximum injection pressure were set to 1.5E6 Sm$^3$/day and 43160 kPa, which is twice the reservoir pressure. According to this value it would be possible to inject approximately 1 million ton of CO$_2$ from a single well per year. Because of low porosity and permeability this amount of injection is high, so constant pressure condition will control the amount of injection. An example of constant pressure condition just for 2 years of injection is shown in Fig. 11. After 2 years of injection, bottom hole pressure smoothly increases by reaching the injected gas in top of the reservoir near the well. Solubility and minimization of CO$_2$ decreases the bottom hole pressure after the geological time.

In this case the cumulative injected volume after 10 years of operation will be 2.96E9 Sm$^3$ (4.86 million tone) which occupies just 2% of the reservoir volume. The generalization of results to the total area showed that an ordinary reservoir in Fars zone will have the capacity to store more than 41.41E9 Sm$^3$ (68 million ton CO$_2$) over 10 years of injection. Current CO$_2$ emission in Asaluye is about 1.83E9 Sm$^3$ (3 million tons) per year. Thus, this total amount would be stored through six injection wells over 23 years in this reservoir.

5 CONCLUSION

A geological formation was studied and analyzed for CO$_2$ storage in the south west of Iran. This region is symmetric with Fars area of structural Zagros zone. Dalan formation from Dehram group in Fars area upper the depth of 1500 meters below sea level contains Permian evaporate carbonates and is divided into Higher Dalan, Nar sector, and Lower Dalan. Thick layer of anhydrite in Nar sector
acts as a cap rock for Lower Dalan and is able to trap the injected CO$_2$. Geology and hydrology of this sector is well determined through several wells drilled in the area.

Simulation results showed that one of the reservoirs in this sector was able to sequester 41.41E9 Sm$^3$ (68 million ton) of CO$_2$.

REFERENCES


Lokhorst, A.; Wildenborg, T., (2005). Introduction on CO$_2$ Geological storage-


