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# **GAS-WATER-ROCK INTERACTIONS IN SANDSTONE RESERVOIRS: IMPLICATIONS FOR ENHANCE RE-INJECTION INTO GEOTHERMAL RESERVOIRS AND CO<sub>2</sub> GEOLOGICAL SEQUESTRATION**

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## **ABSTRACT**

Much geothermal energy is stored in sandstone reservoirs in sedimentary basins in China, which is being extracted for direct use of heat. However, the injection rate of waste water is rather low for these reservoirs. Studies on gas-water-rock interactions in sandstone reservoirs have flourished in the last decade due to the need for enhanced oil recovery and the fact that deep saline aquifers in sedimentary basins are promising candidates for geological sequestration of CO<sub>2</sub>. Experiments at laboratory and field scales and numerical modelling of various scales have been carried out. It has been shown by these studies that porosity and permeability of the sandstone reservoirs would increase as a consequence of CO<sub>2</sub> injection. Further tests at the field scale are suggested to verify these predictions and with an attempt to overcome the bottle neck technology in sustainable exploitation of geothermal energy from sandstone reservoirs.

## **1. INTRODUCTION**

It is more difficult to inject waste water into sandstone reservoirs in geothermal field management (Seibt & Kellner, 2003). China, as an example, is rich in low temperature geothermal resources that are found in major sedimentary basins, such as the North China Basin, Northern Jiangsu Basin, Guanzhong Basin and Songliao Basin in Northeast China. Direct use of geothermal heat is mainly dependent on this type of geothermal resources. However, the thermal water occurs not only in limestone reservoirs which are more permeable and easier in terms of re-injection, but also in sandstone reservoirs that are more difficult to handle (Pang, 2000). As a consequence, the rate of injection is as low as <20% in most of the producing fields.

This has become a major technical barrier in sustainable use of geothermal resources in China (Pang, 2007). Conventional acidizing approaches using mixture of HF and HCl to remove calcite and silica scales in geothermal reservoirs, which are applied in many high temperature systems, are not suitable in this circumstance due to the scale of the problem and the cost involved. Therefore, novel approaches have to be searched and tested out.

This paper intends to provide a review of the state-of-the-art on current understanding based on studies already carried out, and considers future studies with emphasis on field scale tests to improve understanding of CO<sub>2</sub>-water-rock interactions in sandstone reservoirs and to provide technical basis for enhanced geothermal re-injection, if appropriate.

## 2. LABORATORY EXPERIMENTS

Laboratory experiments are one of the basic tools to reveal the process of CO<sub>2</sub>-water-rock interaction under simulated reservoir conditions, and are necessary for the evaluation of the potential of CO<sub>2</sub> sequestration, or for improving re-injection conditions of the reservoir. It includes autoclave experiment and core-flooding experiment. The former one mainly provides information on the mechanics of CO<sub>2</sub>-water-rock interaction, while the latter can better reflect the change in porosity and permeability of the rock in addition.

Experimental studies for CO<sub>2</sub>-water-rock interaction focus on sandstone aquifers have been carried out widely since the 1980s, which was stimulated by EOR, and flourished after the concept of CO<sub>2</sub> "mineral trapping" was proposed. Up to now, CO<sub>2</sub>-water-rock interactions have been investigated under various conditions, with pressure range from 1bar to above 600bar, and temperature focus on that of the normal saline aquifers (<80°C). Experiments carried out at more than >100°C are not common seen, yet some has achieved 350 °C (Shiraki and Dunn, 2000; Rosenbauer et al., 2005; Bertier et al., 2006).

Results of autoclave experiments indicate that dissolution of supercritical carbon dioxide into the experimental brine-rock system decreased brine pH, dissolved unstable minerals (feldspar, carbonate cement and silicate texture) and precipitated carbonate minerals. Typical authigenic minerals are dawsonite + Fe-bearing carbonate + other carbonate, and ankerite /dolomite + authigenic quartz (Bertier et al., 2005). A diversity of other fluid-rock reactions can also take place between the mixed fluid and rock that differ from the brine-rock system, depending on differences in minerals, reactive surfaces, and assemblages exposed to the brine. CO<sub>2</sub> core-flooding experiments present different results with respect to change in porosity and permeability of reservoir rock.

Decrease in permeability is concluded to be due to the migration of authigenic clays to pore throats, or resulted from the crystallization of kaolinite in pore spaces when few clay minerals were present originally (Shiraki and Dunn, 2000) which may be characteristic of CO<sub>2</sub>-flooding for formations containing K-feldspar or other soluble aluminosilicates grains.

Increase in permeability can be caused by carbonate dissolution (Ross et al., 1981), but when it was offset by a reduction caused by migration of clay minerals into pore throats, there may be no substantial change to permeability (Bowker and Shuler, 1991).

As can be seen from the above discussion, the injection of CO<sub>2</sub> can lead to dissolution, transport and precipitation of minerals. Increase in the porosity and permeability of the rock can be caused by dissolution, while decrease in the porosity and permeability of the reservoir can be caused by precipitation. Thus, the change in porosity and permeability of rock is affected mainly by the distribution of the rock minerals and the chemical composition of the brine. As the CO<sub>2</sub>-water-rock interactions induced by CO<sub>2</sub>-flooding of reservoirs are complex and highly reservoir specific and cannot easily be generalised (Holloway, 1997), experimental simulations performed on samples of the targeted reservoirs is needed, serving as input constraints for comprehensive geochemical models and for validation of numerical modelling.

### 3. NUMERICAL MODELS

Numerical modelling is employed to predict long-term CO<sub>2</sub>–water–rock interaction, and corresponding changes in porosity and permeability of reservoir matrix.

Studies have shown effects of CO<sub>2</sub> degassing on mineral dissolution and mineral precipitation. Pang & Reed (1998) modelled low temperature systems that are more relevant for the current topic. They found that carbonate in geothermal systems are very sensitive to CO<sub>2</sub> changes. Reactive transport modeling for study of CO<sub>2</sub>-induced mineral alteration in the injection zone has shown changes in reservoir porosity and sequestration of CO<sub>2</sub> in an arkose formation at a depth of about 2 km and 75°C. The mineral alteration induced by injection of CO<sub>2</sub> leads to corresponding changes in porosity. Significant increases in porosity occur in the acidified zones where mineral dissolution dominates. Whereas the porosity decreases within the CO<sub>2</sub> mineral trapping zone due to the addition of CO<sub>2</sub> mass as secondary carbonates to the rock matrix. The transport of dissolved CO<sub>2</sub> and mineral alteration generally decreases porosity, which could result in the formation of a lower permeable barrier that would impact reservoir growth and longevity. Significant CO<sub>2</sub> could be fixed through precipitation of carbonate minerals, which can offer geologic storage of carbon as an ancillary benefit (Fig.1, Xu et al., 2007).

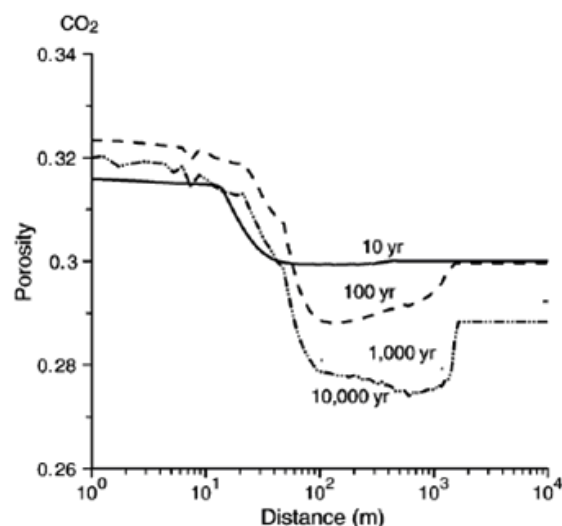


FIGURE1: Porosity distribution at different times (Xu et al., 2007)

The numerical simulation implemented to the Nagaoka CO<sub>2</sub> injection site demonstrates that the geochemical water-rock interaction, which is generally regarded as a longer-term phenomenon than various physical processes, can also affect the reservoir system from the initial stage.

According to the modelling results presented (Sato et al., 2006), the change in porosity of the reservoir rock was estimated to increase by about 2% of initial values during 60a, using the dissolution rate and taking only anorthite dissolution into account in light of relatively low dissolution rate of other minerals.

The time frame of physical and chemical changes is a function of reaction kinetics of mineral dissolution and precipitation, which requires further study. The extent of porosity decrease and amount of CO<sub>2</sub> mineral trapping depends on the primary mineral composition. Sensitivity studies on different rock mineralogy should be performed. Using natural analogues of CO<sub>2</sub> reservoirs, refinements on thermodynamic and kinetic data should be useful.

#### 4. FIELD TESTING WITH CO<sub>2</sub> INJECTION

Frio brine field test provides an insight into field-scale CO<sub>2</sub>–water–rock interaction that implies substantial rapid change in porosity and permeability of reservoir rock. In year 2004, 1600 t of CO<sub>2</sub> were injected at 1500 m depth into a 24-m-thick sandstone section of the Frio Formation, a regional brine and oil reservoir in the U.S. Gulf Coast to investigate the potential for the geologic storage of CO<sub>2</sub> in deep saline aquifers. Fluid samples obtained from the injection and observation wells showed that sharp drops in pH (6.5–5.7), pronounced increases in alkalinity (100–3000 mg/L as HCO<sub>3</sub>) and Fe (30–1100 mg/L), and significant shifts in the isotopic compositions of H<sub>2</sub>O, DIC, and CH<sub>4</sub> following CO<sub>2</sub> breakthrough.

Geochemical modelling indicated that carbonate and iron oxyhydroxides dissolved into the low pH brine. This rapid dissolution of carbonate and other minerals could ultimately create pathways in the rock seals or well cements for CO<sub>2</sub> and brine leakage (Kharaka et al., 2006).

#### 5. DISCUSSION AND CONCLUSIONS

As the world is taking actions towards mitigating global warming, studies of CO<sub>2</sub>-water-rock interactions in deep saline aquifers have been flourished in the last decade or so (Bachu S, 2007). Results based on laboratory experiments and numerical models have shown that porosity of the formation will increase in the vicinity of injection boreholes after injection of CO<sub>2</sub>. The field test of CO<sub>2</sub> injection into the saline aquifer, the Frio Formation at Texas, USA, has also indicated an increase in porosity of the formation (Kharaka et al., 2006).

There are two distinctive features of geothermal reservoirs in China. First of all, most sedimentary basins are continental rather than marine in origin, implying difference in water chemistry and salinity as well as matrix chemistry and mineralogy. Secondly, reservoirs are very often fractured, either in the reservoir or in the cap rock formations. These two factors make the reservoirs different from others that have been tested. It is therefore suggested that future studies should be directed towards providing firm information through more tests at various scales in various types of geothermal reservoirs.

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