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Fracture Characterization and Fluid Flow Simulation with Geomechanical Constraints for a CO_2–EOR and Sequestration Project Teapot Dome Oil Field, Wyoming, USA

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Abstract

Mature oil and gas reservoirs are attractive targets for geological sequestration of CO_2 because of their potential storage capacities and the possible cost offsets from enhanced oil recovery (EOR).

In this work, we analyze the fracture system of the Tensleep Formation to develop a geomechanically-constrained 3D reservoir fluid flow simulation at Teapot Dome Oil Field, WY, USA. Teapot Dome is the site of a proposed CO_2-EOR and sequestration pilot project. The objective of this work is to model the migration of the injected CO_2 in the fracture reservoir, as well as to obtain limits on the rates and volumes of CO_2 that can be injected, without compromising seal integrity. Furthermore we want to establish the framework to design injection experiments that will provide insight into the fracture network of the reservoir, in particular of fracture permeability and connectivity.

Teapot Dome is an elongated asymmetrical, basement-cored anticline with a north-northeast axis. The Tensleep Fm. in this area is highly fractured, and consists of an intercalation of eolian-dune sandstones and inter-dune deposits. The dune sandstones are permeable and porous intervals with different levels of cementation that affects their porosity, permeability, and fracture intensity. The inter-dune deposits consist of thin sabkha carbonates, minor evaporates, and thin but widespread extensive beds of very low-permeability dolomicrites. The average permeability is 30 mD, ranging from 10 – 100 mD. The average reservoir thickness is 50 ft. The caprock for the Tensleep Fm. consists of the Opeche Shale member, and the anhydrite of the Minnekhata member. The reservoir has strong aquifer drive. In the area under study, the Tensleep Fm. has its structural crest at 1675 m. It presents a 2-way closure trap against a NE-SW fault to the north and possibly the main thrust to the west.

The CO_2-EOR and sequestration project will consist of the injection of 1 million cubic feet of supercritical CO_2 for six weeks. A previous geomechanical analysis suggested that the trapping faults do not appear to be at risk of reactivation and it was estimated that caprock integrity is not a risk by the buoyancy pressure of the maximum CO_2 column height that the formation can hold. However, in the present study we established the presence of critically stressed minor faults and fractures in the reservoir and caprock, which if reactivated, could not only enhance the permeability of the reservoir, but potentially compromise the top seal capacity. The results of the preliminary fluid flow simulations indicate that the injected CO_2 will rapidly rise to the top layers, above the main producing interval, and will accumulate in the fractures, where almost none will get into the matrix.

Keywords: Geomechanics; CO_2 EOR-Sequestration; fractured reservoir

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1. Introduction

For CO_2 sequestration to be a feasible carbon management solution, one of the main issues to be addressed is the risk of CO_2 leakage. Depleted or mature oil and gas reservoirs hold great promise as sequestration sites because they have hold hydrocarbons for geological periods, implying the presence of effective trap and seal mechanisms. However, it has long been recognized [1] that fluid injection causes changes in the pore pressure and stress field that by reducing the effective normal stress on the fault plane could trigger slip on pre-existing fractures and faults (see review [2]).

In highly fractured systems as the present one, the occurrence of small faults in the caprock and the potential for slip on these features could potentially compromise the top seal capacity of the target reservoir. Similarly, the presence of these minor faults enhances formation permeability and injectivity of CO_2 inside the reservoir, which greatly affects reservoir performance.

These faults are usually below the resolution limit of conventional 3D seismic, and traditional methods of fracture characterization such as 1D (well logs or cores) or 2D (outcrop analogs) lack the spatially characterization needed to comprehensively asses their impact on reservoir permeability and the potential risk of CO_2 leakage. Therefore an iterative process of modeling and incorporating production and/or injection data from field experiments will help to gain insight into the fractures characteristics of the target formation.

In the present study we characterized the fracture population of the Tensleep Fm. from FMI log interpretations as wells as core and outcrop analogs found in the literature. We performed a critically stressed fracture analyzes to determine which of those fractures have the potential to be reactivated, therefore providing permeability anisotropy inside the reservoir and potential leakage pathways if reactivated outside of the target interval. These findings served as input to the preliminary geomechanically-constrained, fluid flow simulations presented here. These simulations are the first step in an iterative process that will help design, and later incorporate the result of, CO_2 injections experiment to be performed in the Tensleep Fm. These experiments will provide information on critical parameters to predict and evaluate reservoir performance such as fracture permeability, connectivity and distribution.

2. Teapot Dome

Teapot Dome Field (Figure 1) is owned by the U.S. government and operated by the U.S. Department of Energy (DOE) and the Rocky Mountain Oilfield Testing Center (RMOTC). To evaluate the scientific and technical feasibility of field experiments, the project team is working with interested industry and research partners to design CO_2 injection experiments, during a small, short-duration EOR pilot. The pilot will use existing wells and infrastructure and will target the Tensleep Formation, with a minimum of ~60 tons/day CO_2 for a minimum of ~1.5 months.

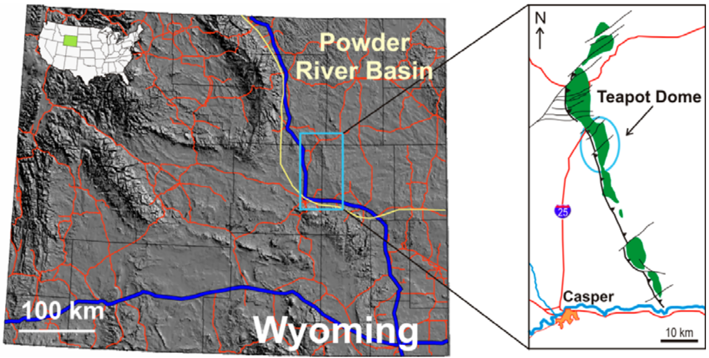

Figure 1: Location of Teapot Dome. Satellite image of Wyoming (left), Salt Creek structural trend, topographic relief in green (right), [3].

Teapot Dome is a basement-cored anticline, fault propagation fold, typical of the Laramide orogeny in the Rocky Mountain Region [4, 5 ,3]. It is bounded on the west by a series of high-angle reverse faults of approximately

35° to 40° east-northeast dip [4]. The anticline is compartmentalized into several blocks by major oblique strike-slip to normal faults involving the basement.

The eolian Tensleep Formation contains multiple sequence boundaries in response to frequent and high-amplitude sea level changes [6, 7]. In this area it consists of interdune deposits such as eolian sandstones, sabkha carbonates, evaporites (mostly anhydrite), and extensive beds of very low permeability dolomicrites. The average porosity is 10% (5 – 20% range), and the average permeability is 30 mD (10 – 100 mD range). The average net thickness is 15 m. The reservoir has a strong aquifer drive and therefore hydrostatic reservoir pressure, and the reservoir temperature is ~88°C. The Tensleep Formation is divided into several intervals, of which the approximately 30 m thick B-Sandstone is the main producing horizon and the proposed injection interval for this experiment. The Opeche Shale plus the anhydrite of the Minnekahta Member of the Permian Goose Egg Formation comprise the regional seal of the Tensleep Fm. throughout Wyoming.

In the area under study, the Tensleep Formation has its structural crest at 1675 m below surface covering an area of approximately 1.2 km^2. The reservoir is trapped against a NE-SW trending fault to the north and possibly against the approximately N-S main thrust (Figure 2).

Chiaramonte et al. [3] performed a comprehensive geomechanical characterization and established that the S1 fault does not appear to be at risk of reactivation and that the caprock integrity is not a risk by the buoyancy pressure of the maximum CO_2 column height that the formation can hold. Figure 2 shows the wells in the area with Formation Microresistivity Imager (FMI) logs, where the orientation of the maximum horizontal stress (S_{Hmax}) was established and the fracture characterization of the present study was performed.

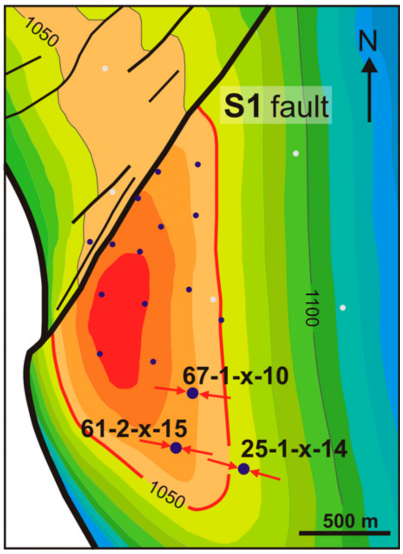

Figure 2: Time-structure map in milliseconds (ms) of Tensleep Formation in the area of interest showing the S1 fault, oil-contact area (red contour line), S_{Hmax} direction (red arrows) and analyzed wells (blue dots) [3].

3. Fractures at Teapot Dome

Several authors [8, 9, 10, 7] have described fractures in the Tensleep Fm., from cores, FMI logs and outcrops, as vertical to near vertical. In particular at Teapot Dome, Lorenz and Cooper [8] performed a fracture characterization in core samples where they found an average of 1 fracture every 5 ft, although with increasing cement content, they noted and increase in fracturing. Therefore, they defined several intervals with different fracture intensity: in high porosity sandstones they described a fracture intensity of approximately 1 fracture every 10 ft, in dolomitic sandstones 1 fracture every 3 ft and in heavily cemented sandstones 1 fracture every ft. Figure 3 shows the dominant sets of open fractures described by [9 and 10] in the Tensleep Fm. at Teapot Dome.

Zham and Hennings [7] documented a complex heterogeneous fracture development in the Alcova anticline, approximately 110 km southwest of Teapot Dome. The authors found that fractures develop at four scales of observation: lamina-bound, facies-bound, sequence-bound, and through-going fractures that span the formation. They documented a detailed facies and fracture-intensity model using LIDAR-scanned outcrops that revealed the existence of a striking variability in fracture intensity caused by original depositional architecture, overall structural deformation, and diagenetic alteration of the host rock. Particularly interesting for reservoir performance are the findings regarding through-going and sequence-bound fractures, as described by the authors. Apparently the overall shift from marine- to eolian-dominated sequences causes an increase in sequence-bound fractures (the largest ones within the more eolian-rich sandstones facies), with the implication that Tensleep facies with better reservoir qualities (i.e., clean eolian sandstones) may also have the largest fractures with the highest intrinsic permeability.
Similarly, the authors described few zones of through-going fractures, interpreted as reactivated shear zones that span the entire Tensleep. These fracture zones might help explain the large quantity of water co-produced with oil from the Tensleep since the initial development of the reservoir. This produced water, with lower salinity than the Tensleep brine, has been attributed to the underneath aquifer (which also provides the pressure support) and that might have vertically migrated up to the oil bearing zone through these through-going fractures [11].

Relationship between fractures and present day stress state

Our previous geomechanical characterization [3] yielded a NF/SS regime with S_{Hmax} Az ~ 116° (red arrows in Figure 3). In a NF stress regime, the optimal direction for slipping is parallel to S_{Hmax}, which is represented by the green line in Figure 3. In the case of a SS regime, there are potentially two optimal directions for slip, each of them at 30° with respect to S_{Hmax}, represented as blue lines in Figure 3.

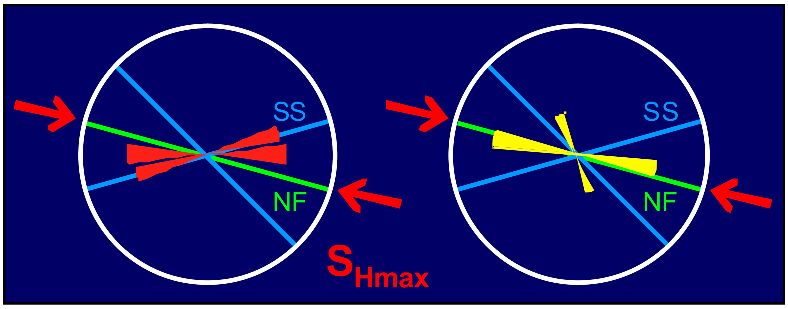

Figure 3: Strike orientation of main fractures sets in the Tensleep Fm. [9] (left) and [10] (right).

Figure 3 also shows the dominant sets of open fractures described by Lorenz [9] and Schwartz et al. [10] for the Tensleep Fm. at Teapot Dome. Comparing the strike of these open fracture sets with the optimal directions for slip in a NF/SS regime, we can observe that at least three of these sets are parallel to one of these optimal directions. In Figure 4 the poles of these fractures are plotted in a stereonet color-coded with the critical pressure needed for a fracture to slip. Fracture sets a, b, and c are very close to the critical pressure needed for reactivation.

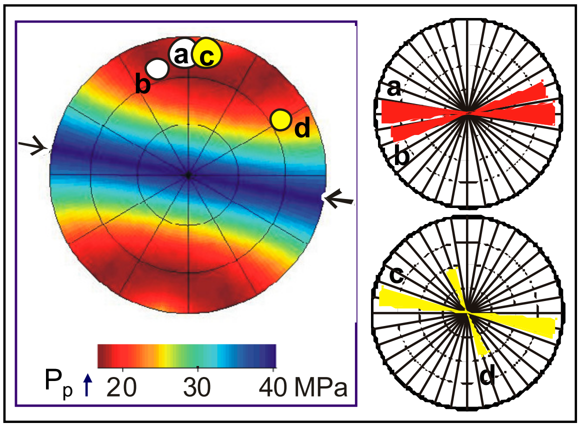

Figure 4: Rose diagrams of the dominant fracture sets at the Tensleep Fm. (right) and the poles of these sets color-coded with the critical pressure needed to reactivate them (left). Note the black arrow in the bottom indicating the hydrostatic pore pressure (~16.5 MPa).

Similarly, we have performed a fracture characterization in FMI logs from four wells in the area of interest, where we mapped several fractures sets in the reservoir as well as in the caprock (Figure 5). Some of these sets coincide with previous fracture characterizations as the ones mentioned in the previous paragraphs.

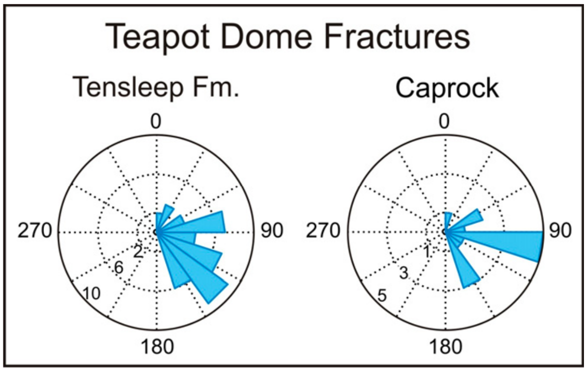

Figure 5: Fractures sets mapped in four FMI well logs in the S1 area

Figure 6 shows plots of the coulomb failure function (CFF) as a function of fracture pole orientation for the caprock and the Tensleep fractures. When the CFF is close to zero, it indicates that the fracture is critically stressed (white dots).

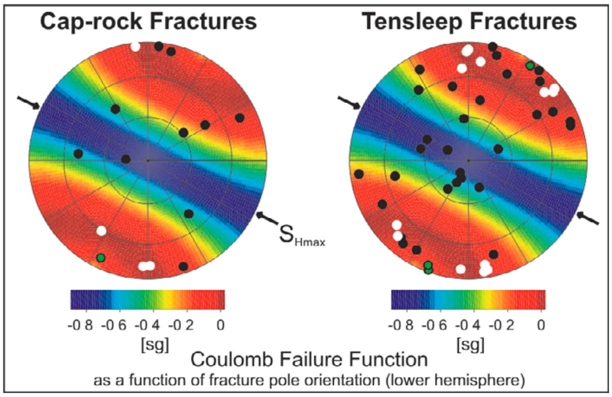

Figure 6: Observed Tensleep Fm. fractures (right) and caprock fractures (left) form four wells of the area under study. The white dots are the poles of the fractures that are critically stressed.

Several of these fractures are critically stressed, which could have a positive impact in reservoir permeability and injectivity but constitutes a potential risk for seal integrity, either if the caprock fractures are reactivated or if the reservoir fractures propagate into the caprock.

If any of these two scenarios occur, the reactivation of these minor faults will most likely result in microseismic activity. This microseismicity could be monitored to map the vertical CO_2 migration and identify potential leakages as well as to improve the spatial fracture characterization.

4. Preliminary Fluid Flow Simulation

We have develop a stochastic 3D reservoir model of the Tensleep Formation, as input for a fluid flow simulation, using the geomechanical constraints and critically stressed fracture analysis described in the present paper and in [3]. Our objective is to model the migration of the injected CO_2, as well as to obtain limits on the rates and volumes of CO_2 that can be injected, without compromising seal integrity.

The geological model was based on a structural and stratigraphic seismic interpretation, well logs, and core data. We used geostatistics to populate the model with porosity and permeability distributions (see details of the geological model and simulations in [12]).

The geomechanical constraints mentioned above established the maximum allowable injection rates as well as pressure limits to be avoided at the top of the reservoir and at the fault boundary. Similarly, we incorporated a fracture permeability anisotropy aligning the simulation grid with the optimal direction for slip in order to capture the preferential opening of pre-existing fractures. In the case shown in Figure 7, the grid is aligned subparallel to the S_{Hmax} direction which corresponds to a normal faulting environment.

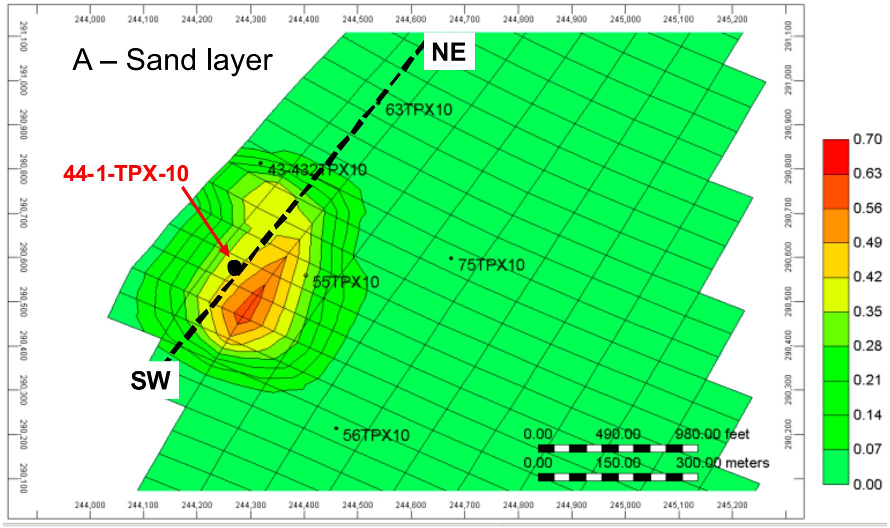

Figure 7: Injection of 1 MMcfd of CO_2 for 6 weeks: Gas Saturation in fractures after 6 weeks of injection in the uppermost layer, ASand.

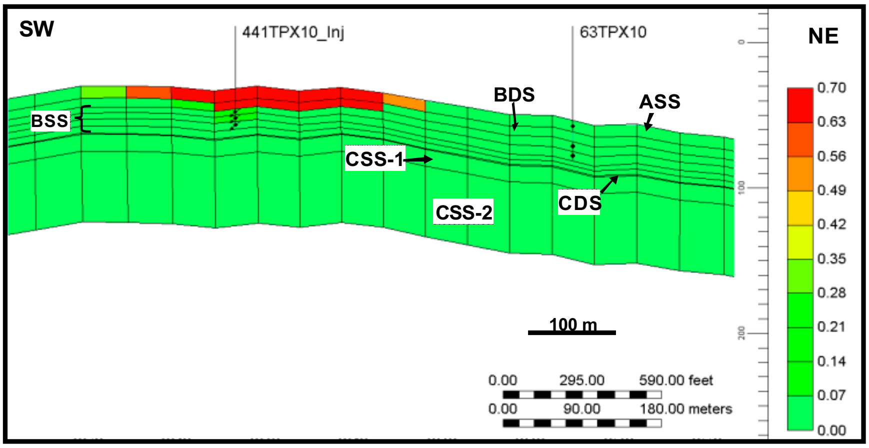

Figure 8: Gas Saturation in the fractures after 6 weeks of injection. See location of this profile in Figure 7.

The results of the preliminary fluid flow simulation (Figure 7 and 8) showed that the pressure increase is minimal during the pilot project not constituting a risk for fault stability or seal integrity. However, buoyancy and mobility of CO_2 could represent a problem for the EOR performance. CO_2 was injected in the main producing interval to dissolve in the oil, but almost immediately rose to the top layers through the high permeability fracture network, taking almost a year to start saturating the fractures in the main interval. The mobility of the gas results in early breakthroughs in the closer wells with their consequent shut-in and loss of production.

These results highlight the need to better constrain critical parameters such as fracture permeability, connectivity and distribution. Some constraints are expected from the field experiments envisioned at Teapot Dome.

Further work is necessary to evaluate the potential for existing production data to constrain the sequence-bound and through-going fracture model described above.

5. Summary

A fracture characterization was performed with four FMI logs from the area of interest as well as fracture data from the literature. Some of these fractures where found critically stressed, both in the Tensleep Fm. and in the caprock. The presence of these minor faults enhances formation permeability and injectivity of CO_2. However, the potential for slip on these faults could eventually compromise the top seal capacity of the Tensleep Fm. if these minor faults extend up into the cap rock.

The results of the fracture characterization, as well as previous geomechanical characterization, were incorporated into a preliminary fluid flow simulation, using to model the migration of the injected CO_2, as well as to obtain limits on the rates and volumes of CO_2 that can be injected, without compromising seal integrity.

The results of the preliminary fluid flow simulation showed that the pressure increase is minimal during the pilot project not constituting a risk for fault stability or seal integrity. However, buoyancy and mobility of CO_2 could represent a problem for the EOR performance.

The results form field experiments as the ones proposed at Teapot Dome, will be crucial to help constrain key parameters that greatly affect the fluid flow simulations results, such as fracture permeability, connectivity and distribution.

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