Seismicity Characterization around the Farnsworth Field Site for Combined Large-Scale CO₂ Storage and EOR

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Abstract

Induced seismicity at levels noticeable to the public or higher is a concern for long-term, large-scale geologic carbon storage. To lower the risk of induced seismicity, it is desirable to sequester CO₂ within a region where earthquakes are rare. We characterize the natural seismicity around the Farnsworth field site for the Phase III project of the U.S. Southwest Regional Partnership on Carbon Sequestration. We study all available catalog earthquake information within a region of approximately 180 km × 220 km (2 × 2 degrees) centered at the Farnsworth field. We find that there is no recorded catalog earthquake within a region of approximately 30 km in radius from planned CO₂ injection well No. 13-10A. The earliest earthquake recorded within our study region occurred in 1907, and the maximum magnitude of all recorded earthquakes since then is 4.8. Out of all the earthquakes recorded in this region, only four of them have magnitudes larger than 4. Our seis-

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micity study indicates that the seismic risk for large-scale geologic carbon storage combined with enhanced oil recovery at the Farnsworth field may be relatively low. This characterization of natural seismicity around the Farnsworth field also benefits the ongoing monitoring of induced seismicity at the site.

Keywords: Carbon sequestration, enhanced oil recovery, Farnsworth, earthquake catalog, seismicity, site characterization.

1. Introduction

Geologic storage of carbon dioxide is one of the most attractive methods for reducing CO₂ emission while allowing the continued use of fossil energy. Carbon dioxide may be retained in proper geological formations for very long periods of time. CO₂ can also be injected into an oil field for enhanced oil recovery (EOR) to offset the cost of geologic carbon capture and storage (CCS), and transforms CCS into carbon capture, utilization and storage (CCUS).

Various projects have been established to help develop the technology, infrastructure, and regulations to implement CCUS in different geologic formations. In 2003, The United States Department of Energy (DOE) created a network of seven Regional Carbon Sequestration Partnerships (RCSP) to study the feasibility of capturing and permanently storing CO₂ in different regions across the United States and part of Canada. The seven RCSPs include Big Sky Carbon Sequestration Partnership, Midwest Geological Sequestration Consortium-Illinois Basin, Midwest Regional Carbon Sequestration Partnership, Plains CO₂ Reduction Partnership, Southeast Regional Carbon Sequestration Partnership, Southwest Regional Partnership on Carbon Sequestration, and West Coast Regional Carbon Sequestration Partnership (Litynski et al. 2006).

19 The RCSP initiative in the United States is implemented in three phases: the
20 Characterization Phase (also referred to as Phase I), Validation Phase (Phase II),
21 and Development Phase (Phase III). The Characterization Phase (2003–2005)
22 characterized the potential for CO₂ storage in each region. The Validation Phase
23 (2005–2011) focused on small-scale field tests to validate regional sequestration
24 opportunities. The Development Phase (2008–2018+) is for large-scale field tests
25 to evaluate safe, effective, and long-term storage at large scales (Rodosta et al.
26 2011; Litynski et al. 2013).

27 The Southwest Partnership on Carbon Sequestration (SWP) is one of seven
28 RCSPs. The study region of SWP is the southwestern United States, which in-
29 cludes Arizona, Utah, New Mexico, Colorado, Oklahoma, Texas, Kansas, and
30 Wyoming. In the Characterization Phase, SWP confirmed that this region has
31 significant potential for CO₂ storage in oil and gas fields, saline formations, and
32 unmineable coal seams (Litynski et al. 2008). In the Validation Phase, SWP has
33 completed small-scale pilot projects to test potential CO₂ storage via enhanced
34 coal bed methane (ECBM) extraction, EOR, and terrestrial storage (Rodosta et al.
35 2011). The ongoing SWP Phase III project is to verify combined large-scale stor-
36 age and EOR at the Farnsworth field.

37 Farnsworth field is located in Ochiltree County in northern Texas. The primary
38 target reservoir is the Morrow formation, which is at an average depth of about
39 7,700 ft (2350 m) and consists of incised valley-fill Pennsylvanian-age sandstone
40 that extends from Colorado to Texas (Bowen 2005). The project plan is to inject
41 one million tons of CO₂ over a period of five years. A variety of characterization
42 and monitoring techniques are used, including seismic methods (3D seismic sur-
43 face surveys, vertical seismic profiling, crosswell tomography, passive seismic)

44 and some other geophysical and geochemical analyses. The goal is to evaluate
45 the effectiveness of large-scale storage operation and to develop technologies for
46 ensuring 99 percent storage permanence and reduction of potential risks.

47 Safe, long-term, and large-scale underground geologic storage of carbon diox-
48 ide faces a number of challenges (Boot-Handford et al. 2014). One of the chal-
49 lenges is the potential risk associated with induced seismicity (National Research
50 Council 2013). Injection of a large amount of CO₂ into deep porous rock in-
51 creases pore pressure. The increased pore pressure on preexisting faults reduces
52 the frictional resistance to fault slip, and earthquakes may be induced if the faults
53 are critically stressed. Induced moderate earthquakes may cause concern to the
54 public, damage infrastructure, and threaten the seal integrity of the storage forma-
55 tion, leading to potential leakage of CO₂ (Nicol et al. 2011; Zoback and Gorelick
56 2012).

57 To lower the risk of induced seismicity, it is desirable to sequester CO₂ within
58 a region where natural earthquakes are rare. Natural earthquakes provide infor-
59 mation about distribution and properties of active faults, and thus may indicate the
60 potential for induced seismicity to some level.

61 In this work, we characterize natural seismicity around the Farnsworth field as
62 one method of assessing the potential risk of induced seismicity for SWP's Phase
63 III project. The natural seismicity characterization also provides some baseline
64 information for passive seismic monitoring during and after the CO₂ injection. We
65 find that there is no recorded catalog earthquake within a region of approximately
66 30 km in radius from planned CO₂ injection well No. 13-10A.

2. Farnsworth Field Site

The Farnsworth Unit is an active CO₂ injection petroleum recovery site managed by Chaparral Energy, LLC. This unit started development in the mid 1950s and started water flooding in the 1960s. The CO₂ flooding began in 2010.

The Farnsworth Unit is located in the Anadarko Basin of northern Texas (Texas Panhandle) (Fig. 1). The Anadarko Basin is approximately 50,000 square miles in size, and covers western Oklahoma, northern Texas panhandle, eastern Colorado, and western Kansas. The basin is bounded on the south by Amarillo Uplift and Wichita Mountains, on the east by Nemaha Uplift, on the west by Cimarron Arch and Las Animas Arch, and on the north by Central Kansas Uplift. The Anadarko Basin contains Cambrian through Permian sediments with a thickness of more than 40,000 ft (12 km) in its deep southern portion, and is one of the largest oil and gas regions in the United States (Johnson 1989). The targeted Pennsylvanian-age Morrow formation has an estimated CO₂ storage capacity of more than 10 million tons, and has produced more than 100 million barrels of oil and 500 billion cubic feet of gas as of 2005 (Bowen 2005).

There are more than one planned CO₂ injection well at the Farnsworth Unit, but they are close to planned CO₂ injection well No. 13-10A, so we use well No. 13-10A as the reference location in the study. We study the seismicity within a region of approximately 180 km × 220 km (2 × 2 degrees) centered at well No. 13-10A at the Farnsworth Unit as shown as the dashed square in Fig. 1. Within this study area, the major geological features include Anadarko Basin, Palo Duro Basin, and Amarillo Uplift that separates the two basins. Amarillo Uplift is a west-northwest trending area with uplifted Cambrian igneous rocks and the overlying strata (Johnson 1989). The uplift is part of a major structural feature that

92 extends from northern Texas to southwestern Oklahoma, where it is known as
93 Wichita Mountains. This major structural feature is part of the Pennsylvanian-
94 age Ancestral Rocky Mountain orogenic belt that extends from Utah to Oklahoma
95 (Ver Wiebe 1930). The borders of Amarillo-Wichita Uplift are formed by reverse
96 faults with lengths of hundreds of kilometers. These faults are displaced verti-
97 cally as much as 40,000 ft (12 km) with steep boundaries between the basin and
98 uplift (Johnson 1989; Perry 1989). Regional, left-lateral strike-slip displacements
99 have also been observed in this fault system (Budnik 1986; McConnell 1989).
100 The combination of vertical and lateral tectonic movements results in a complex
101 zone of compressional overthrusting, tensional faulting, step faulting, and vertical
102 dipping formations (Evans 1979).

103 Seismic hazard in Texas is generally low. According to the US seismic hazard
104 map, the peak ground acceleration with 2% probability of exceedance in 50 years
105 is smaller than about 0.05g in Texas, in contrast to more than about 0.5g in south-
106 ern California. Within the state of Texas, Texas Panhandle is a region with the
107 second highest seismic risk level (Frohlich and Davis 2002). Several earthquakes
108 have been felt in Texas since 1900, but none of them was especially large or have
109 caused any damage (Frohlich and Davis 2002).

110 **3. Seismic Data Sources**

111 We search in all available catalogs to obtain the earthquake records around the
112 Farnsworth Unit. The catalogs used in this study include:

- 113 1. ANSS (Advanced National Seismic System)
- 114 2. OKGS (Oklahoma Geological Survey)
- 115 3. IRIS (Incorporated Research Institutions for Seismology)

- 116 4. ISC (International Seismological Center)
- 117 5. NCEER (National Center for Earthquake Engineering Research)
- 118 6. CEUS-SSC (Central and Eastern United States Seismic Source Characteri-
119 zation for Nuclear Facilities)
- 120 7. USArray

121 Some of these catalogs contain data of earthquakes in short periods of time
122 (e.g., USArray), while others cover long periods of time. The detailed information
123 about earthquakes recorded in each catalog is shown in Table 1. Note that there
124 was no seismic instrument in Texas until 1948 (Northrop and Sanford 1972), so
125 the earthquake records before 1948 was practically based on historical felt reports.
126 While the location uncertainties for instrument recorded earthquakes in this region
127 may be around a few kilometers, the location uncertainties for historical events
128 may be about tens of kilometers. Even with current instrumental coverage in Texas
129 Panhandle, the seismicity record is still not complete for events with magnitudes
130 smaller than approximately 2.5.

Table 1: Information of earthquakes (EQs) in the study area recorded by each catalog.

Catalog	ANSS	OKGS	IRIS	ISC	NCEER	CEUS-SSC	USArray
Numbers of EQs	29	27	33	37	11	39	7
Period of EQs	1974-2013	1980-1994	1982-2013	1966-2013	1907-1980	1907-2008	2009-2010

131 4. Seismicity Characterization

132 All of the earthquakes documented in the catalogs used in this study are shown
133 in Fig. 2. Some events have multiple records in different catalogs. These multiple

134 records for the same event may be the same or show some difference. We ex-
135 amine the catalogs carefully to compile a list of earthquake records based on the
136 credibility of each catalog, and show the results in Fig. 3.

137 A total of 72 earthquakes are compiled in the study area (Table A.2). As
138 shown in Fig. 3, most of these earthquakes are located in the state of Texas, and
139 to the south of Farnsworth Unit. Many of these events are likely associated with
140 Amarillo uplift. Uncertainties in epicentral locations of events, however, make
141 it hard to associate these earthquakes with specific faults. No any earthquakes
142 are recorded within a circular region with a radius of 30 km from planned CO₂
143 injection well No. 13-10A at the Farnsworth field.

144 The earliest reported earthquake in this study area dates back to 1907, with
145 an assigned magnitude of approximately 3. Felt reports for earthquakes have also
146 been found later in 1917, 1925, 1936, 1966, and 1974, before the modern seismic
147 instruments were in place. The largest earthquake recorded in this area occurred
148 in 1925, and has an assigned magnitude of 4.8. Only four events that occurred in
149 the study area have magnitudes larger than 4. Many of the largest earthquakes are
150 historical events with limited records, and thus there is considerable disagreement
151 on the details of the earthquakes, including their locations, magnitudes, and ori-
152 gins. For example, the magnitude of the earthquake in 1925 was also reported to
153 be as large as 5.4 (Frohlich and Davis 2002). The event in 1959 was also claimed
154 to be a series of sonic booms (Frohlich and Davis 2002).

155 The earthquake records with magnitudes smaller than 2 are all from the local
156 OKGS catalog. The smallest earthquake detected in this area has a magnitude of
157 1.4. All except one of the earthquakes with magnitudes larger than 3 are located
158 south of the Farnsworth Unit (Fig. 4). The only larger event north of Farnsworth

159 Unit is located at the border between Texas and Oklahoma. This earthquake oc-
160 curred in 1974, and has a magnitude of 4.5.

161 Most of the earthquakes in this study area are shallow with depths shallower
162 than 10 km. Only three recorded earthquakes show depths deeper than 10 km
163 (Fig. 5). The deepest event has a depth of 24 km. It occurred in 1974 with a
164 magnitude of 4.5.

165 During the last five years, all of the earthquakes with magnitudes larger than
166 2.0 in the study area occurred south of the Farnsworth Unit. Only three earth-
167 quakes with magnitudes larger than 3.0 were recorded, and their magnitudes are
168 all smaller than 4.0. Records for earthquakes with magnitudes smaller than 2.0 is
169 not available for this period.

170 Since Texas Panhandle is a region with a long history of petroleum production,
171 it is possible that not all of the recorded earthquakes in this area are natural. Some
172 of the earthquakes may have origins related to oil field activities (Frohlich and
173 Davis 2002).

174 **5. Conclusions**

175 We have performed seismicity characterization for Farnsworth Unit, the field
176 demonstration site of the U.S. Southwest Regional Partnership on Carbon Seques-
177 tration for large-scale combined CO₂ storage and EOR. We have compiled earth-
178 quake information based on available catalogs for a region about 180 km × 220 km
179 (2 × 2 degrees) centered at a planned CO₂ injection (well No. 13-10A) at the
180 Farnsworth field. The earliest earthquake recorded in this region dates back to
181 1907. Only four earthquakes with magnitudes larger than 4 were recorded ever
182 since, and the largest earthquake in this region has a magnitude of 4.8. Most of the

183 earthquakes in the study area are associated with Amarillo Uplift, and are located
184 south of the Farnsworth Unit. For earthquakes larger than magnitude 3.0, there is
185 only one event located north of the Farnsworth Unit. No earthquakes have been
186 found for a circular region with a radius of about 30 km from planned CO₂ injection well No. 13-10A at the Farnsworth Unit. During the last five years, there are
187 only three earthquakes that have magnitudes larger than 3.0 in this region. Based
188 on our study, the Farnsworth field site has low seismicity, and could be suitable
189 for large-scale storage of CO₂ with relatively low seismic risk. It should be noted,
190 though, that the background seismicity can only have indications for active faults,
191 thus the possibility of future significant induced seismicity cannot be eliminated.
192 Mitigation techniques may be employed to avoid significant induced seismicity.
193

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Figure 1: The tectonic structure around the study area within the dashed square. The Farnsworth Unit for the SWP Phase III project is denoted by a red triangle. Green lines delineate faults in this region (Davis and Northcutt 1989).

Figure 2: Earthquake locations from different catalogs represented by different symbols. Red triangle denotes planned CO₂ injection well No. 13-10A at the Farnsworth field.

Figure 3: All earthquakes (blue dots) recorded in the study area. Red triangle denotes planned CO₂ injection well No. 13-10A at the Farnsworth field. The dashed circle with a radius of 30 km indicates an area without recorded earthquakes.

Figure 4: (a) Earthquake locations from all the catalogs. Different circles represent different magnitudes. (b) All the earthquakes with magnitudes larger than 3.0.

Figure 5: Earthquakes with depths larger than 10 km.

Figure 6: All earthquakes occurred in the last five years.

204 **Appendix A. List of all recorded earthquakes near the Farnsworth field site**

Table A.2: List of compiled earthquakes in the study area.

Date	Time	Latitude	Longitude	Magnitude	Catalog
1907/04/00	00:00:00.00	35.500	-101.200	3.00	CEUS-SSC
1917/03/27	23:38:00.00	35.300	-101.300	3.00	CEUS-SSC
1925/07/30	12:17:00.00	35.400	-101.300	4.80	NCEER
1936/06/20	03:24:03.50	35.310	-100.770	4.40	NCEER
1959/02/10	20:05:00.00	35.500	-100.900	4.20	NCEER
1966/07/20	09:04:59.50	35.650	-101.140	3.90	ISC
1974/02/15	13:33:49.20	36.500	-100.693	4.50	ANSS
1978/08/03	00:35:37.09	36.690	-100.160	2.30	CEUS-SSC
1980/02/21	20:42:03.49	35.292	-101.084	2.90	OKGS
1980/06/09	22:37:12.29	35.476	-100.998	3.30	OKGS
1982/02/13	09:48:25.37	35.577	-101.176	2.40	OKGS
1983/03/11	16:50:48.26	36.830	-100.120	2.90	CEUS-SSC
1983/01/18	04:08:59.08	35.507	-100.816	2.10	OKGS
1985/04/24	10:04:38.23	35.339	-100.368	2.20	OKGS
1985/05/30	08:47:06.06	35.653	-100.924	2.20	OKGS
1986/11/05	13:34:46.20	36.993	-101.561	2.40	ANSS
1986/04/09	06:58:14.34	35.813	-101.031	1.60	OKGS
1986/12/22	00:17:25.53	36.212	-100.350	1.80	OKGS
1986/05/27	11:12:02.47	35.374	-101.719	1.80	OKGS
1988/05/13	00:33:41.09	35.297	-101.656	2.20	OKGS
1988/05/13	00:42:56.44	35.795	-101.311	1.40	OKGS

1989/04/24	01:00:27.26	35.648	-100.213	1.70	OKGS
1989/07/17	03:32:16.67	36.242	-101.414	2.20	OKGS
1989/07/18	06:21:11.12	36.254	-100.109	2.10	OKGS
1990/12/16	05:05:22.28	35.628	-100.742	2.50	OKGS
1990/07/01	13:06:41.49	35.382	-101.619	2.70	OKGS
1990/07/13	22:20:18.20	35.848	-101.467	2.70	OKGS
1990/03/26	20:56:18.19	35.381	-100.428	2.50	OKGS
1991/03/15	14:17:30.38	36.660	-100.600	2.40	CEUS-SSC
1991/04/12	05:50:52.68	35.486	-100.902	2.40	OKGS
1991/08/24	07:35:09.98	35.284	-100.741	2.20	OKGS
1991/08/24	08:12:30.96	35.448	-101.284	2.30	OKGS
1991/06/16	09:32:52.91	36.171	-100.259	1.70	OKGS
1991/05/07	14:16:58.46	36.199	-100.459	3.00	OKGS
1992/10/23	09:29:15.19	35.847	-100.732	2.30	OKGS
1994/02/15	21:51:33.85	36.105	-101.388	3.10	OKGS
1994/03/07	09:48:25.03	35.870	-100.103	1.70	OKGS
1994/03/07	09:53:22.41	35.933	-100.240	1.90	OKGS
1997/11/14	11:25:32.72	36.860	-101.630	2.40	CEUS-SSC
1999/10/25	23:19:51.68	36.950	-100.070	2.80	CEUS-SSC
2000/08/02	12:21:29.90	35.585	-101.855	2.70	ISC
2000/08/07	17:19:08.00	35.392	-101.812	3.30	ANSS
2000/08/07	18:34:09.00	35.392	-101.812	3.00	ANSS
2000/08/07	21:36:21.00	35.392	-101.812	3.00	ANSS
2000/08/10	13:39:50.00	35.392	-101.812	3.00	ANSS

2000/08/17	01:08:05.45	35.390	-101.814	3.90	ANSS
2000/12/16	22:08:54.00	35.400	-101.800	3.90	ANSS
2002/01/16	15:25:32.45	35.341	-101.818	2.50	ANSS
2002/03/31	02:54:08.13	35.359	-101.824	2.80	ANSS
2003/09/24	15:02:09.09	35.277	-101.742	3.30	ANSS
2003/10/28	23:20:13.00	35.280	-101.740	2.40	ANSS
2005/03/17	19:19:50.94	35.354	-101.797	2.40	ANSS
2006/02/18	05:49:41.45	35.672	-101.794	3.50	ANSS
2006/03/28	23:55:11.49	35.363	-101.871	3.00	ANSS
2007/02/07	07:02:17.99	35.347	-101.764	2.50	ANSS
2007/06/15	01:08:38.09	35.527	-101.000	2.90	ANSS
2007/09/27	15:21:02.06	35.471	-100.108	3.00	ANSS
2008/10/12	12:08:15.77	35.621	-100.315	3.00	ANSS
2008/10/14	03:07:28.03	35.766	-100.714	3.70	ANSS
2009/05/27	07:49:48.00	36.221	-101.597	2.30	IRIS
2009/05/30	05:09:06.00	35.454	-100.263	3.00	IRIS
2009/06/10	18:47:12.00	35.314	-101.802	2.60	IRIS
2009/07/02	08:12:30.00	35.297	-101.814	2.50	IRIS
2010/05/21	19:06:12.00	35.460	-100.245	2.80	IRIS
2010/06/17	17:19:41.00	35.694	-101.029	3.20	IRIS
2010/10/13	12:50:53.00	35.511	-100.189	3.00	IRIS
2012/01/03	17:04:27.98	35.377	-101.766	2.80	ANSS
2012/02/27	04:30:47.25	36.154	-100.542	2.80	ANSS
2012/08/12	00:36:05.15	35.372	-101.905	3.30	ANSS

2012/12/15	19:51:06.25	35.272	-100.068	2.70	ANSS
2013/04/26	05:09:58.70	35.424	-100.238	2.80	ANSS
2013/05/14	05:17:19.00	35.638	-100.342	2.90	IRIS

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Figure

Figure

Figure 1

Figure

Well 13-10A

$10 \text{ km} < \text{depth} \leq 20 \text{ km}$

$20 \text{ km} < \text{depth} \leq 30 \text{ km}$

Figure

Well 13-10A

$2 < M \leq 3$

$3 < M \leq 4$