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Energy Procedia 1 (2009) 2887–2894

Energy Procedia
www.elsevier.com/locate/procedia

GHGT-9

CO_2 storage risk minimization through systematic identification and assessment of faults: a Williston Basin case study

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Abstract

The Williston Basin is considered a tectonically stable area with only a few major inactive faults. Over the last 50 years, extensive hydrocarbon exploration in the basin has demonstrated that smaller faults do exist and closer evaluation is necessary to determine the nature of this faulting. An area near the town of Dickinson, North Dakota, has been identified as a potential location for CO_2 storage/enhanced oil recovery. A thorough geologic assessment of the area has identified structural anomalies that may indicate the presence of faulting, which, in turn, may affect precise CO_2 storage site selection.

Keywords: CO_2 storage; CO_2 EOR; salt tectonics; faulting; geologic characterization

1. Introduction

The Plains CO_2 Reduction (PCOR) Partnership is one of seven regional partnerships under the U.S. Department of Energy's (DOE's) Regional Carbon Sequestration Partnership (RCSP) Program. As part of the RCSP Program, the PCOR Partnership is tasked with ensuring that the region is prepared to implement large-scale CO_2 storage in geologic formations in the near future. One of the most important aspects of this preparation is to identify and assess the potential of regional geologic formations to store CO_2.

The PCOR Partnership region (Figure 1) contains several sedimentary basins, including the Williston Basin, which encompasses part of North Dakota, South Dakota, and Montana in the United States and part of Saskatchewan and Manitoba in Canada. The Williston Basin sediments were laid down in an ancient interior sea as a series of transgressive and regressive sequences. These sediments represent every geologic time period from the Cambrian through the Tertiary, reaching a total thickness of over 4500 m in the depocenter. Lithologies in the basin include high permeability/porosity sandstones, limestones, and dolomites layered with impermeable or nearly impermeable shales, evaporites, and tight carbonates which act as good seals to vertical fluid migration.

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doi:10.1016/j.egypro.2009.02.063

Figure 1. The PCOR Partnership region contains several sedimentary basins, many of which have large hydrocarbon deposits and great potential to store CO_2.

Regionally, the Williston Basin is relatively inactive tectonically with only a few major fault systems in the sedimentary rock package. The lack of tectonic activity and associated faulting and the abundant commercial oil and gas accumulations makes the Williston Basin an attractive target for CO_2 storage and CO_2 enhanced oil recovery (EOR) activities. The Antelope, Nesson Anticline Boundary, Heart River, and Cedar Creek Faults have long been recognized as significant fault systems in the Williston Basin, but relatively little has been published about faulting outside of these systems. Characterization of the Williston Basin over the past 50–60 years as part of extensive hydrocarbon exploration has demonstrated that faulting does indeed exist outside of the major fault systems. These smaller faults may be associated with the larger fault systems; however, it is likely a result of localized basement fault block movement and/or salt dissolution and subsequent cavern collapse. One area where basement fault block movement and salt tectonics may have occurred is near the town of Dickinson, North Dakota, United States. Because of its close proximity to several large CO_2 point sources, maturing oil fields, and thick saline formations, this area was examined as part of the PCOR Partnership regional characterization activities (Figure 2).

The Dickinson Study Area covers an areal extent of approximately 800 km^2 and contains sufficient geologic data for characterization down to a depth of about 3000 meters. In this study area are several potential CO_2 storage and CO_2 EOR target formations with adequate data for an evaluation of their storage potential. The target formations identified in this area are, from the bottom up, the Mississippian Lodgepole carbonate mounds (oil reservoirs), Mississippian Heath carbonates (oil reservoirs), Pennsylvanian Tyler sandstones (oil reservoirs), Pennsylvanian/Permian Broom Creek sandstones and carbonates (saline formation), and the Cretaceous Dakota sandstones (saline formation). The sealing formations for each formation are tight carbonates, evaporites, and shale

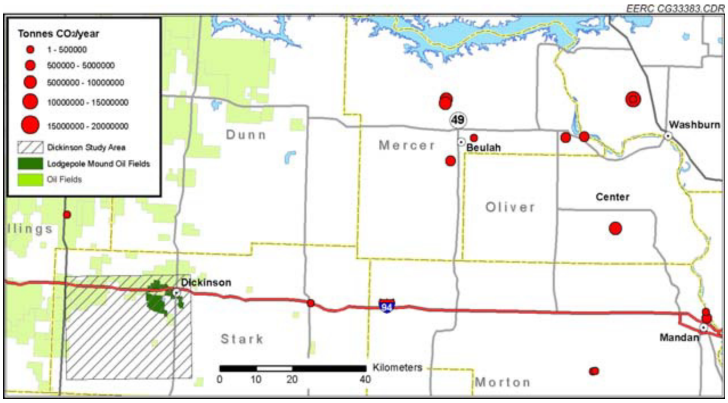

Figure 2. The Dickinson Study Area is located in western North Dakota, close to several large point sources of CO_2, and it contains several very productive oil fields, as well as several thick saline formations.

layers, and overlying all target formations is approximately 1000 meters of Cretaceous Pierre, Greenhorn, and Mowry shale which should act as an additional stratigraphic seal. Initially, the study area appeared to be stratigraphically and structurally simple; however, closer inspection revealed some abrupt changes in some of the structure maps and in the formation isopach maps. As a result of this study, the methods by which sites are assessed in the PCOR Partnership area were modified so that identification of subtle structural and stratigraphic features, including areas that may be faulted or fractured, are more easily identified.

2. Site assessment methodology

Sites for CO_2 storage or CO_2 EOR are typically selected by employing a series of preliminary evaluation tools to determine the site's amenability to CO_2 storage. Ideally, when evaluating a prospective site for CO_2 storage and/or CO_2 EOR, a variety of petrophysical data is examined, including well logs, core data, production/injection data, well tests, and seismic surveys. Data availability can vary widely from region to region, and sometimes even within a relatively small area. Such is the case with the Dickinson area, where there are plentiful well logs, core analysis, and local fluid production/injection data in the northern half of the study area but relatively sparse data in the southern half of the study area. Unfortunately, seismic surveys are not available. Because of the absence of seismic data, the site characterization workflow for the Dickinson area was modified to maximize the use of well log data to develop the greatest understanding of the subsurface structure and petrophysical properties. The first step was to load all the well tops, well logs, and core data into a commercial geological modeling software package [1] and pick and correlate the formation tops. After the formation tops were checked for quality, isopach maps were made of the formations to identify areas of thinning and thickening which could represent changes in the depositional environment or postdepositional processes. The well log work indicated structural anomalies were present in the area and, as a result, a variety of activities were conducted to determine their likely nature, cause, and implications. Additional information, most of a qualitative nature, was gathered on the area, including aeromagnetic and Bouguer gravity survey results, aerial photographs, previously published literature, and maps and testimony from an oil field unitization hearing. This evaluation also included a trip to the field to verify observations reported in the literature. This information was then synthesized and interpreted.

3. Evidence for faults

It was apparent from the isopach maps that several formations had great variability in thickness, and the structure maps of the formations exhibited abrupt elevation changes. These characteristics suggest that there was potential for a fault and/or a missing section of the formation. The deepest formation where local thickening and thinning was identified was the Lodgepole Formation. From the well logs, local thick spots were identified representing a clean limestone indicative of the Waulsortian-like mounds of the lower Lodgepole Formation [2]. Four salt layers above the Broom Creek Formation and below the Dakota Formation were identified and mapped for thickness from well logs, with all exhibiting great variability in thickness. The isopach anomalies for each salt were interpreted not to be caused by depositional thinning but rather from some postdepositional process such as salt dissolution and collapse (Figure 3). Aeromagnetic and Bouguer gravity anomaly surveys and aerial photographs were examined for any further evidence of abrupt changes in the subsurface or on the surface that may be suggestive of faults. Unfortunately, the resolution of the aeromagnetic and gravity surveys was not high enough to confidently determine the cause of the anomalies. However, aerial photographs of the study area show several linear outcrops, bluffs, and waterways that could have formed as a result of subsurface salt collapse and/or faulting (Figure 4).

Previously published work has described surface expression of faults in some of the areas that correlate to features identified in aerial photographs. With this in mind, the study area was visited in August 2008 to verify reports in the literature and look for further surface evidence of faults (Figure 5). Linear features of displacement were identified, mapped, and correlated to those reported in the literature. Although the apparent faults could not be extrapolated deep into the subsurface with any confidence, the literature [2–4] combined with the formation isopach maps strongly suggest that they are the direct result of salt dissolution and subsequent collapse and an indirect result of past basement fault block reactivation. There is evidence from an evaluation performed by Conoco [3], prior to the Lodgepole play discovery well, indicating the presence of a structural high covering strata from at least the Ordovician Winnipeg Formation through the Mississippian Madison. In Conoco's testimony to the North Dakota Oil and Gas Commission to get the Lodgepole discovery well permitted in the desired location, Conoco showed the presence of extensive faulting in deeper strata and demonstrated how it had created a structural high (Figure 6). It is also suggested in literature that postdepositional fault block reactivation caused extensive fracturing within the Lodgepole mounds creating secondary porosity [4]. This fault block reactivation could have occurred several times after the deposition of the Lodgepole mounds, and there is evidence that at least one event occurred after the Late Permian – Early Triassic, possibly associated with the Laramide Orogeny activity at the end of the Cretaceous [5]. This later activity can be inferred from differential dissolution of the Permian Opeche Salts, Permian Pine Salts, and Jurassic Dunham Salts. The hypothesis in this case is that reactivation of the basement fault block caused faulting that extended through the Opeche, Pine, and Dunham Salts, allowing fluids to flow through the salt layers and dissolve them along the edge and irregularly from the interior. The differential dissolution in these members could

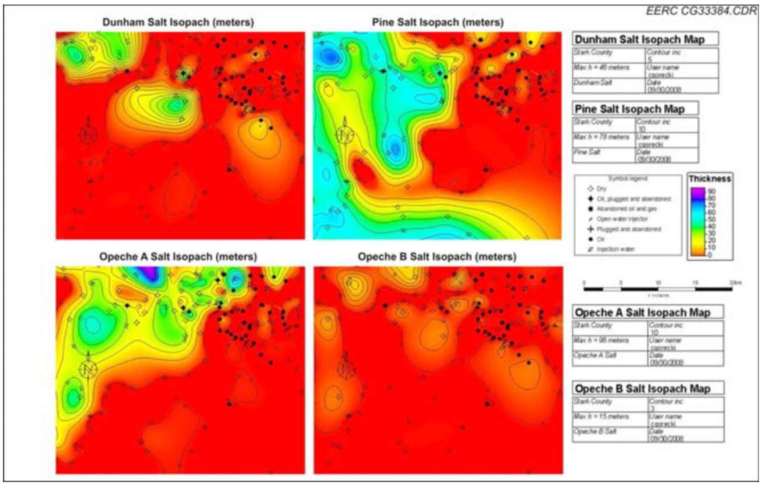

Figure 3. Salt isopach maps of Dunham, Pine, Opeche A and B Salts in the Dickinson Study Area, with the well locations. The thickness varies greatly in each salt layer as a result of dissolution from the edge and from within along possible faults.

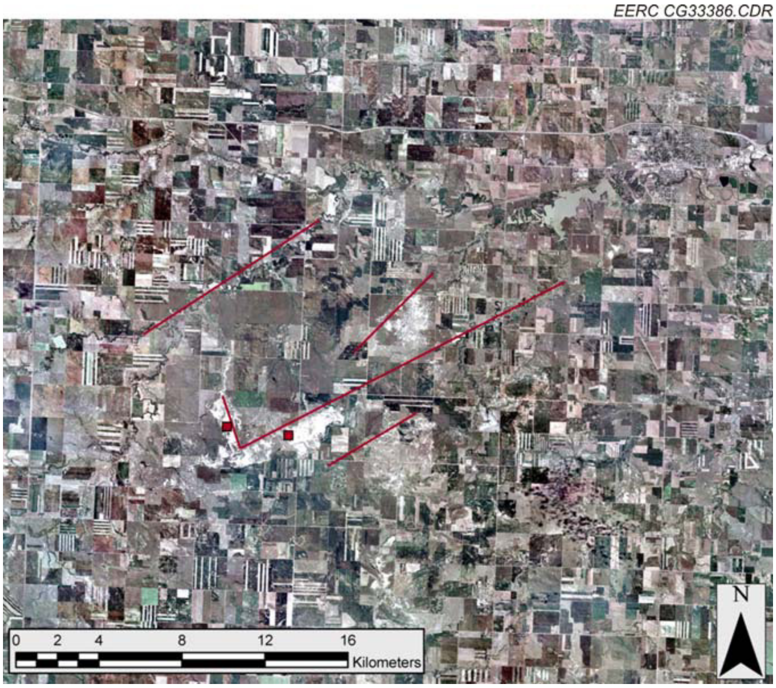

Figure 4. Aerial map of the Dickinson Study Area illustrating the linear trending waterways, bluffs, and buttes (shown with red lines); the evidence from this study suggests that these features formed as a result of faulting. The red squares denote the locations of identified surface fault expressions.

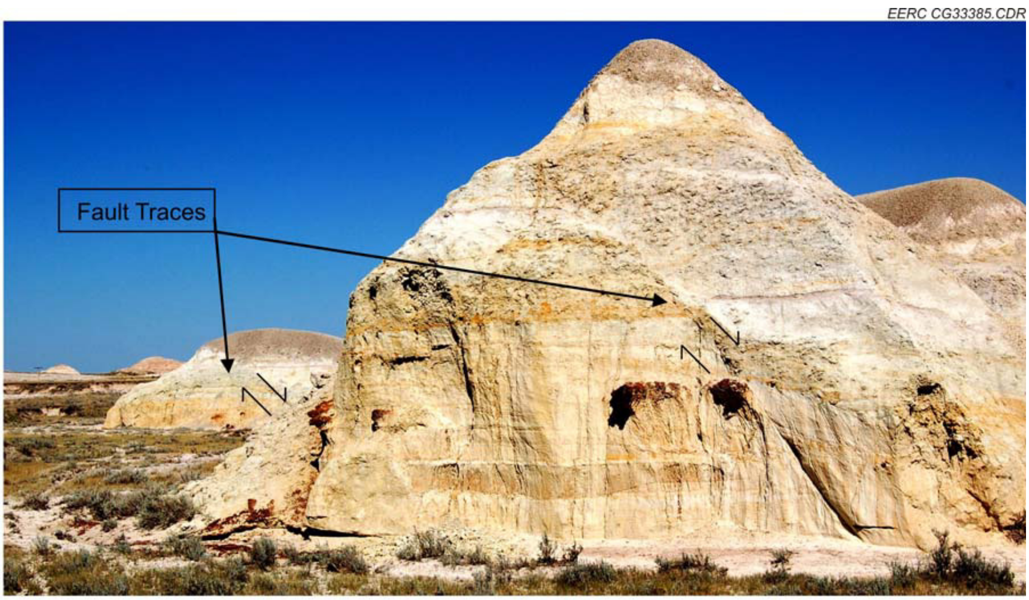

Figure 5. Image of the surface expressions of one of the two faults examined while the site was visited. This fault can be seen on two separate outcrops.

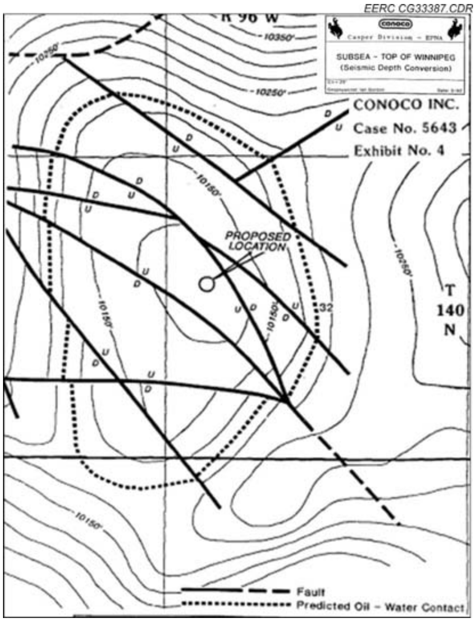

Figure 6. Exhibit No. 4 presented to the North Dakota Oil and Gas Commission by Conoco as part of Case Hearing No. 5643, demonstrating potential faulting in the Dickinson Field, near the town of Dickinson, North Dakota.

have been compounded by dissolution and collapse in lower salts, creating a complex series of normal and reverse faults which extended through the overlying members [6, 7]. There is evidence that the dissolution and subsequent collapse of the Opeche, Pine, and Dunham Salts postdates the deposition of the Cretaceous Pierre and may have occurred after the Oligocene [5, 8]. This is also supported by the presence of long linear bluffs and the Little Badlands, which are formed out of Eocene Golden Valley and Oligocene Chadron sedimentary rocks. These surface features line up roughly with areas of missing Opeche, Pine, and Dunham Salts and could be partially attributed to the collapse of a salt cavern within these members (Figure 7).

4. Implications of faults for CO_2 EOR/storage in the Dickinson area

Multistage faulting in the Dickinson area helped to create the Lodgepole Waulsortian-like mounds, and postdepositional fracturing as a result of reactivation has created good reservoir properties in the mounds. Several very productive Lodgepole oil fields have been developed, including the Eland, Stadium, Dickinson, West Dickinson, Hiline, and other oil fields. To date, these fields have had total cumulative production of over 8.6 million m^3 oil (54 million bbl) from separate Lodgepole Waulsortian-like mounds or pools within these mounds [9]. In these mounds, the faulting and fracturing has created conduits for flow which connected pore spaces and allowed the dissolution of some of the carbonate minerals, creating a network of interconnected vugs, increasing both the porosity and permeability of the formation. The secondary porosity generation of the Lodgepole mounds made them capable of storing large amounts of hydrocarbons, and yet these mounds have proven to be excellent structural traps capable of containing hydrocarbons for long periods of geologic time. It is likely that the Eland, Stadium, Dickinson, and West Dickinson Fields would be good candidates for CO_2 EOR as all four of these fields have been under successful water-flooding operations for the past 10 years and have sufficient oil in place to make tertiary recovery operations economically feasible. Even if these mounds were not used for CO_2 EOR, they would all make good targets for CO_2 storage once production ends.

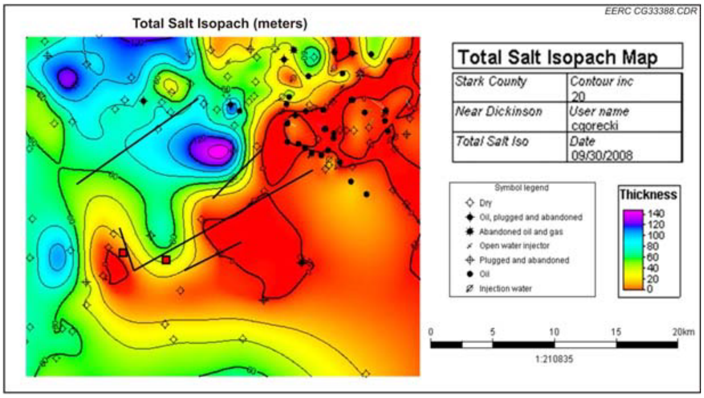

Figure 7. From the Total Salt Isopach (combination of the Dunham, Pine, and Opeche A and B Salts) map, there appears to be a correlation between surface features and abrupt changes in the total salt thickness. The surface lineaments are represented by the black lines, and the location of surface fault expressions are denoted by the red squares.

Faulting may likely extend through the Heath and Tyler Formations, and there is oil production from several pools within both. This indicates that there are at least some zones in these strata that are capable of trapping and containing formation fluids for extended periods of geologic time. In these formations, faulting does not appear to have compromised seals, and the faults may be sealing, creating these structural traps. In other areas of the Mississippian Madison and Broom Creek Formations, sufficient well log, core, and other data density are not available to determine whether there are any good trapping structures or if faulting has created conduits for fluid flow out of these formations. In these formations, further analysis would be necessary to determine the efficacy of CO_2 storage and/or CO_2 EOR.

In the Dakota sandstones, evidence suggests that faulting and fracturing are quite prevalent. Irregularity in the Dakota Formation top is quite obvious, and complex faulting and fracturing have created a series of structures which may or may not be capable of trapping formation fluids and/or injected CO_2. At this point, no major hydrocarbon discovery has been made in the Dakota, although this in itself should not necessarily be considered as evidence that overlying seals have been compromised. Overlying the Dakota Formation is approximately 1000 meters of Cretaceous Pierre, Greenhorn, and Mowry Shales which should act as a good stratigraphic seal as long as the faults and major fractures in these layers are closed to fluid flow. More work and testing would be necessary to determine the location and transmissibility of these faults and fractures.

5. Conclusions/recommendations

In the Dickinson Study Area, several formations have been identified that may be good targets for CO_2 storage and/or CO_2 EOR. As often is the case, the oil reservoir targets have plentiful data. It seems evident by the millions of cubic meters of oil and substantial associated gas produced from these pools that, even though the Mississippian Lodgepole mounds were formed through tectonic activity and subsequently fractured as a result of fault reactivation in the Oligocene over 20 million years ago, they have sufficient reservoir and cap rock properties to hold and contain formation fluids and CO_2 for long periods of geologic time. In this respect, it does not appear faulting has negatively impacted the potential use of the Lodgepole mounds for large-scale CO_2 storage. In fact, evidence suggests that faulting and fracturing have made the Lodgepole mounds excellent candidates for large-scale CO_2 storage and EOR.

In the Mississippian Heath and Pennsylvanian Tyler Formations, faulting is likely present; however, there are several productive oil pools in these formations. There are many dry wells separating the individual pools, and this could be an indication that faulting has created spill point leakage pathways or that the total oil accumulation in each pool is relatively low. Further analysis of these fields would be necessary to determine whether these oil reservoirs would be good candidates for CO_2 storage or EOR.

Both the Pennsylvanian/Permian Broom Creek and Cretaceous Dakota Formations in the Dickinson area could act as excellent CO_2 storage sites. Faulting is evident in both formations and has, at some point, allowed fluid movement that dissolved over 100 meters of salt from four salt layers which overlie the Broom Creek and underlie the Dakota Formations. Salt dissolution and subsequent collapse in the Dickinson Study Area have created a very structurally complicated geologic setting. The structures created as a result could be good CO_2 storage sites; however, it is difficult to determine from the available data whether these faults are sealing or partially transmissible. Further analysis, testing, and drilling would be necessary to determine whether the sites are capable of containing injected CO_2 for an indefinite period of geologic time.

The implications of the faulting and fracturing, with respect to CO_2 storage in the Dickinson area, is that many of these faults and fractures may be closed and have no transmissibility. In fact, the presence of large oil and gas accumulations in several of the formations suggests that faulting may actually have created excellent structural traps, which could be exploited for CO_2 storage. These structural traps may also exist in the shallower formations and could actually provide the structure that could prevent vertical and lateral migration of the CO_2 and thereby reduce the footprint of a CO_2 plume. It is also important to note that, historically, there has been no evidence of induced seismicity in this area even though there has been extensive water flooding in many of the formations for secondary oil recovery.

The Dickinson Study Area initially appeared to be stratigraphically and structurally simple; however, closer inspection revealed a geologically complicated setting with stratigraphic and structural highs and lows as well as faulting and fracturing. A thorough evaluation of the Dickinson Study Area, which included the incorporation of all of the available oil field data, geologic survey data, previously published literature, and visits to the study area, has supported the identification of subtle subsurface features and allowed evaluators to make inferences as to the potential causes and implications of these features.

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