The Deadwood Formation: A Potential Stratigraphic Unit for CO_2 Sequestration

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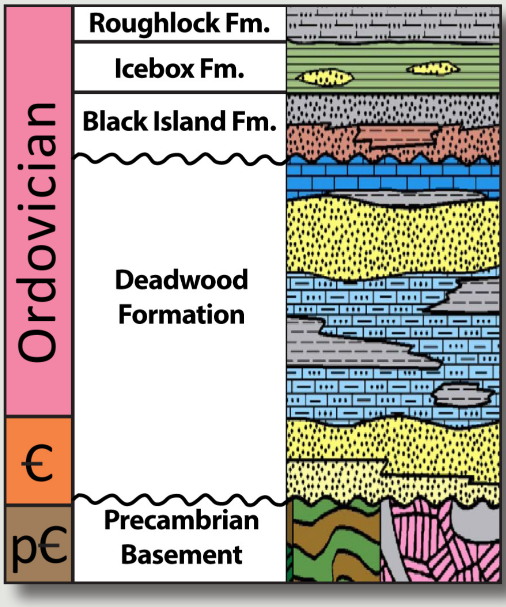

Figure 1. Stratigraphic column of the Deadwood Formation and adjacent stratigraphic units. Modified from Murphy et al. (2009).

INTRODUCTION

The Deadwood is one of several formations currently being evaluated in North Dakota for potential CO_2 sequestration, which is the process of capturing and storing carbon dioxide (fig. 1). There are presently five ethanol plants and six coal-fired power plants operating in the state, which could be future locations for CO_2 sequestration operations (fig. 2). Recently evaluated for CO_2 sequestration by the United States Geological Survey (USGS), the Deadwood was reported to meet the necessary geologic criteria for CO_2 sequestration, which includes depth, thickness, formation water chemistry, porosity and permeability, but volumetric storage calculations were not reported (Buursink et al., 2014).

GEOLOGY

The Deadwood Formation (Deadwood) is the deepest sedimentary unit within the Williston Basin, and was deposited at around 480-500 million years ago, during the Late Cambrian to Early Ordovician (fig. 1) (LeFever et al., 1987; Murphy et al., 2009; Sarnoski, 2015). The Deadwood is primarily comprised of siliciclastics, quartz-rich sandstones interbedded with siltstone and shale/claystone, with lesser amounts of carbonate beds

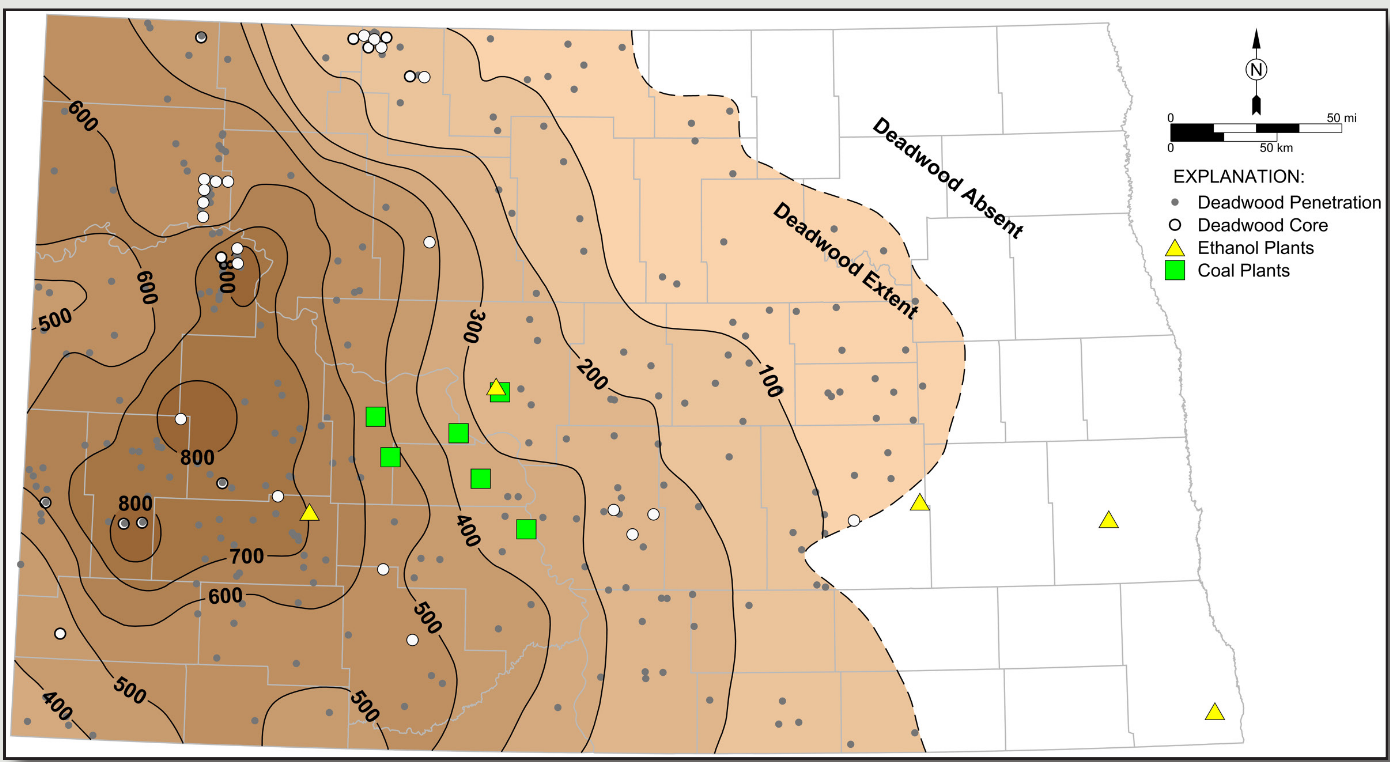

Figure 2. The extent and thickness map of the Deadwood Formation in North Dakota with Deadwood well penetrations and core locations. Isopach contours are in 100-foot intervals and are modified from LeFever et al. (1987). Coal-based powerplant locations from Lignite Energy Council (2020) and ethanol plant locations from North Dakota Ethanol Council (2020).

stratigraphically positioned within the middle and upper portions of the unit (LeFever et al., 1987; Sarnoski, 2015). The siliciclastic portions of the Deadwood have been interpreted to range from deeper water marine (shales) to upper and lower shoreface settings (siltstones to sandstones) (LeFever et al., 1987; Sarnoski, 2015). Meanwhile, the carbonate intervals have been interpreted as offshore buildups that formed seaward of a siliciclastic coastline (LeFever et al., 1987).

ECONOMIC HISTORY

The Deadwood has been a relatively minor producer of oil and gas in the Williston Basin of North Dakota. Only 15 wells have produced from the Cambro/Ordovician, Deadwood, and Winnipeg/Deadwood oil and gas pools. Production from those 15 wells totals 511,293 barrels of oil (<0.1% of cumulative North Dakota production), 1,129,524 barrels of water, and 59,118,866 million cubic feet of gas (NDOGD, 2020). Furthermore, over 99% of the gas production is from the Winnipeg/Deadwood pool, which includes reservoir(s) in the overlying Black Island Formation.

The Deadwood has also experienced non-hydrocarbon economic activity in the Saskatchewan portion of the Williston Basin. Helium was commercially produced from the Deadwood near Swift Current, Saskatchewan from four wells during 1963 to 1977 (Yurkowski, 2016). After a multi-decade hiatus, helium exploratory drilling recommenced in 2004 followed by production in 2014, which continues to present day (Yurkowski, 2016; Giles, 2020). The Deadwood is also currently being developed by Deep Earth Energy Production Corporation (DEEP) for geothermal power generation near Torquay, Saskatchewan (Murphy, 2021). To date, DEEP has drilled five geothermal wells targeting the Deadwood at depths of approximately 11,500 feet. and temperatures near 250°F (Murphy, 2021). Lastly, located in southeastern Saskatchewan, the Aquistore Project is an on-going site of CO_2 sequestration, which has stored over 300 tonnes of CO_2 to date from SaskPower's Boundary Dam Carbon Capture Facility (PTRC, 2020). The Aquistore Project takes a portion of the CO_2 captured from a nearby coal-fired power plant (Boundary Dam) and injects the CO_2 into the Deadwood Formation (PTRC, 2020).

INDUCED SEISMICITY CONSIDERATIONS

Induced seismicity (earthquakes) can occur when fluid is injected at depths proximal to a naturally occurring fault or fault zone. The injected fluid can elevate fluid pressures which in turn reduces the effective stresses at depth and can promote earthquake occurrences. Induced earthquakes have been associated with wastewater injection operations (Savage, 2017). However, many injection wells do not appear to induce earthquakes, even some that directly penetrate faults (Savage, 2017). Still, the Deadwood directly overlies Precambrian basement, from which many Williston Basin faults originate. Injection into the Deadwood may carry a greater risk in some areas for induced seismicity versus other, shallower formations.

Current state regulations require operators seeking a Carbon Dioxide Storage Facility Permit to complete local and regional faulting/tectonic evaluations. Any indication of linear structure/ fault trends that connect one or more Deadwood sandstone layers to the basement may force the operator to use a shallower injection zone or relocate, depending on the suitability of shallower formations. Depending on the location/area, the Deadwood can contain multiple sandstone layers that occur at separate stratigraphic positions. For example, a deeper sandstone layer may reside at the base of the Deadwood which connects to the basement through a fault whereas an overlying, shallower sandstone layer within the middle to upper portions of the Deadwood might not connect.

VERTICAL SEAL

Also important for sequestering CO_2 is a vertical seal, or an overlying, low porosity/permeability rock layer that will keep the injected CO_2 from migrating vertically out of the injection target layer. The Deadwood contains both intraformational low porosity/ permeability carbonate layers and shale beds (fig. 1). Additionally, the Icebox Formation overlies the Deadwood, which typically consists of more than 100 feet of clay-rich shale that regionally extends beneath much of North Dakota's subsurface (fig. 1) (Ellingson, 1995). The Icebox Formation has also been noted to form a vertical seal for hydrocarbon entrapment (Chimney et al., 1992), and serves as the CO_2 sequestration seal at the Aquistore Project site (PTRC, 2020).

RESERVOIR (STORAGE) QUALITY

The ability of sedimentary rock to take on (store) CO_2 or any other fluid/gas will largely be a function of porosity and permeability. Porosity is the percentage of pore volume within a rock, and in sandstones is typically the void space in between individual sand grains (e.g. fig. 3). Permeability represents the ability of a rock to

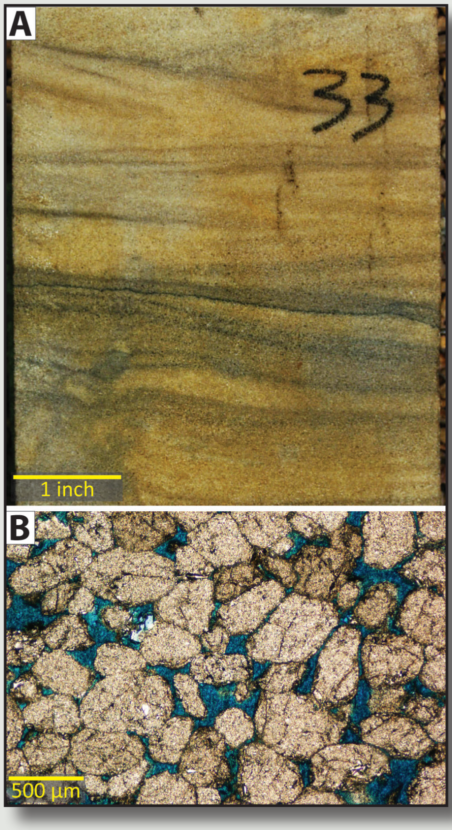

Figure 3. Example of a porous sandstone core interval from the Deadwood Formation in Mobil Oil's William Bernhardt #1 (NDIC: 8088, API: 33-089-00242, S28-T141N-R93W). A) Core photograph from a depth of 12,433 feet, and B) thin-section photomicrograph from a depth of 12,432 feet in which blue staining shows the open pore space between sand grains.

transmit fluids and is typically measured in darcies or millidarcies. Permeability is related to both the size and connectivity between the pores in a rock. Overall, the higher porosity and permeability of a rock, the greater its storage potential and ability to transmit fluids and/or gases.

Like many formations in the Williston Basin, the Deadwood contains variable porosity and permeability, both vertically and laterally. Figure 4 shows the representative distribution of porosity and permeability for Deadwood core samples from North Dakota. Although many of the Deadwood core samples contain relatively low porosity (<5%) and permeability (<1 md), there are also numerous Deadwood core samples with very high porosity (>15%) and permeability (>100 millidarcies). Porous Deadwood sandstones have been utilized for hydrocarbon (oil and gas) and helium production, are currently being developed for deep geothermal energy generation, and one day in the near future may also be utilized for CO_2 sequestration.

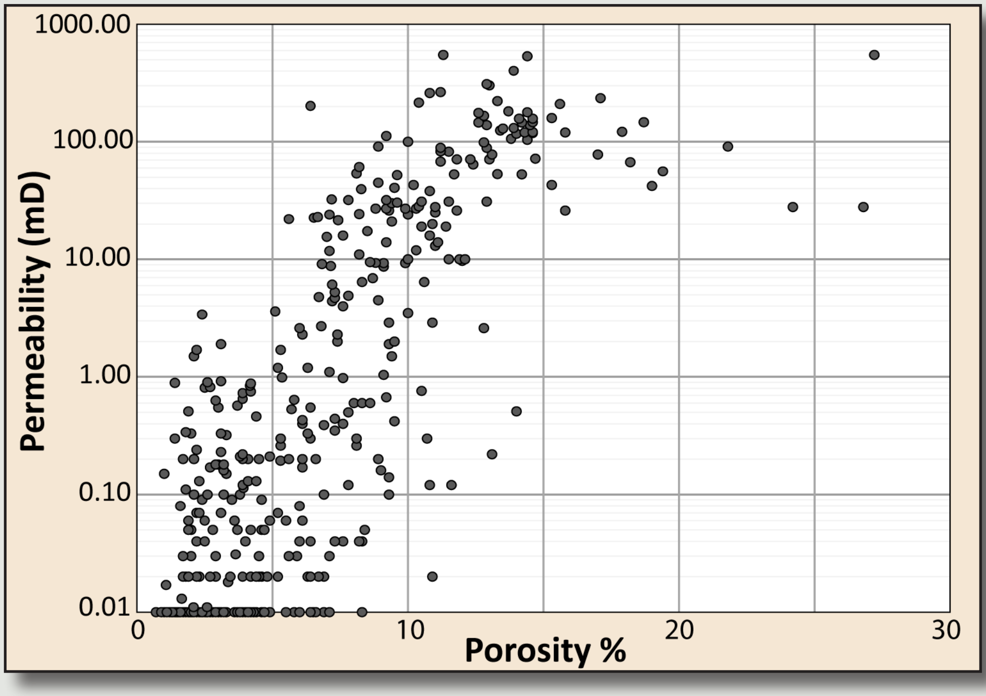

Figure 4. Porosity versus permeability plot for compiled, representative Deadwood Formation core-plug samples.

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