

Origination of Produced Water (Brine) in the Williston Basin

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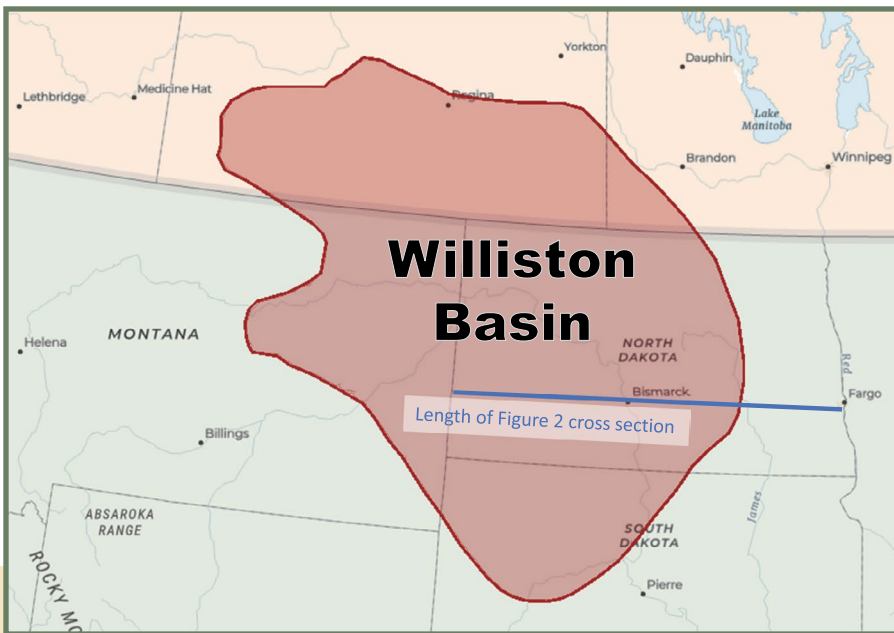


Figure 1. Geographical boundary of the Williston Basin. The blue transect line represents the cross section shown in Figure 2.

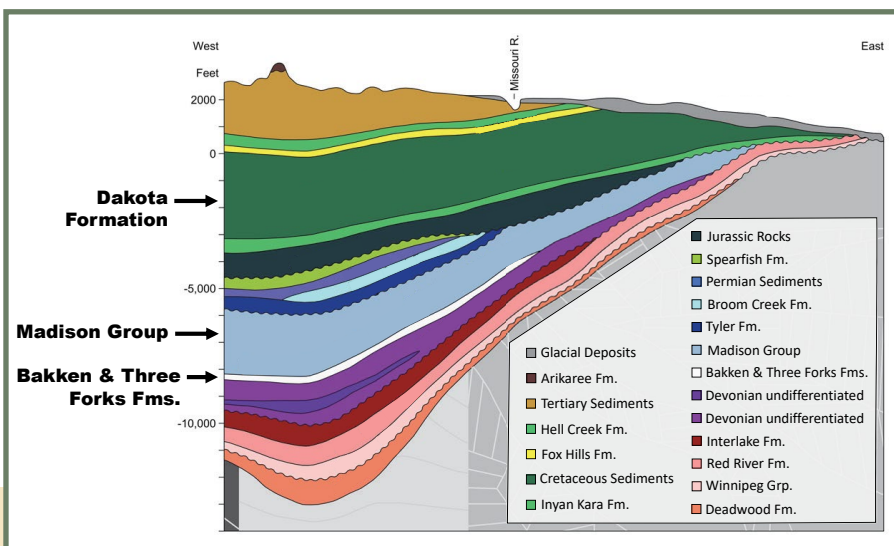


Figure 2. Cross section of the Williston Basin in North Dakota adapted from the North Dakota Geological Survey. Cross section is not drawn to scale.

Williston Basin Context

The Williston Basin is a sedimentary basin found in southern Saskatchewan, southeastern Manitoba, eastern Montana, northwestern South Dakota, and North Dakota. A large portion of North Dakota is underlain by the Williston Basin. The Williston Basin is one of the most complete sequence of sediments found worldwide spanning the past 500 million years. The geographical extent of this 110,000-square-mile basin is shown in Figure 1.

The oldest sedimentary unit in the Williston Basin (the Deadwood Formation) was deposited in the early Cambrian period over 500 million years ago with younger sediments being almost continuously deposited up until the Quaternary period (about 2.5 million years ago). Exceptions to this include four brief moments in time not recorded with the rest of the geologic history represented within the Williston Basin. The Williston Basin is made up of a wide variety of rocks that were deposited in terrestrial, fluvial (river) and, most abundantly, marine settings. The depth and relative thicknesses of rocks that make up the Williston Basin in North Dakota are shown in Figure 2.

History of Oil and Gas Exploration

Some of the most notable rock units within the Williston Basin are the Bakken and Three Forks Formations, as they currently hold most of the oil and natural gas that North Dakota produces today. Oil was first discovered in North Dakota in 1951, and historically the Madison Group (consisting of the Mission Canyon and Charles Formations) produced most of the oil and natural gas during the mid to late 1900s when conventional production techniques dominated this area (Figure 3). In the early 2000s, oil production from the Bakken and Three Forks Formations began to exceed production from the Madison Group due to advances in unconventional drilling (Figure 3).

Unconventional drilling involves drilling down vertically to a kickoff point where drilling then continues horizontally through rock units. Once drilling is complete, hydraulic fracturing, also known as “fracking,” is used to further increase production in rocks with poorly connected pore systems. As proppant-bearing (containing sand and or man-made ceramic beads) frac fluid is pumped in, pressures increase, causing rocks to fracture. Frac fluid rich in proppant then enters the induced fracks, which are then held open by sand or ceramic material.

Conventional drilling, on the other hand, usually only involves drilling down vertically into large oil and natural gas reservoirs. There is often no need for fracking when conventional methods are used; however, fracking has at times been applied on vertical wells. Although unconventional drilling is more labor intensive and time consuming, its use allows access to immense amounts of untapped reserves of oil and natural gas within the Bakken and Three Forks Formations that far surpass reserves found within the Madison Group and other conventional reservoirs in the Williston Basin.

Geology and Formation of Oil and Gas Holding Rocks

The Bakken Formation is an offshore marine deposit composed of both shale and siltstone and ranges in thickness from 75 to 150 feet. The Three Forks Formation directly underlies the Bakken Formation and is a nearshore marine deposit composed of shale, siltstone and dolomite. The Three Forks Formation reaches 250 feet thick near west-central North Dakota.

The Bakken Formation was deposited during both the late Devonian and early Mississippian Periods (about 360 million years ago), and the Three Forks Formation was deposited during the late Devonian Period (385-359 million years ago). Despite being two separate rock formations, the Bakken and Three Forks are often thought of as being one unit. The Bakken and Three Forks Formations range from 8,500 to 10,000 feet in depth below ground surface in the western part of North Dakota.

Millions of years and a variety of geologic processes are required to transform marine sands and silts into rocks that contain oil, natural gas and the by-product brine water. Oil and natural gas originate from aqueous derived plant and animal debris, sometimes referred to as organic material, that was altered by high temperatures and pressures in anaerobic (without oxygen) conditions. The amount of organic material that was deposited over 350 million years ago was dependent on rates of deposition and sedimentation. Many continental sediments erode from high points like hills or mountain tops and are deposited in depressional areas like basins, lakes or oceans (Figure 4). This is why there is a continuous accumulation of sediments in marine basins.

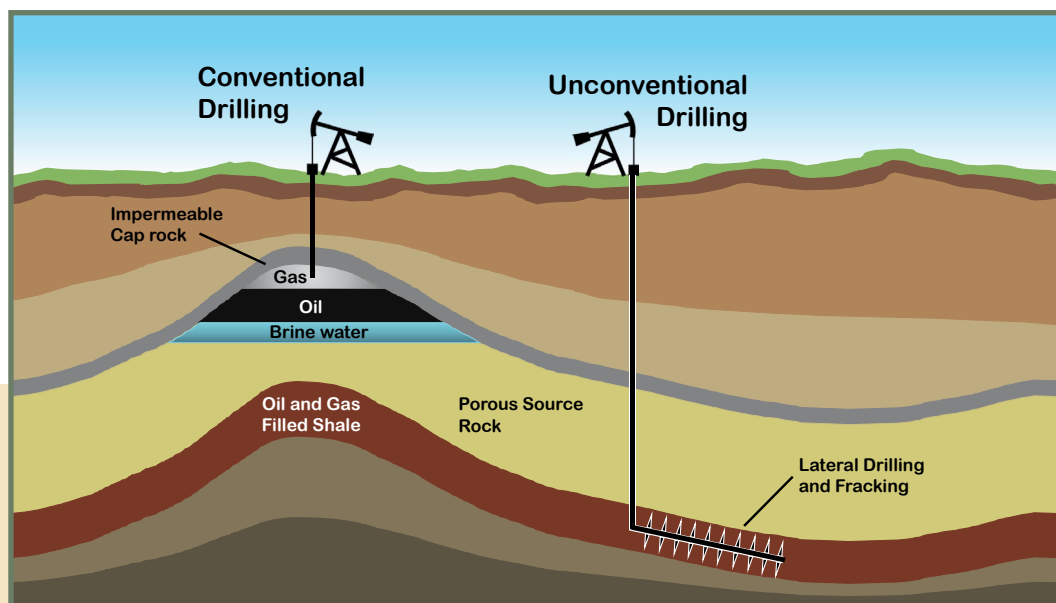


Figure 3. Schematic showing the difference between conventional oil extraction compared to unconventional oil extraction.

Formation and Occurrence of Oil, Gas and Brine

Conditions leading to the formation of oil and natural gas need to be ideal. This means that there needs to be favorable climate conditions to support appropriate plant and animal communities necessary for forming petroleum fuels. Low energy depositional environments are necessary to bury organic material and promote anaerobic degradation before organic material can be scavenged upon. Beach environments, for example, are less than ideal for organic matter accumulation because as waves crash upon the shore, water is aerated and the contact between bacteria and organic material is accelerated leading to decomposition rather than accumulation.

As sedimentation occurred in marine environments, organic material was buried by sediments that were loosely compacted and, during a majority of the Paleozoic era (540–248 million years ago) in North Dakota, saturated with sea water. As deposition and sedimentation continued, organic material and salts (primarily NaCl) from sea water were concentrated as water was squeezed out from between pore spaces due to increased pressures building above (Figure 5).

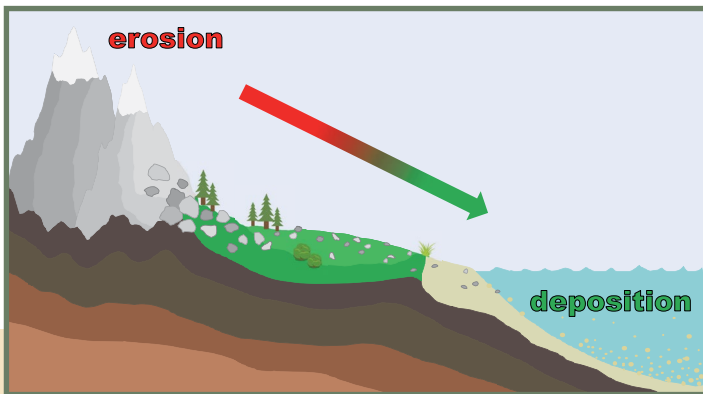


Figure 4. Schematic showing erosion occurring at higher elevations and deposition occurring at lower elevations.

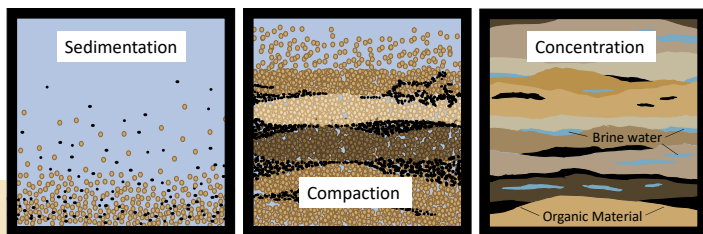


Figure 5. Schematic showing sedimentation and compaction of marine sediments and organic material and concentration of ocean water and organic material composed of plant and animal debris.

Pressures and temperatures build as sedimentation continues and at depths of about 0.6-1.2 miles (1-2 km) below ground surface and at temperatures of about 120 degrees Fahrenheit, accumulated plant and animal debris is converted into a substance known as kerogen through a process called diagenesis. Kerogen is a waxy, insoluble, sedimentary organic material. The formation of kerogen from plant and animal material is the first step in altering organic material into fossil fuels (Figure 6).

At depths reaching 1.8-3.0 miles (3-5 km) below ground surface and temperatures ranging from 180-250 degrees Fahrenheit (80-120 degrees Celsius), kerogen is converted into oil through a process called catagenesis, which is a type of thermal degradation. The formation of natural gas comes later only if temperatures continue to increase to between 250-300 degrees Fahrenheit (120-150 degrees Celsius). If temperatures continue to rise to near 400 degrees Fahrenheit (200 degrees Celsius), however, oil and natural gas will go through a process called metagenesis. Metagenesis will mineralize oil and gas, turning them into graphite, as they combust under high temperatures and thus will no longer be a fossil fuel. Although increasing temperatures and pressures drive the transformation of organic material to oil and gas, time is an additional factor not shown in Figure 6. High temperatures and pressures that continue for prolonged periods of time are much more effective at generating oil and gas than short surges of these conditions.

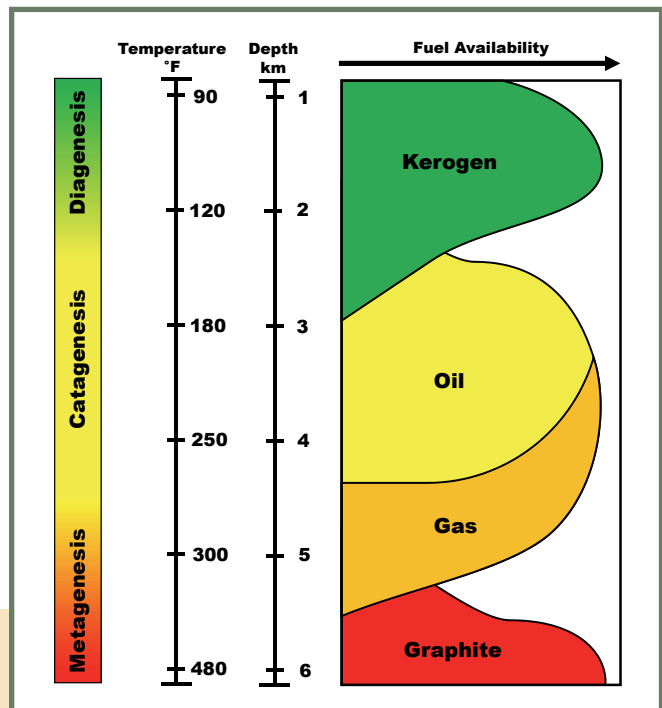


Figure 6. Chart showing fuel availability and thermal degradation processes given different pressure and temperature regimes.

Oil and natural gas tend to move through connected pore spaces in rock and accumulate in areas where porosity in rocks is low and permeability is no longer feasible. Concentrated ocean water, also known as brine, brine water or produced water, also travels through rocks and accumulates with oil and natural gas. In these pockets where there is stratification due to density differences, oil floats on brine and gas floats on oil (Figure 7).

Production and Separation of Oil, Gas and Brine

This heterogeneity (distinct stratification) of brine, oil and gas is disrupted by drilling and fracking processes. Disturbances caused by high intensity fracking and pumping cause oil, gas and brine to be brought to the surface as an emulsion (a homogenous mixture) (Figure 8). The amount of brine produced in the Williston Basin alongside oil and gas varies through time. Newer wells typically produce about a 2:1 to 4:1 ratio of oil to brine, whereas older wells produce ratios ranging from 1:2 to 1:100 of oil to brine.

There are onsite and offsite processes that aim to separate brine from oil and gas because of the negative impacts that brine can have on machinery, refinery equipment and the environment. Once at the surface, gas readily separates from oil and brine through density differences in onsite tanks, leaving oil and brine behind. Below, Figure 9 shows a simplified version of how brine, oil and gas are separated from each other. In these same tanks, some brine separates from oil without assistance. Additional heat, pressure, separation agents and mixing elements are often necessary to remove brine from oil before further, offsite refinery processes can take place.

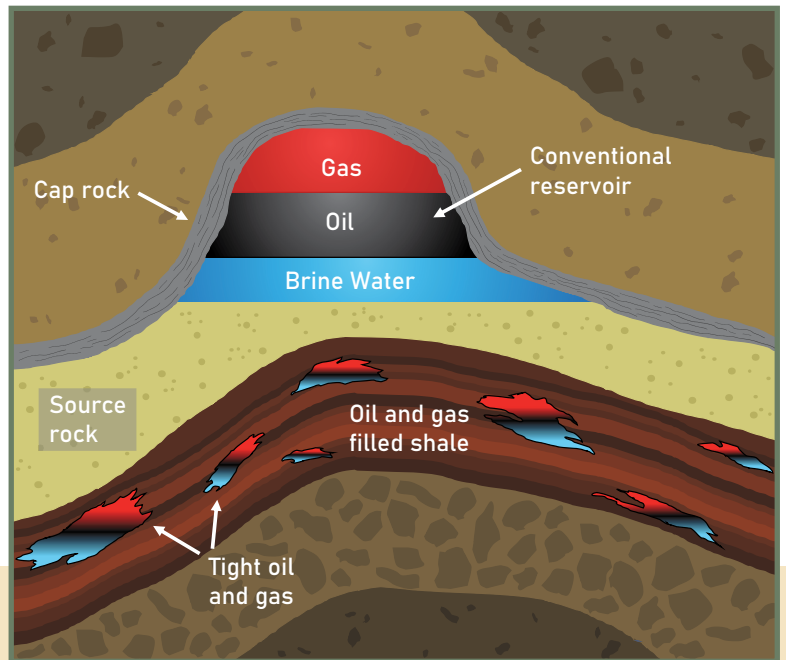


Figure 7. Schematic showing three sources of oil and natural gas: a conventional oil and gas reservoir, a tight oil and gas reservoir and an oil- and gas-filled shale.

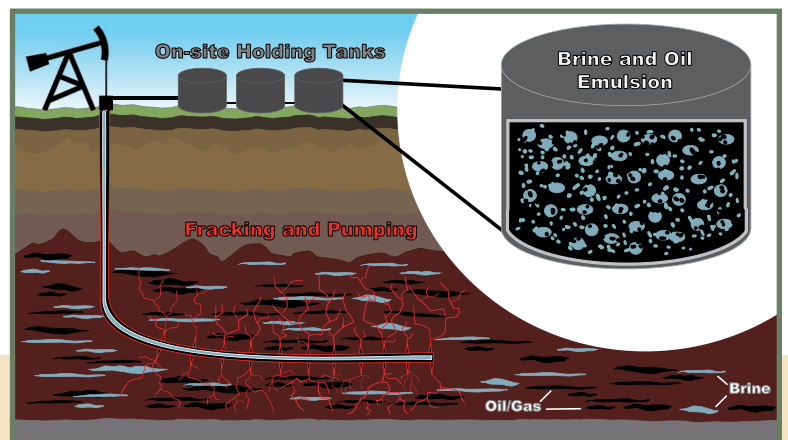


Figure 8. Fracking into an oil shale to access poorly connected reservoirs of oil, gas and consequently, brine water. High energy fracking causes oil and water to emulsify.

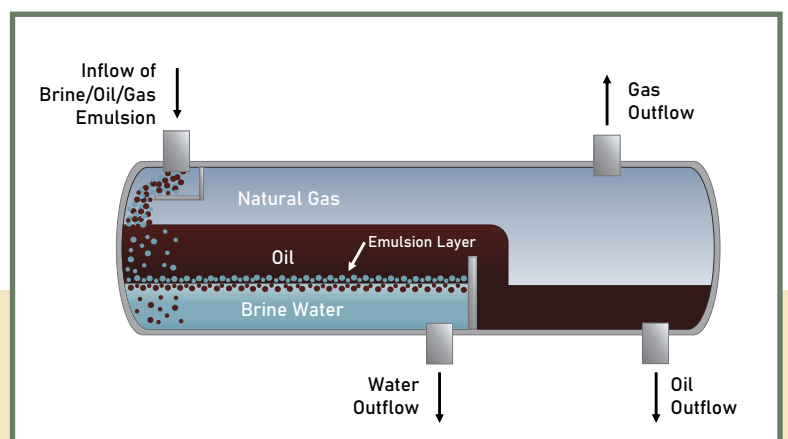


Figure 9. Idealized on-site tank used for the purpose of demulsifying brine, oil and gas.

Potential Risks of Disposal and Transportation

Once brine is separated from oil and gas, it then needs to be safely disposed. Disposal is typically done through deep well injection into the Dakota Formation (Figure 2), which is a Cretaceous-age rock unit (108-94 million years ago) nearly 5,000 feet below ground surface in western North Dakota. Pipelines are the most common mode of transporting brine to injection site (Figure 10a). Trucks are also used to transport brine because they are versatile for shorter distances (Figure 10b).

Most brine spills occur during the transportation of brine to an injection well site. In many cases, these spills can go initially undetected, especially when pipelines fail underground. Brine spills can range from a few hundred gallons to upwards of a few million gallons. Brine impacted areas often exhibit sparse vegetation (Figure 11a) and an accumulation of salts at the surface (Figure 11b). Brine spills can often be worse than oil spills because oil will naturally degrade over time, whereas brine is inorganic and does not degrade. For more information on the environmental impacts of brine refer to NDSU Extension publication R1850, Environmental Impacts of Brine (Produced Water).



(a)



(b)

Figure 10. (a) Pipelines on a well pad (Harold Rhodes) and (b) an example of a tanker truck used to transport both fresh water and brine water (Sam Croat).



Figure 11. (a) Sparse vegetation near a well-pad in Glenburn, North Dakota, and (b) salt crust that has accumulated at the surface near a well-pad in Glenburn, North Dakota.

Spill Reporting and Response

The log of these spills can be found on the North Dakota Department of Environmental Quality website: https://deq.nd.gov/wq/4_spill_Investigations/Reports.aspx. Reporting a spill can also be done through the state of North Dakota website: <https://www.spill.nd.gov/>. Brine is an unavoidable by-product of the oil and gas industry. Close monitoring and quick mitigation of pipelines and leaks are important to prevent large, accidental spills from occurring and impacting large areas or volumes of soil and subsoil.

References

- Abel, M., Perrin, M., & Carbonera, J. L. (2015). Ontological analysis for information integration in geomodeling. *Earth Science Informatics*, 8(1), 21–36. <https://doi.org/10.1007/s12145-015-0211-9>
- Alberta Environment. (2001). Salt Contamination Assessment & Remediation Guidelines. *Environmental Service, Environmental Sciences Division*.
- Allison, E. & Mandler B. (2018). Transportation of Oil, Gas, and Refined Products The methods, volumes, risks, and regulation of oil and gas transportation. *American Geosciences Institute*. 15, 1-15. www.americangeosciences.org/critical-issues
- Anna, L. O., Pollastro, R., & Gaswirth, S. B. (2010). Assessment of Undiscovered Oil and Gas Resources of the Williston Basin Province of North Dakota, Montana, and South Dakota. *Geological Survey Williston Basin Province Assessment Team U.S. Geological Survey Digital Data Series DDS-69-W*. 1-15. <http://www.usgs.gov/pubprod>
- Bader, J. W., Lefever, J. A., Nesheim, T. O., & Stollorf, T. D. (2018). Bakken-Three Forks Formations Madison Group Spearfish Formation. *North Dakota Geological Survey*. 1-75.
- Barbour, S. L., & Yang, N. (1993). A review of the influence of clay-brine interactions on the geotechnical properties of Ca-montmorillonitic clayey soils from western Canada. *Canadian Geotechnical Journal*, 30, 920-934. <https://doi.org/10.1139/t93-090>
- Bluemle, J. P. (2016). North Dakota's Geologic Legacy: Our Land and how it Formed. *North Dakota State University Press*.
- De Jong, E. (1982). Reclamation of Soils Contaminated by Sodium Chloride. *Canadian Journal of Soil Science*, 64, 351-364. <https://doi.org/10.4141/cjss82-039>
- Donohue, C. M., & Barrie, C. D. (2021). A review of the Bakken petroleum systems in the United States and Canada: Recognizing the importance of the Middle Member play. *AAPG Bulletin*, 105(9), 1847–1866. <https://doi.org/10.1306/04122120093>
- Egloff, G., B., Aime, M., Nelson, E. F., Maxutov, C. D., & Wirth III, C. (1937). Desalting Crude Oils. <http://onepetro.org/trans/article-pdf/127/01/48/2177681/spe-938048-g.pdf>
- Franzen, D., Kalwar, N., Wick, A., & DeSutter, T. (2019). Sodicy and Remediation of Sodic Soils in North Dakota. North Dakota State University Extension Service Pub. SF1914. <https://www.ag.ndsu.edu/publications/crops/sodicity-and-remediation-of-sodic-soils-in-north-dakota#section-12>
- Gaswirth, S. B., Lillis, P. G., Pollastro, R. M., & Anna, L. O. (2010). Geology and Undiscovered Oil and Gas Resources in the Madison Group, Williston Basin, North Dakota and Montana. *The Mountain Geologist*, 47(3), 71-90.
- Gerhard, L. C., Anderson, S. B., Lefever, J. A., & Carlson, C. G. (1982). Geological Development, Origin and Energy Mineral Resources of the Williston Basin, North Dakota. *North Dakota Geological Survey*, 66(8), 989-1020. <https://doi.org/10.1306/03b5a62e-16d1-11d7-8645000102c1865d>
- Green, A. W., DeSutter, T. M., Daigh, A. L. M., & Meehan, M. A. (2019). Wicking Salts from Brine-Contaminated Soils: A Potential Method for In Situ Remediation. *Agricultural & Environmental Letters*, 4(1), 180069. <https://doi.org/10.2134/ael2018.12.0069>
- Green, A., DeSutter, T. M., Meehan, M. A., Daigh, A. L. M., & O'Brien, P. L. (2020). Produced water's impact on soil properties: Remediation challenges and opportunities.
- Guerra, K., Dahn, K., & Dundorf, S. (2011). Oil and Gas Produced Water Management and Beneficial Use in the Western United States. *Bureau of Reclamation*. [Online.] <https://www.usbr.gov/research/dwpr/reportpdfs/report157.pdf>
- Helms, L. (2008). Horizontal Drilling. *DMR Newsletter*, 35(1), 1-3. <https://www.dmr.nd.gov/ndgs/documents/newsletter/2008Winter/pdfs/Horizontal.pdf>
- Hobson, G. D., & Tiratsoo, E. N. (1975). Introduction to Petroleum Geology. *Scientific Press*.
- Jury, W. A. & Weeks, L., V. (1978). Solute-travel Time Estimates for Tile-drained Fields III. Removal of a Geothermal Brine Spill from Soil by Leaching. *Soil Science Society of America*, 42(5), 679-684. <https://doi.org/10.2136/sssaj1978.03615995004200050003x>
- Konkel, L. (2016). Salting the Earth: The Environmental Impact of Oil and Gas Wastewater Spills. *Environmental Health Perspectives*, 124(12), A230–A235. <https://doi.org/10.1289/EHP.124-A230>
- Lauer, N. E., Harkness, J. S., & Vengosh, A. (2016). Brine Spills Associated with Unconventional Oil Development in North Dakota. *Environmental Science and Technology*, 50(10), 5389–5397. <https://doi.org/10.1021/acs.est.5b06349>
- LeFever, J. A. (2014). Source Beds. *North Dakota Geological Survey*.
- LeFever, J. A., & Nordeng, S. H. (2008). The Bakken Formation: Revisited. *North Dakota Geological Survey*.
- Lin, Z., Lin, T., Lim, S. H., Hove, M. H., & Schuh, W. M. (2018). Impacts of Bakken Shale Oil Development on Regional Water Uses and Supply. *Journal of the American Water Resources Association*, 54(1), 225-239. <https://doi.org/10.1111/1752-1688.12605>
- Meehan, M., Sedivec, K., DeSutter, T., Augustin, C., & Daigh, A. (2017). Environment Impacts of Brine (Produced Water). North Dakota State University Extension Service Pub. R1850. <https://www.ag.ndsu.edu/publications/environment-natural-resources/environmental-impacts-of-brine-produced-water>
- Mohamed, I. M., Block, G., Abou-Sayed, O., & Abou-Sayed, A. S. (2017). Industrial waste injection feasibility in North Dakota. *Journal of Petroleum Science and Engineering*, 159, 267–278. <https://doi.org/10.1016/j.petrol.2017.09.028>
- Murphy, E. C., Nordeng, S. H., Juenker, B. J., & Hoganson, J. W. (2009). North Dakota Stratigraphic Column. *North Dakota Geological Survey*, 91.
- Murphy, E.C. (2010). Bakken and Three Forks basics. *North Dakota Geological Survey*.
- Ourisson, G., Albrecht, P., & Rohmer, M. (1984). The Microbial Origin of Fossil Fuels. *Scientific American*. 251(2), 44–51. <https://doi.org/10.2307/24969433>
- Pereira, J., Velasquez, I., Blanco, R., Sanchez, M., Pernalet, C., & Canelón, C. (2015). Crude Oil Desalting Process. In *Advances in Petrochemicals*. <https://doi.org/10.5772/61274>
- Ranaee, E., Ghorbani, H., Keshavarzian, S., Ghazaeipour Abarghoei, P., Riva, M., Inzoli, F., & Guadagnini, A. (2021). Analysis of the performance of a crude-oil desalting system based on historical data. *Fuel*, 291. <https://doi.org/10.1016/j.fuel.2020.120046>
- Sublette, K. L., Moralwar, A., Ford, L., Duncan, K., Thoma, G., & Brokaw, J. (2005). Remediation of a spill of crude oil and brine without gypsum. *Environmental Geosciences*, 12(2), 115–125. <https://doi.org/10.1306/eg.11160404040>
- Thamke, J. & Chesley-Preston, T. (2013). Williston Basin Layer. *United States Geological Survey*.
- Thayee Al-Janabi, O. Y., Ibrahim, M. S., Waheed, I. F., Sayda, A. W., & Spearman, P. (2019). Breaking water-in-oil emulsion of Northern Iraq's crude oil using commercial polymers and surfactants. *Polymers and Polymer Composites*, 28(3), 187–198. <https://doi.org/10.1177/0967391119868118>
- Tissot, B.P., & Welte, D. H. (1978). Petroleum Formation and Occurrence: A New Approach to Oil and Gas Exploration. *Springer-Verlag*. <http://dx.doi.org/10.1007/978-3-642-96446-6>
- Vandenbroucke, M., & Largeau, C. (2007). Kerogen origin, evolution and structure. In *Organic Geochemistry*, 38(5), 719-833. <https://doi.org/10.1016/j.orggeochem.2007.01.001>
- Wang, J., Yuan, G., Lu, J., & Wu, J. (2021). Leaching of salt-affected soil amended by leonardite. *Physical Geography*, 42(3), 226–239. <https://doi.org/10.1080/02723646.2020.1738980>
- Yassin, A. N. A., Mohamed, B. E. H., Morsi, M. S., Osman, M. E., & Mohamed, M. T. (2019). Petroleum Refinery Process Design & Naptha Methaforming – Simulation Using Aspen HYSYS. *Alexandria University*.

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