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Tectonic Map of the Western Dakotas Uplift and Surrounding Areas

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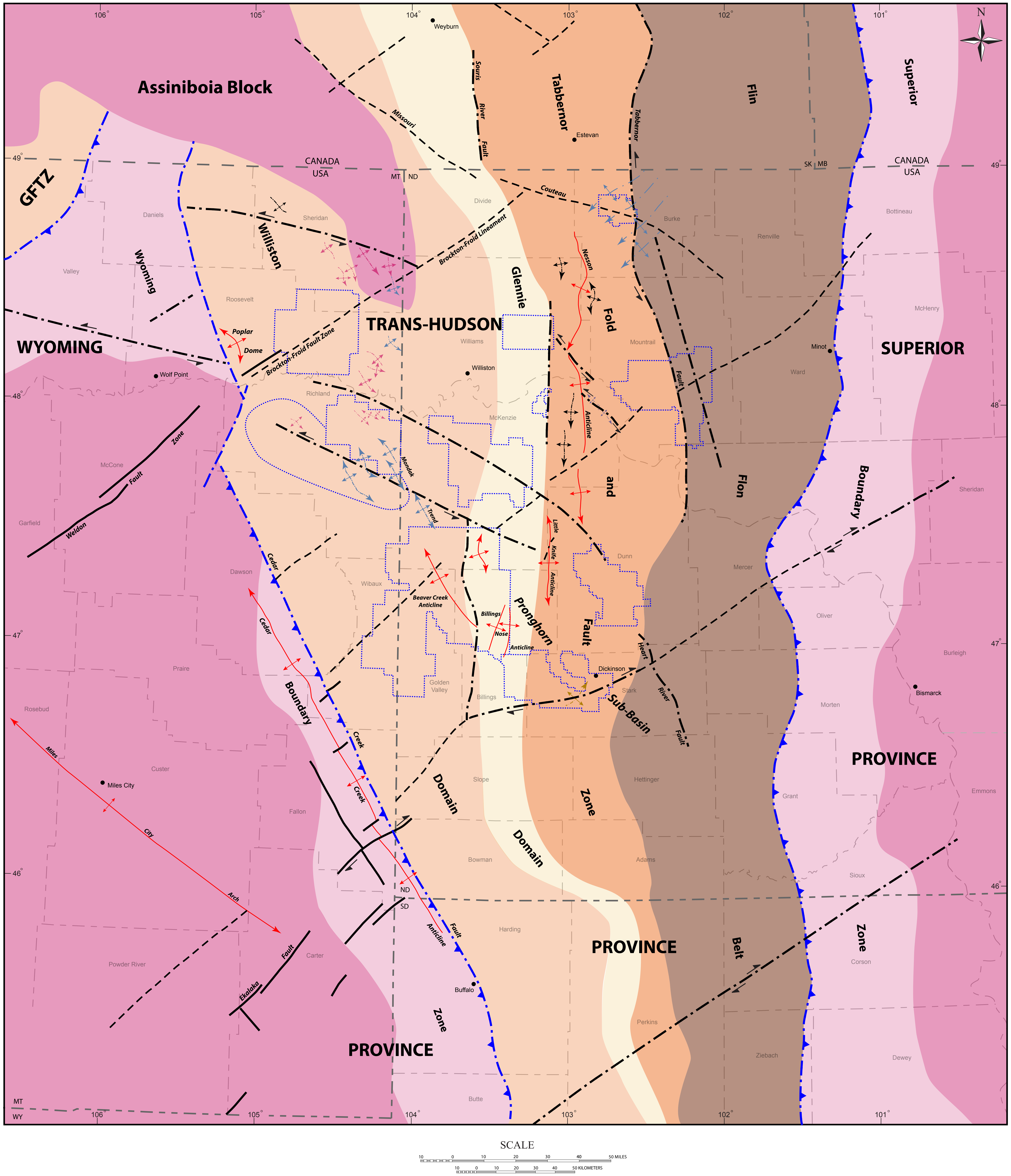

DISCUSSION

Background

The importance of understanding the relationship of basement rocks on basin development and the sedimentological/structural history of the Williston Basin has long been recognized. Ballard (1963) suggested that a depositional hinge-line for the eastern portion of the Williston Basin was coincident with the boundary between two basement provinces (Trans-Hudson and Superior). With the aid of geophysics, including seismic, aeromagnetics, and isostatic gravity, later workers refined that interpretation to propose a more tectonically complex basement model (Green et al., 1985). The relationship between basement anisotropies (Bader, 2018a, 2019a) and the control these features may have on Phanerozoic tectonism, sedimentation, and facies architecture in the Williston Basin was addressed by Brown and Brown (1979), Clement (1987), Gerhard et al. (1987), and Marsh (2017). These studies showed that basement anisotropy may have significant control on Phanerozoic tectonic events, basin development, sedimentation, and ultimately hydrocarbon generation and entrapment; an important concept that requires further evaluation in North Dakota.

Precambrian Basement

The Precambrian basement underlying the Williston Basin can be divided into three geological provinces (Green et al., 1985). The Archean Wyoming and Superior Provinces are cratonic masses (protocontinents) that were sutured together in the Paleoproterozoic (Green et al., 1985; Corrigan et al., 2009; Bader, 2019b). They are separated by back-arc/fore-arc basins and arc terranes of the Proterozoic Trans-Hudson Province; the sum of which define a continental scale collision zone.

Cratonic Provinces

Rocks of the Superior Province underlie most of eastern North Dakota and South Dakota, as well as Manitoba, and consist primarily of Archean granite/greenstone and gneissic terranes (McCormick, 2010). The Wyoming Craton underlies eastern Montana, western Saskatchewan, western South Dakota, and the tip of southwestern North Dakota. It consists of quartz-rich gneissic rocks that have been affected by younger granitic intrusions also of Archean age (Sims et al., 2004). Baird et al. (1996), proposed the existence of a third, smaller Archean cratonic block (Assiniboia/Dakota block) that is present under northwestern North Dakota/northeastern Montana and into southern Saskatchewan. It is possible that, with further investigations, similar smaller Archean basement blocks will be discovered within the Trans-Hudson orogen. Rocks of the Wyoming Province are in contact with rocks of the Paleoproterozoic Trans-Hudson Province along the Cedar Creek fault, a major basement-rooted suture/fault located in southeastern Montana. A similar suture that defines the eastern boundary of the Trans-Hudson orogen with the Superior Province is present just east of Minot and extends approximately 340 km N–S across central North Dakota.

Trans-Hudson Province

Between the Superior and Wyoming cratons are rocks of the Trans-Hudson orogenic belt. Rocks of this zone are relatively complex; having been deposited as oceanic sediments in a rift basin during an early Paleoproterozoic rifting event that perhaps separated the once single Wyoming/Superior cratonic mass (Bader, 2019b). Later, the rift basin (Manikewan Ocean) closed and collisions accreted Proterozoic island arc complexes and associated sediments to the Archean continental margins. Canadian workers have shown that the Trans-Hudson orogen is an extremely complicated zone of numerous accreted terranes defined by major basement-rooted sutures/faults that strike N–S (White, et al., 2005).

Basement Anisotropies

Structural inheritance is significant in other Rocky Mountain basins, such as the Bighorn and Powder River Basins of Wyoming and Montana (Bader, 2018a, 2019a). Basement fabrics and structural grain are potential zones of weakness that may eventually guide/influence later tectonic events. Thus, deposition of overlying sediments, Phanerozoic tectonic events, surface geomorphology, development of natural resources (including oil and natural gas, as well as some gravel/sand deposits), and location of geothermal highs, all of which are important in North Dakota, may be controlled by basement architecture. However, structural inheritance has not been well studied in North Dakota, partially due to the significant presence of glacial cover across the state, and the lack of any surface exposure of Precambrian rocks. Therefore, this map was created to better understand those relationships.

The Western Dakotas and Central Montana uplifts have had on-going recent attention by researchers and industry alike (Gerhard, et al., 1987; Nordeng, et al., 2010; Bader; 2019a, 2019b, 2020), generally due to increased activity in the Bakken over the last two decades. Numerous data-rich studies, incorporating geological, geophysical, structural, and tectonic synopses, have recently been completed allowing for development of a more comprehensive and modern tectonic model for the area (Sims et al., 2004; McCormick, 2010; Bader, 2018a, 2019a).

Methods

This map encompasses areas outside of the Western Dakotas uplift including the easternmost portion of the Central Montana uplift and the northernmost limit of the Black Hills arch, all of which are centrally located within the Great Plains Physiographic Province of the United States. It was generated utilizing a variety of methods and a multitude of sources. Typical methods for preparing a tectonic map include use of previous published data on major structural features in the area (commonly basement-rooted fundamental structures) as a basis for the map. These may include major zones or terranes in basement rocks (Sims et al., 2004; White et al., 2005; McCormick, 2010; Bader, 2019a, 2019b), generally revealed through seismic, aeromagnetic, and/or gravity studies. Major structures mapped at the surface and cutting the sedimentary cover may also complement the map (Vuke et al., 1986, 2007). Stratigraphic/depositional studies can also be used to reveal lesser, but still significant structures based mainly on thickness and facies changes across major deformation zones. Deformation of the sedimentary cover above major strike-slip basement-rooted fault zones (Bader, 2019a, 2020) may also be used to identify significant tectonic features that might otherwise go unrecognized (i.e., there are no facies/thickness changes across the deformed zone). Finally, major surface lineaments can be evaluated as to tectonic significance and added to the map (Anderson, 2011). All these methods were used in compiling this map; however, the map is not intended to show every lineament, fault, or fold in the study area.

Major basement terranes were “stitched” together utilizing previously published maps (Sims et al., 2004; White et al., 2005; McCormick, 2010; Bader, 2019b). Tectonic elements from Montana are from Vuke, et al. (1986, 2007) and Sims et al. (2004). Tectonic elements for North Dakota were gathered from numerous sources including Lindsay and Kendall (1985), Gerhard et al. (1987), Chimney et al. (1992), Kent et al. (2004), Nordeng et al. (2009, 2010), Sonnenberg and Pramudito (2009), Anderson (2011), and an unpublished, vintage Canadian Hunter oil/gas fields map of the Williston Basin that was also used as a base map. Subsurface anticlinal folds are generally from numerous Paleozoic horizons identified on detailed structure contour maps for numerous oil and gas fields across eastern Montana and western North Dakota (North Dakota Geological Society, 1962; Denson and Gill, 1965; Montana Geological Society, 1985; Nesheim, 2018). These anticlinal trends were then used to identify potentially significant basement-rooted fault zones.

Observations

Major tectonic elements of the mapped area exposed at the surface generally include anticlinal folds, such as the Miles City arch, Poplar Dome, Cedar Creek, Nesson, Little Knife, Billings Nose, and Beaver Creek anticlines. Smaller, subsurface anticlinal traces across the western part of North Dakota and eastern Montana define structure on various horizons. These traces are commonly en échelon, and left- or right-stepping, thus they may define possible basement-rooted wrench-fault zones similar to those seen across the Central Montana uplift. This large region of eastern Montana is characterized by fault/fold zones that define buried wrench faults striking WNW and NE (Bader, 2019a). Similar, NW- and NE-striking features appear in the Western Dakotas uplift to the east of the Cedar Creek fault (Anderson, 2011). The Mondak trend is an excellent example of such a feature as it is a classic group of left-stepping en échelon folds that likely define a WNW-striking basement-rooted fault in the subsurface. Therefore, along with the N-S sutures described above, three general structural trends are noted for the Western Dakotas uplift; N-S, NE, and NW. Similar trends have been noted by Bader (2018a, 2019a) across a large region from SW Wyoming to NE Montana, where he showed mechanical and temporal evidence for structural inheritance in basement rocks related to Precambrian convergence and subsequent reactivation during the Laramide orogeny. His work suggests that Precambrian development of Laurentia proceeded from SW to NE during several convergent events that took place from the Neoarchean (~3.0 Ga) through the Paleoproterozoic (~1.7 Ga), culminating with the terminal docking of the Superior craton with Trans-Hudson rocks/sediments as the Manikewan ocean closed (Bader, 2019b); thus setting the stage for development of the present-day Western Dakotas uplift. This initially resulted in fracturing the northeastern Wyoming craton into conjugate shear pairs during WSW convergence early in Trans-Hudson orogenesis (Bader, 2020) and these features are now recognized as reactivated Laramide wrench-fault zones across eastern Montana (Bader, 2019a). Later in the Trans-Hudson orogeny, numerous suture/subduction zones developed as the Manikewan ocean probably opened and closed several times. The collision events from ocean basin closures are ultimately defined by the major N-S fault zones (sutures) observed in western North Dakota. These zones probably developed originally as very deep shear-zones at the brittle-ductile transition within the crust during Precambrian convergent events. NW and NE trends were likely created through pure shear during the final E–W docking of the Superior craton at the end of the Trans-Hudson orogeny. This docking likely fractured the juvenile rocks of the Trans-Hudson orogen forming conjugate shears trending NW-SE and NE-SW (Anderson, 2011). Finally, these three major directions of Precambrian anisotropy in basement rocks were subsequently reactivated during the Phanerozoic when plate tectonic stresses were conducive to movement along these earlier-formed zones of weakness, most recently during the Sevier/Laramide orogeny. Such Phanerozoic movements on basement rocks have created the numerous subtle anticlinal closures in sedimentary cover rocks that commonly trap hydrocarbons across the Williston Basin (Nordeng, et al. 2010; Marsh, 2017; Bader, 2018b, 2018c; Nesheim, 2018). Recognition of these faults zones and associated subsidiary structures is critical because, even in horizontally-drilled unconventional reservoirs, many hydrocarbon accumulations may still be controlled by structural closure(s) related to wrenching and some of these closures may be nearly impossible to detect with conventional mapping techniques (e.g., structure contour, seismic, etc.).

References

Anderson, F.J., 2011, Structural relationships between surface lineaments and basement faulting in the northeastern Williston Basin, in Robinson, J., Gaswirth, S., and LeFever, J.A., eds., The Bakken-Three Forks petroleum system in the Williston Basin: Rocky Mountain Association of Geologists Guidebook, p. 376–392.

Bader, J.W., 2018a, Structural inheritance and the role of basement anisotropies in the Laramide structural and tectonic evolution of the North American Cordilleran foreland, Wyoming: Lithosphere, v. 11, no. 1, p. 129–148.

Bader, J.W., 2018b, Continued petroleum exploration of the Birdbear/Duperow Formations (Devonian), North Dakota: North Dakota Department of Mineral Resources Geo News, v. 45, no. 2, p. 19–23.

Bader, J.W., 2018c, Stratigraphic and structural relations of the Birdbear Formation (Devonian), western North Dakota: North Dakota Geological Survey Geologic Investigation 214.

Bader, J.W., 2019a, Structural inheritance for the Laramide Central Montana uplift–A wrench fault tectonic model related to Proterozoic orogenesis in the foreland of the North American Cordillera: Northwest Geology, v. 46, p. 21–39.

Bader, J.W., 2019b, An ancient Everest: Precambrian basement terranes of the Williston Basin: North Dakota Department of Mineral Resources Geo News, v. 46, no. 1, p. 30–34.

Bader, J.W., 2020, Wrench fault tectonics: North Dakota Department of Mineral Resources Geo News, v. 47, no. 1, p. 20–24.

Baird, D.J., Nelson, K.D., Knapp, J.H., Walters, J.J., and Brown, L.D., 1996, Crustal structure and evolution of the Trans-Hudson orogen: Results from seismic reflection profiling: Tectonics, v. 15, no. 2, p. 416–426.

Ballard, F.V., 1963, Structural and stratigraphic relationships in the upper Paleozoic rocks of eastern North Dakota: North Dakota Geological Survey Bulletin, v. 40, p. 956–984.

Brown, D. L., and Brown, D. L., 1987, Wrench-style deformation and paleostructural influence on sedimentation in and around a cratonic basin: in Peterson, J.A., Kent, D.M., Anderson, S.B., Pilatzke, R.H., and Longman, M.W., eds., Williston Basin—Anatomy of a cratonic oil province: Rocky Mountain Association of Geologists, Denver, Colorado, p. 57–70.

Chimney, P.J., Treska, C.E., and Wolosin, C.A., 1992, Richardton/Taylor fields–U.S.A., Williston Basin, North Dakota: American Association of Petroleum Geologists Treatise of Petroleum Geology, Stratigraphic Traps III, p. 421–445.

Clement, J.H., 1987, Cedar Creek: A significant paleotectonic feature of the Williston basin: in Peterson, J.A., Kent, D.M., Anderson, S.B., Pilatzke, R.H., and Longman, M.W., eds., Williston Basin—Anatomy of a cratonic oil province: Rocky Mountain Association of Geologists, Denver, Colorado, p. 323–336.

Corrigan, D., Pehrsson, S., Wodicka, N., Kemp, E., 2009, The Palaeoproterozoic Trans-Hudson orogen: A Prototype of modern accretionary processes: Geological of London Special Publications 2009, v. 327, p. 457–479.

Denson, M.D., and Gill, J.R., 1965, Uranium-bearing lignite and carbonaceous shale in the southwestern part of the Williston Basin-A regional study: United States Geological Survey Professional Paper 463, 75 p.

Gerhard, L.C., Anderson, S.B., and LeFever, J.L., 1987, Structural history of the Nesson anticline, North Dakota: in Peterson, J.A., Kent, D.M., Anderson, S.B., Pilatzke, R.H., and Longman, M.W., eds., Williston Basin—Anatomy of a cratonic oil province: Rocky Mountain Association of Geologists, Denver, Colorado, p. 423–432.

Green, A.G., Weber, W., and Hajnal, Z., 1985, Evolution of Proterozoic terrains beneath the Williston Basin: Geology, v. 13, no. 9, p. 624–628.

Kent, D.M., Thomas, P.L., and Heck, T., 2004, Geological mapping of Mississippian strata in southeastern Saskatchewan, northwestern North Dakota, and northeastern Montana (IEA Weyburn CO2 monitoring and storage project): in Summary of Investigations 2004, v. 1, Saskatchewan Geological Survey, Saskatchewan Industry Resources, Miscellaneous Report 2004-4.1, 22 p.

Lindsay, R.F., and Kendall, C.G.ST.C., 1985, Depositional facies, diagenesis, and reservoir character of the Mississippian cyclic carbonates in the Mission Canyon Formation, Little Knife field, Williston Basin, North Dakota: in Roehl, P.O., and Choquette, P.W., eds., Carbonate Petroleum Reservoirs, Springer Verlag, New York, p. 175–190.

Marsh, A., 2017, Overview of paleotopography on the sub-Mesozoic unconformity and hydrocarbon accumulation in the Mississippian Madison Group of southeastern Saskatchewan: Saskatchewan Geological Survey Summary of Investigations 2017, v. 1, p. 1–10.

McCormick, K.A., 2010, Precambrian basement terranes of South Dakota: South Dakota Geological Survey Bulletin 41, 37 p., 1 sheet, scale 1:100,000.

Montana Geological Society, 1985, Montana oil and gas fields symposium: Oil and gas fields of Montana, v. 1 and 2.

Nesheim, T.O., 2018, Spatial distribution of elevated oil saturations within the Midale subinterval (Mississippian Madison Group), Burke County–North Dakota: North Dakota Geological Survey Geologic Investigation 213.

Nordeng, S.H., LeFever, J.A., Anderson, F.A., Bingle-Davis, M., and Johnson, E.H., 2009, An examination of the factors that impact oil production from the middle member of the Bakken Formation in Mountrail County, North Dakota: North Dakota Geological Survey Report of Investigation 109.

Nordeng, S.H., LeFever, J.A., Anderson, F.A., and Johnson, E.H., 2010, Oil generation rates and subtle structural flexure: Keys to forming the Bakken sweet spot in the Parshall Field of Mountrail County, North Dakota: AAPG Search and Discovery Article #20094.

North Dakota Geological Society, 1962, North Dakota oil and gas fields symposium: Oil and Gas fields of North Dakota, v. 1, 219 p.

Sims, P.K., O'Neill, J.M., Bankey, V., and Anderson, E., 2004, Precambrian Basement Geologic Map of Montana—An Interpretation of Aeromagnetic Anomalies: United States Geological Survey Scientific Investigations Map 2829, scale 1:1,000,000, 1 sheet.

Sonnenberg, S.A., and Pramudito, A., 2009, Petroleum geology of the giant Elm Coulee field, Williston Basin: American Association of Petroleum Geologists Bulletin, v. 93, no. 9, p. 1127–1153.

Vuke, S.M., Colton, R.B., Stickney, M.C., Wilde, E.M., Robocker, J.E., and Christensen, K.C., 1986, Geology of the Baker and Wibaux 30 x 60-minute quadrangles, eastern Montana and adjacent North Dakota: Montana Bureau of Mines and Geology Geologic Map 41.

Vuke, S.M., Porter, K.W., Lonn, J.D., and Lopez, D.A., 2007, Geologic Map of Montana: Montana Bureau of Mines and Geology Geologic Map 62.

LEGEND

▨	Williston Domain (Proterozoic)–meta-sedimentary, granite/felsic gneiss (SD)
▨	Glennie Domain (Proterozoic)–quartz diorite to granodiorite orthogneiss (CA); granite/granodiorite (SD)
▨	Tabbernor Fault and Fold Zone (Proterozoic)–volcanic, volcaniclastic, and plutonic rocks of various composition, and gneiss (CA)
▨	Flin Flon Belt (Proterozoic)–granite, greenstone. arc volcanic and plutonic rocks including felsic, intermediate, mafic, and ultramafic intrusions, mafic volcanics, clastic sedimentary rocks and metamorphic equivalents (CA); granite and quartzite (SD)
▨	Wyoming Boundary Zone–gneiss and granite (MT); felsic gneiss and granite (SD); schist, granite, quartzite, banded iron formation (SD/BH)
▨	Wyoming Province (Archean)-gneiss and granite (MT)
▨	Superior Boundary Zone–schist, granite, gneiss, diorite, granodiorite, gabbro, and quartzite (SD)
▨	Superior Province (Archean)–greenstone and granite (CA/SD)
— — ⇄	Lineament–arrows indicate inferred direction of lateral movement
━━ ⇄	Surface Fault–arrows indicate direction of lateral movement
━ · ━ ⇄	Subsurface Fault–arrows indicate inferred direction of lateral movement
━ · ▲	Reverse Fault/Province Boundary–Sawteeth on upper plate
✛	Surface Anticline–showing axial trace and plunge direction
✛	Subsurface Anticline–showing axial trace and plunge direction; drawn from structure contours on various horizons
—	Structure contours on top of the Chadron Formation
—	Structure contours on top of a Madison Formation horizon (e.g., Midale beds, Green Point marker of Ratcliffe)
—	Structure contours on top of the Bakken Formation
—	Structure contours on top of a Red River Formation horizon (e.g., base of C-Anhydrite)
⬚	Major oil/gas field

BH–Black Hills, CA–Canada, MT–Montana, ND–North Dakota, SD–South Dakota, GFTZ–Great Falls Tectonic Zone