North Dakota Geological Survey
Geologic Investigation No. 193
Plate III

Sequence Stratigraphy of the Inyan Kara Formation, Northwestern North Dakota
Extracting the Maximum from Minimal Core and Outcrop Data

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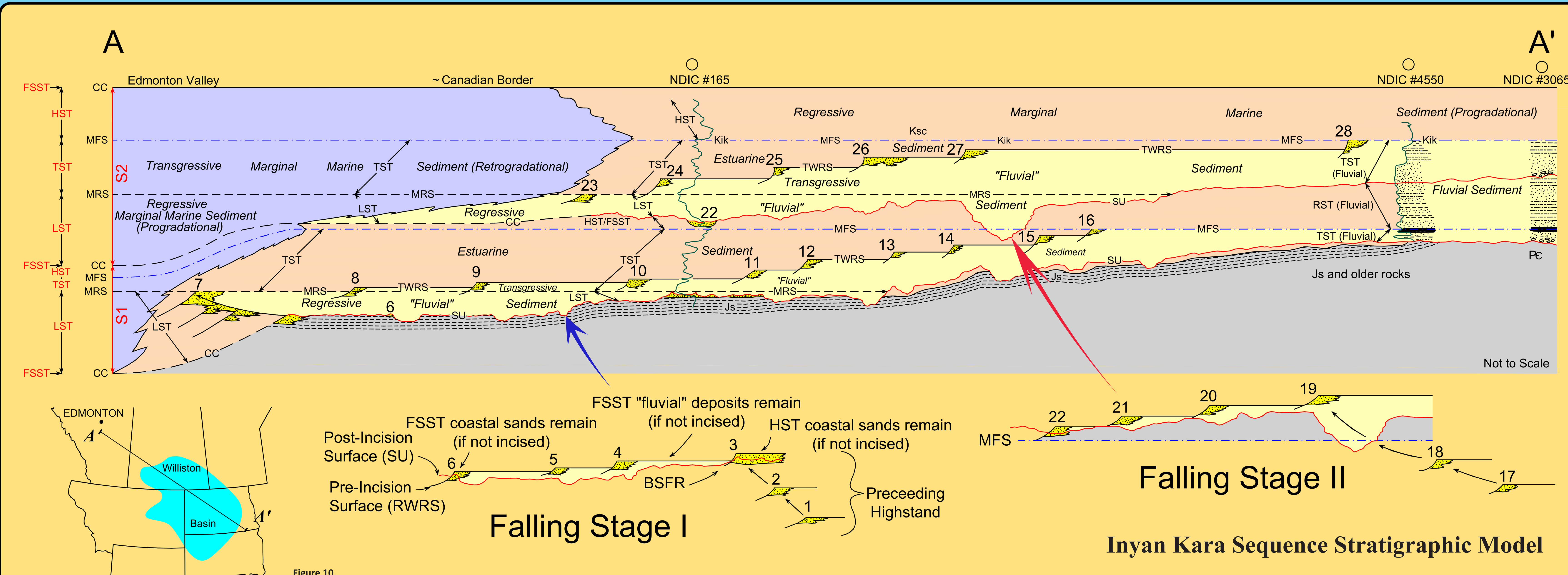


Figure 10.
Inyan Kara sequence stratigraphic model showing evolution of coastline through time (Numbers 1-28), sequence stratigraphic surfaces, systems tracts, and sequence boundaries. S1 = Sequence 1, S2 = Sequence 2, RWRS= Regressive Wave Ravinement Surface, TWRS = Transgressive Wave Ravinement Surface, Js = Jurassic Swift Formation, Kik = Cretaceous Inyan Kara Formation, Ksc = Cretaceous Skull Creek Formation, Pc = Precambrian; see Figure 8 for other abbreviation definitions.

Saltwater Disposal Wells in North Dakota

The first commercial oil well in North Dakota was drilled by Amerada Petroleum in 1951 (AOGHS, 2015). The first saltwater disposal (SWD) well in North Dakota began operating in 1953. Although North Dakota has been producing oil since 1951, only since 2005 has the Bakken oil boom made North Dakota the fourth largest oil-producing state in the U.S., and one of the largest onshore plays in the country. With these significant increases in oil production came similar increases in produced water production. Presently, North Dakota produces over a million barrels per day of produced water, requiring innovative methods and strategies to dispose of these prodigious amounts of waste fluids.

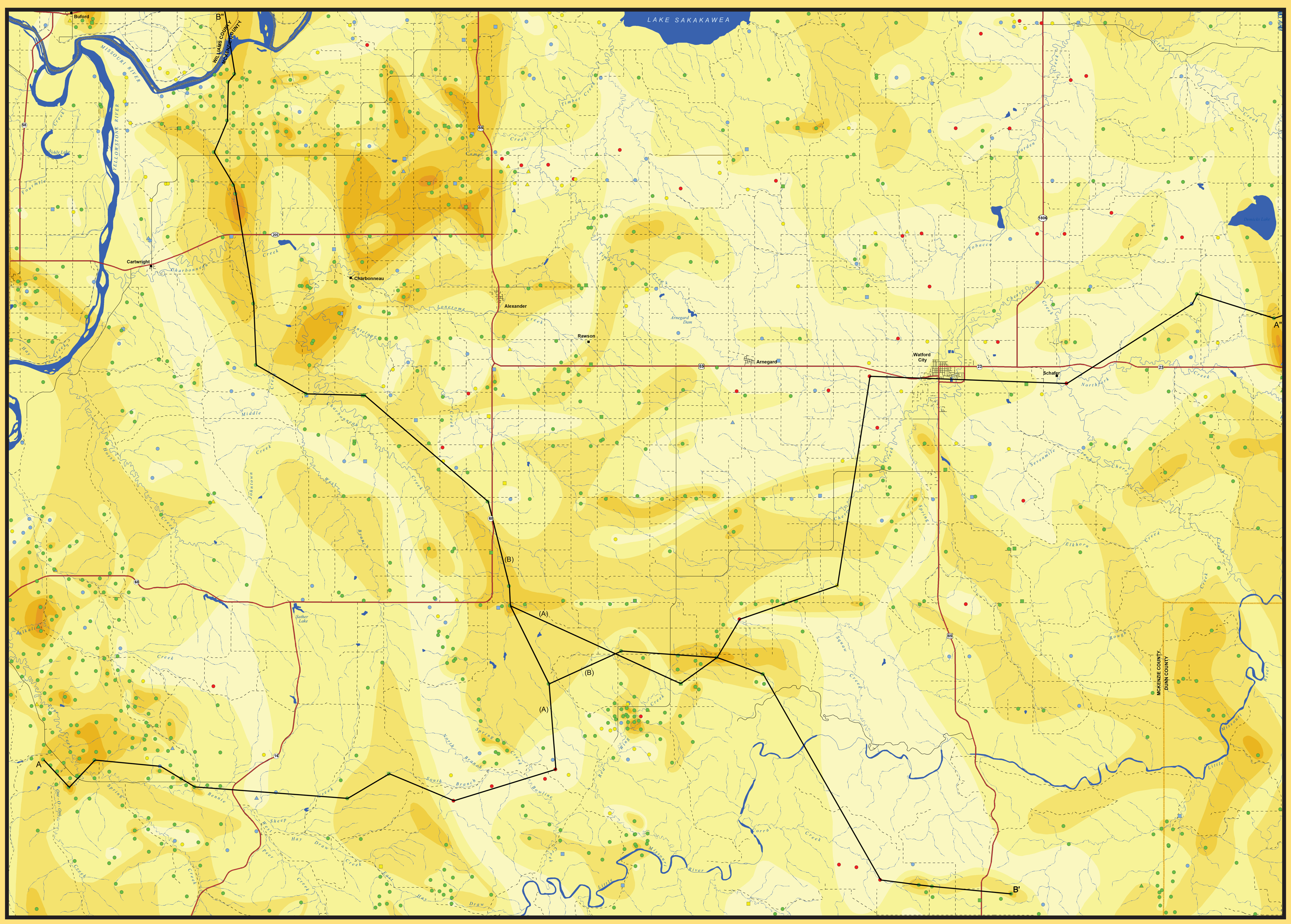
Prior to the development of hydraulic fracturing and refined horizontal drilling techniques, oil production in North Dakota was much less than it is today. During the years 1995-2005, North Dakota produced more than 320 million barrels of oil and over 670 million barrels of produced water. In 2005, 185 SWD wells were operating in North Dakota (Fig. 11).

Oil and gas production over the last decade has increased significantly with the discovery of the Parshall field in Mountrail County in 2004 and the use of horizontal drilling/hydraulic fracturing technology. Most of this production has come from the Bakken-Three Forks petroleum system. North Dakota has produced nearly 1.5 billion barrels of oil over this time period. Produced water over this same time frame is also significant, with over 1.7 billion barrels generated. Approximately 90% of this produced water was disposed of in the Inyan Kara. In August 2015, there were 435 active SWD wells in North Dakota, 412 of these are Dakota Group/Inyan Kara wells (Fig. 12). The amount of produced water generated from 2005 to 2015 was nearly three times the amount generated in the preceding decade (Figs. 11 and 12).

Future of Produced Water in North Dakota

North Dakota produced its three billionth barrel of oil in January 2015 (NDIC, 2015) and it is estimated that four billion barrels will be achieved by 2018. That is four billion barrels or more of produced water to deal with since the 1950s; over 220 billion gallons, enough water to supply the 19 million people of the New York metropolitan area for one year. Of course, this water is not drinkable, and because 98% of produced water from onshore wells is injected back into the subsurface (Clark and Veil, 2009), operators in North Dakota will need to have new, innovative, and environmentally sound practices in managing produced water disposal.

In support of this effort, the NDGS is preparing a series of Inyan Kara isopach maps and cross-sections (Fig. 13) to help operators identify ideal locations for SWD wells in North Dakota. These publications show Inyan Kara injectable sandstone thicknesses and trends that can be used with supporting data and road maps to identify potential well locations. These maps and cross-sections are extremely useful because Inyan Kara sandstone trends are very unpredictable, going from hundreds of feet of continuous sandstone to virtually nothing over a distance of only a few thousand feet (roughly 600 m). These maps and cross sections will assist in the disposal of produced water in North Dakota for many decades to come.



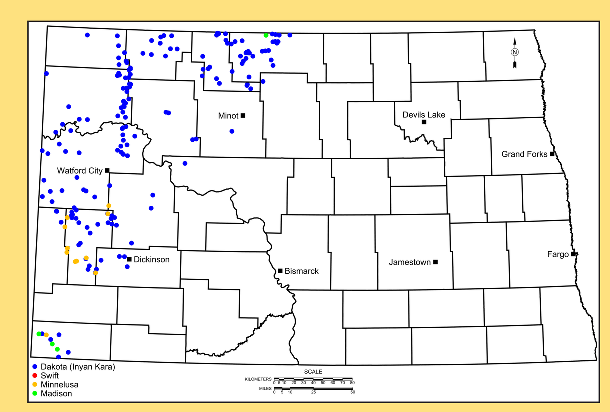


Figure 11.
Active saltwater disposal wells in North Dakota, January 2005.

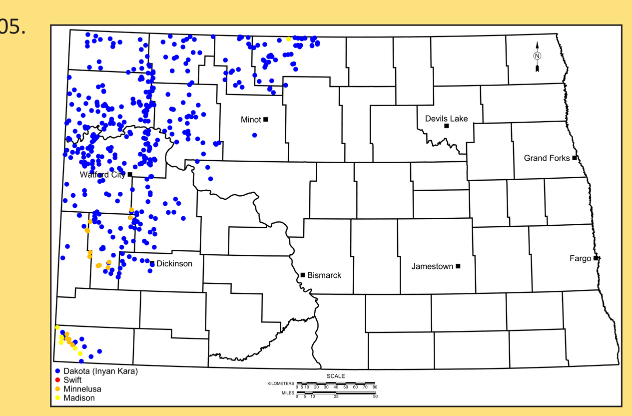


Figure 12.
Active saltwater disposal wells in North Dakota, August 2015.

INYAN KARA SANDSTONE - ISOPACH INTERVALS (feet)

300–250, 250–200, 200–150, 150–100, 100–50, 50–0

CONTROL WELL TYPES/RESERVOIR QUALITY

- Well - Sandstone > 100 ft., < 5% very fine sand to silt, and/or laterally continuous
- Well - Sandstone 50-100 ft., 5-10% very fine sand to silt, and/or laterally continuous
- Well - Sandstone 5-50 ft., 10-20% very fine sand to silt, and/or laterally discontinuous
- Well - Sandstone 0-5 ft., > 20% very fine sand to silt, and/or laterally discontinuous

AVERAGE MONTHLY INJECTION (barrels/one pound per square inch)

- Active SWD Well: > 150 bbls/psi
- Active SWD Well: 50-150 bbls/psi
- Active SWD Well: < 50 bbls/psi
- Inactive SWD Well: > 150 bbls/psi
- Inactive SWD Well: 50-150 bbls/psi
- Inactive SWD Well: < 50 bbls/psi

Culbertson	Williston	Stanley
Sidney		Parshall
Glendive	Grassy Butte	Killdeer

Adjoining 100K Maps

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Figure 13.
Inyan Kara sandstone isopach map and cross-sections, Watford City 100K Sheet, North Dakota (Bader, 2015).