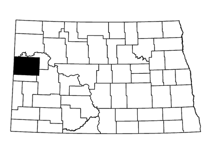
North Dakota Geological Survey
Geologic Investigation No. 189

Edward C. Murphy, State Geologist
Lynn D. Helms. Director Dept of Mineral Resources

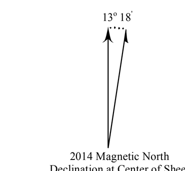


Inyan Kara Sandstone Isopach Map

Watford City 100K Sheet, North Dakota

Culbertson	Williston	Stanley
Sidney		Parshall
Glendive	Grassy Butte	Killdeer

Adjoining 100K Maps



Jeffrey W. Bader
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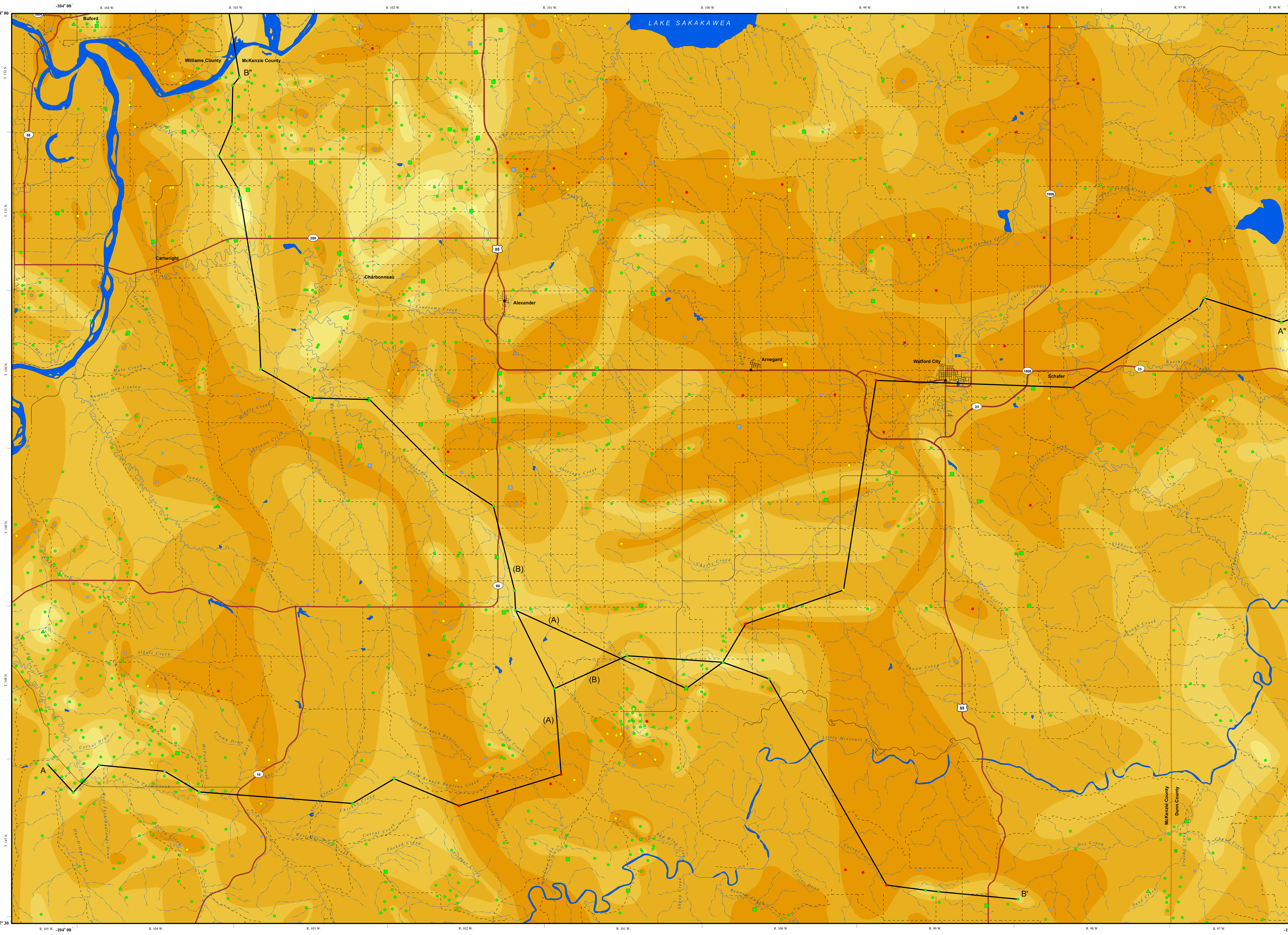


INTRODUCTION

Significant volumes (> 1-million barrels/day) of co-produced water are generated daily during production operations for oil and gas in North Dakota. Most produced water is brine (saltwater), with very high concentrations of total dissolved solids. Produced water has historically been considered a waste in the oil and gas industry. Subsurface injection is the industry-preferred alternative for produced water disposal. Because produced water is brine, produced water disposal wells are referred to as saltwater disposal wells (SWD wells).

THE DAKOTA GROUP

Geology of the area is the major factor in determining if injection is a viable option for produced water disposal. North Dakota's Williston Basin has an ideal sequence of geologic units (Dakota Group) present at an optimal depth for produced water disposal. The Lower Cretaceous Dakota Group consists of four formations in descending order (see Cross-Sections A-A' and B-B').

- Mowry Formation - marine shale
- Newcastle Formation - marginal marine sandstone
- Skull Creek Formation - marine shale
- Inyan Kara Formation - marginal marine and non-marine sandstone and shale

Overlying the Dakota Group are several thousand feet of Cretaceous marine deposits including the Pierre Formation, a very thick, impermeable shale. The Jurassic Swift Formation uncomformably underlies the Dakota Group and consists of up to 600 ft. (183 m) of marginal marine shale with interbedded limestone. The Dakota Group is approximately 750 ft. (229 m) thick at depths of approximately 5,325-6,075 ft. (1,624-1,853 m) in the center of the Watford City 100K Sheet (WC-100K).

These Cretaceous and Jurassic units provide a complete succession of rocks for produced water injection. Of specific importance is the Inyan Kara Formation, which consists of sandstones and shales deposited in incised valleys along the coastline of the Cretaceous Western Interior Seaway. These valleys were cut by north-northwesterly flowing rivers that drained into the seaway from highlands in southern North Dakota, Minnesota, and Canada. The valleys formed as the Cretaceous seaway regressed from North Dakota twice over a period of approximately 10 million years. The seaway transgressed back into the area forming estuaries, and sands were deposited in the valleys as sea-level rose, again in two transgressive events. Eventually the sea completely flooded all of North Dakota and the overlying marine units were deposited.

Inyan Kara sandstones deposited in these valleys are thick, porous (20-30% porosity), and permeable (Darcy level) enough to accept the injected water and the lateral continuity of the units allows for injected water to move into the formation (see Cross-Sections A-A' and B-B'), especially along valley trends.

Although some lateral continuity is important, these units must have good seals above to protect shallow aquifers. The overlying Cretaceous shales provide such a seal and, along with the underlying Swift Formation, allow for excellent confining layers that will vertically contain injected brines within the Inyan Kara. The Inyan Kara is present only in the subsurface of the Williston Basin in North Dakota extending across most of the state. The formation ranges in thickness from 275-300 ft. (84-92 m) in the west-southwest part of the WC-100K to 550-723 ft. (168-221 m) in a formational depocenter located in the Red Wing Creek field in the south-central part of the WC-100K.

ISOPACH OF INYAN KARA FORMATION SANDSTONES

This map presents thickness contours (isopachs) of interpreted injectable sandstone bodies present within the Inyan Kara Formation in the WC-100K. The map and associated cross-sections were constructed in order to identify favorable areas where the potential for encountering sandstone bodies for injection of produced water is greater. Geographical features such as roads and cities are also presented to better assist in well placement.

The map and cross-sections were prepared using wireline logs (gamma ray and resistivity) from 1,081 wells across the WC-100K that were available for interpretation and assessment of sandstone thicknesses and lateral continuity. Several valley trends (yellows), oriented to the north-northwest, can be identified on the map. In between these valleys, in the interfluve areas (darker brown), sandstones are thinner, much less continuous, and have lower porosity and permeability than incised valley sandstones. Therefore, interfluve sandstones are less desirable for injection of produced water.

Reservoir quality ranges using physical data (e.g., thickness, grain size) from each well are presented. Historic SWD well injection/pressure data from active and inactive SWD wells are also included.

INYAN KARA SANDSTONE - ISOPACH INTERVALS (feet)

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

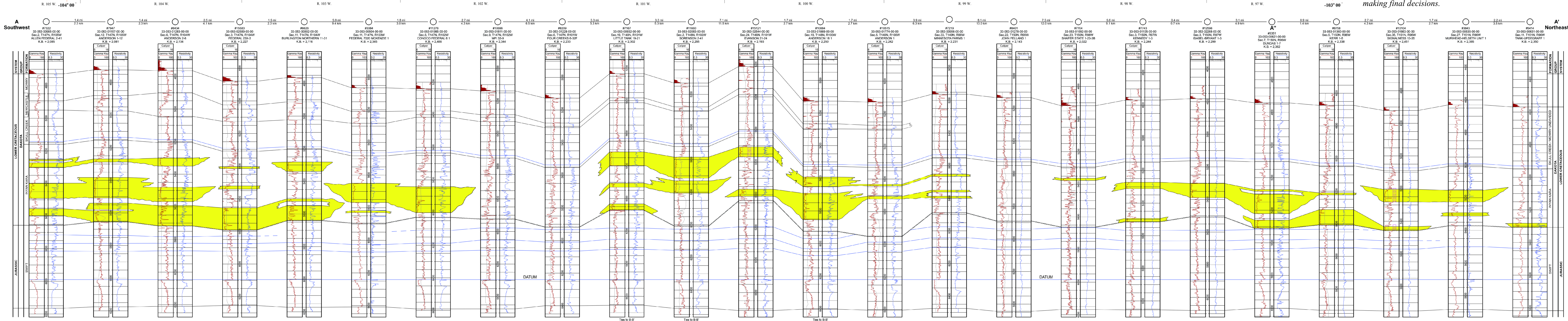
CONTROL WELL TYPES/RESERVOIR QUALITY

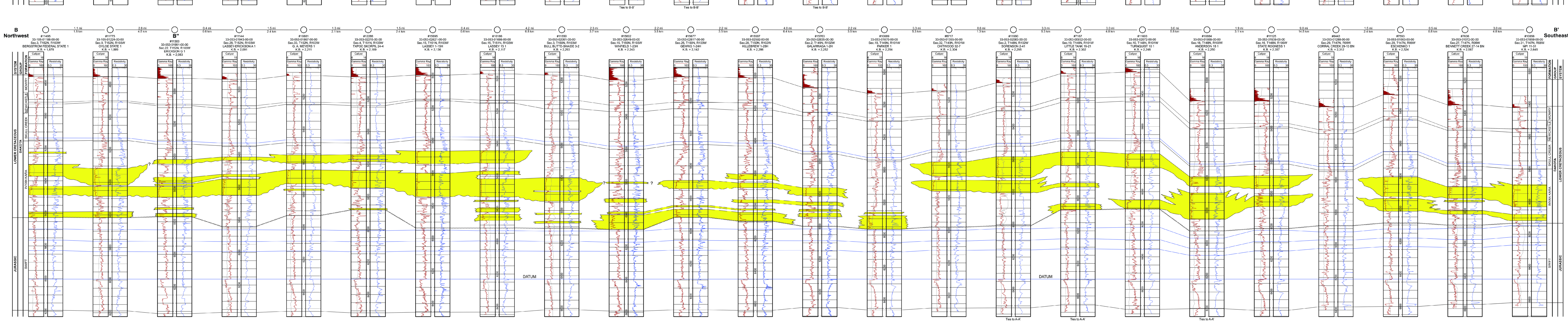
- Well/Sandstone > 100 ft < 5% very fine sand to silt, and/or laterally continuous
- Well/Sandstone 50-100 ft, 5-10% very fine sand to silt, and/or laterally continuous
- Well/Sandstone 5-50 ft, 10-20% very fine sand to silt, and/or laterally discontinuous
- Well/Sandstone 0-5 ft, > 20% very fine sand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

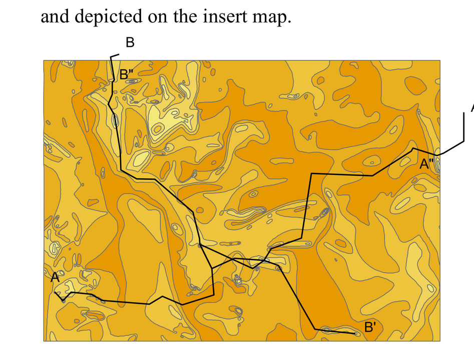
Control points are included with contour lines and cross-sections to assist the user in evaluating general trends of potentially injectable sandstone bodies. Please note, lateral variability of sandstones can be very great with thickness changes of hundreds of feet in less than 1/2 mile. Therefore, this map should be used only to verify areas of greater sandstone thickness/trends rather than absolute values, especially away from control points. Wireline logs in the area should be accessed and evaluated prior to making final decisions.





CROSS-SECTIONS

In order to display incised valley geometries in cross-section, it was necessary to extend A-A' into the adjacent Parshall 100K Sheet and B-B' into the Williston 100K sheet as detailed below and depicted on the insert map.



Cross-Section Vertical Scale: .75 inches = 200 feet

EXPLANATION

- Correlation Line
- Correlation Line - Uncertain
- Correlation Line - Inferred
- Correlation Marker Horizon
- Unconformity
- Sandstone Body
- Active Salt Water Disposal Well Perforated Interval

Other Features

- City
- Water
- River/Stream
- Stream - Intermittent
- County Boundary
- Federal Highway
- State Highway
- Paved Road
- Unpaved Road

Map Scale 1:100,000

0 1 2 3 4
Miles

Mercator Projection — 1927 North American Datum
Standard parallel 47° 45' — Central meridian 103° 30'

Note: This map was expanded beyond the normal Watford City 100k Sheet to include an additional width of two miles to the Montana border.

Cartographic Compilation: Elroy L. Kadrmas
Drafting: Ken Urlacher