Mapping Sandstones of the Inyan Kara Formation for Saltwater Disposal in North Dakota

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Introduction

The North Dakota Geological Survey (NDGS) is performing a detailed state-wide investigation of the Inyan Kara Formation (Dakota Group) to support industry needs for underground disposal of produced water. Sandstones of the formation are the primary subsurface injection zone for produced water in North Dakota. Produced water is the salty formation water that is generated as a by-product of oil and gas production. Over one-million barrels of co-produced water are generated daily during production operations in North Dakota. Subsurface injection is the industry-preferred alternative for produced water disposal. Therefore, because of the prodigious volumes of saltwater generated, and the economics of such disposal, it is important to fully understand the variables involved in selecting locations for saltwater disposal wells. These variables would include access; proximity to producing/future exploration wells; and most importantly, geology. To assist with well placement, the NDGS is preparing detailed isopach (thickness) maps at scales of 1:100,000 (100K), utilizing data from thousands of wells per 100K sheet to help industry better understand sandstone trends of the formation. Such detail is necessary because Inyan Kara sandstone thicknesses can change quickly, going from hundreds of feet of continuous sandstone to virtually no sandstone over a very short distance (< 0.5 mile). Cross-sections are also included to help operators visualize the lateral complexity of the sandstone geometry.

Inyan Kara Depositional Setting

Before any mapping program can begin, one must understand the geology, especially for subsurface mapping where the rocks may not be available for study. This is particularly true for the Inyan Kara, because the depositional environment is complex and only a few subsurface cores are available.

Inyan Kara sediments were deposited in a coastal setting adjacent to the Cretaceous Seaway from approximately 115 to 105 million years ago (fig. 1). The unit marks the beginning of the initial sea-level rise of the Early Cretaceous. At this time, North Dakota was at latitudes that were much more humid and tropical, and dinosaurs roamed the broad/low relief coastlines. Numerous rivers flowed across the coastal plain to the sea (fig. 1). Sea-level variations caused shoreline shifts; with the coastline moving landward during transgression, and seaward during regression. Major sea-level fluctuations occur due to tectonic events such as uplift of mountain ranges, or global sea-level changes based on water volume in the oceans, or both; combining for a net relative change in sea level. Inyan Kara sediments were deposited over western North Dakota during two of these transgressive/regressive cycles as relative sea-level fluctuated. Sedimentation along the shoreline was complex, consisting of estuaries (drowned river valleys), that formed as the encroaching sea filled valleys that were cut by rivers flowing towards the retreating sea during the previous fall in relative sea-level.

Sequence Stratigraphy

Sequence stratigraphy, the study of stacking packages within sedimentary rocks and the surfaces that separate them, was developed for just such coastal, cyclic depositional settings as described above. The sequence stratigraphic surfaces are generated by changes in relative sea-level, and can be consistently recognized in rocks, both in core and on geophysical logs making them very useful in identifying the best sandstones for produced water injection.

Figure 1. Paleogeographic map of the North Dakota area during Inyan Kara time (c.a., 106 Ma). Modified from Blakey (2014).

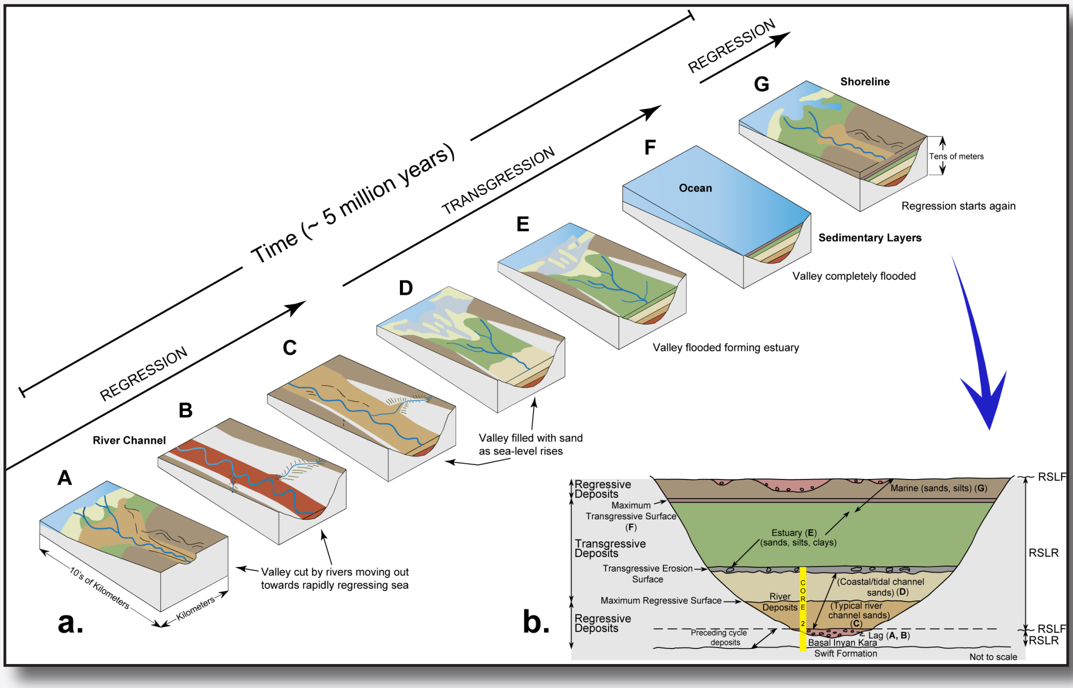

Figure 2. Block diagrams showing evolution of a typical incised valley at a transgressive river mouth (2a) and associated cross-section (2b). RSLF = Relative Sea-Level Fall, RSLR = Relative Sea-Level Rise.

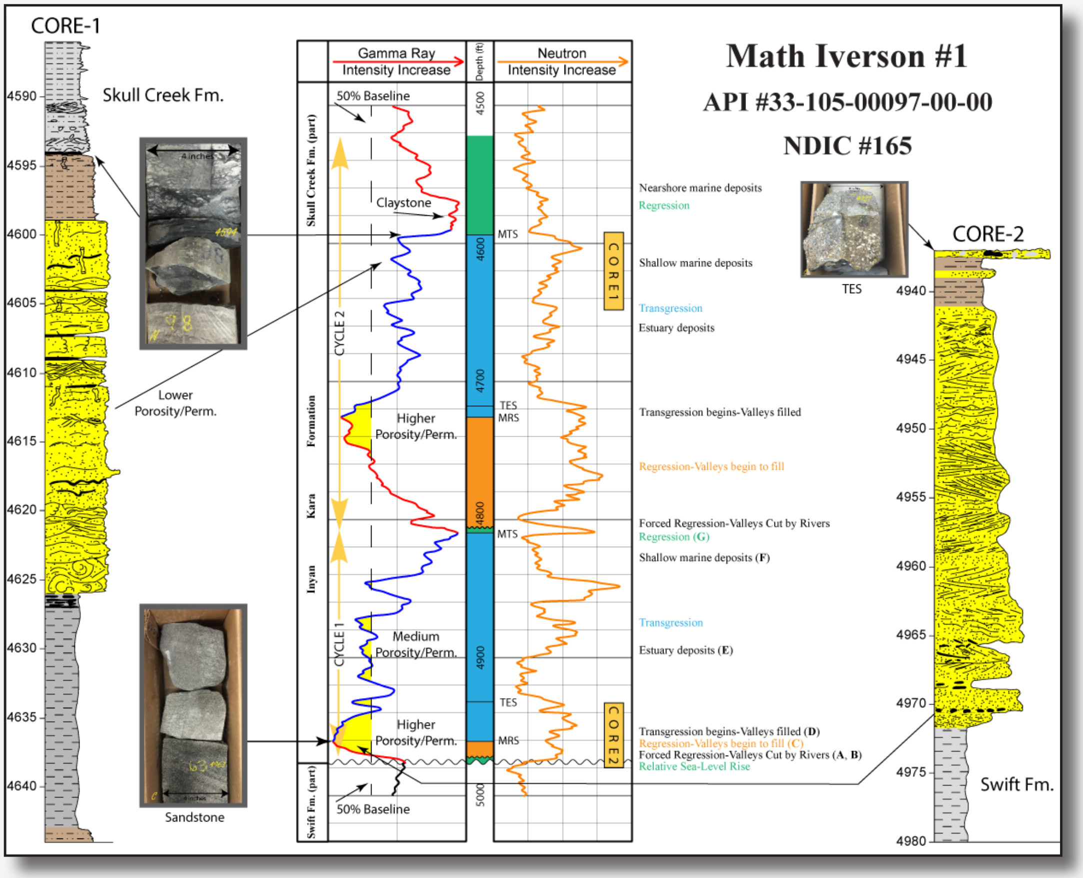

Figure 3. Geophysical well logs from the Math Iverson #1 well, Williams County, North Dakota, showing incised valley and valley fill deposits of the Inyan Kara Formation. Bold letters (A-F) correspond to figure 2a. MTS = Maximum Transgressive Surface, MRS = Maximum Regressive Surface, Perm. = Permeability, TES = Transgressive Erosion Surface

One typical evolution cycle for an incised valley deposit is shown on figure 2a. The Inyan Kara was deposited, along with the lower portion of the overlying Skull Creek Formation in two of these cycles (fig. 3). Each cycle records the movement of the shoreline through regressive, transgressive, and regressive events. The following discussion is for one cycle that takes place over a very long time period of millions of years, as shown on figure 2a. Early in the initial regressive phase, sea-level is dropping rapidly; therefore, rivers on the coastline will move quickly towards the retreating sea, eroding the shoreline and the now exposed sea-floor shelf (fig. 2a-A/B). Sea-level then begins to rise late in the first regressive phase and the newly cut valleys are filled with sand (fig. 2a-C). As transgression proceeds, sea-level continues to rise and the valleys are filled with more sand until fully drowned forming an estuary (fig. 2a-D/E). The sea eventually floods the entire area at the peak of transgression (fig. 2a-F), and the process then starts over with another regression (fig. 2a-G). The corresponding sedimentary deposits are shown in a cross-section through the lower portion of an Inyan Kara incised valley found at subsurface depths of approximately 5,000 feet (fig. 2b), as interpreted from core and logs. The cross-section shows the various sedimentary deposits of sand (Layers C and D) that are mapped for produced water injection, and the location of a rock core that was taken from the Math Iverson #1 well located in Williams County.

The logs for the Math Iverson #1 well include both sequence stratigraphic cycles for the Inyan Kara/lower Skull Creek interval (fig 3). Because identifying sandstones with good porosity/permeability for injection is the goal of the mapping program, the gamma ray log is most useful. The gamma ray log is a good sandstone/shale indicator; it gives a strong radioactive signal for clayey sediments (high in radioactive minerals) and a weak signal for clean sands (low in radioactive minerals). The corresponding neutron log is a good porosity indicator, with increasing intensity for greater porosity. In addition, figure 3 shows Inyan Kara cores/photographs taken from the Math Iverson #1 well, with Core-2 that is also shown on figure 2b. The main sequence stratigraphic surfaces shown on the log are the maximum regressive surface (MRS) and the maximum transgressive surface (MTS) that are also shown on figure 2b. The inflection (right to left/red and left to right/blue) of the gamma ray log changes at each of these surfaces and represents the regressive/transgressive or transgressive/regressive transition. Therefore, if only logs are available, as is the case for most of North Dakota, one can still easily determine the nature of the sedimentary environment/sandstone quality (i.e., sand porosity/permeability), as described in the narrative on the right portion of the log and shown on figs. 2a and 2b. Thus, identification of sequence stratigraphic surfaces on logs allows for accurate mapping of sandstone bodies in the Williston Basin of North Dakota.

So why is all of this so important? Estuaries occupying incised valleys are ubiquitous along transgressive coastlines in modern environments and were likely so in the past (Dalrymple et al., 1992). Estuaries and incised valley deposits are complex because of the wide ranging and fluctuating depositional environments and processes that occur in a coastal setting. They are excellent sediment traps and, because deposition occurs in paleo valleys, they are commonly preserved. This is especially useful, not only for potential produced water reservoirs, but for oil and gas reservoirs in other sedimentary basins throughout the world. However, such deposits have not been well recognized in the rock record until the last few decades.

Mapping Process

Maps and cross-sections are prepared utilizing several logs (gamma ray, resistivity, and neutron density) and core to identify potential

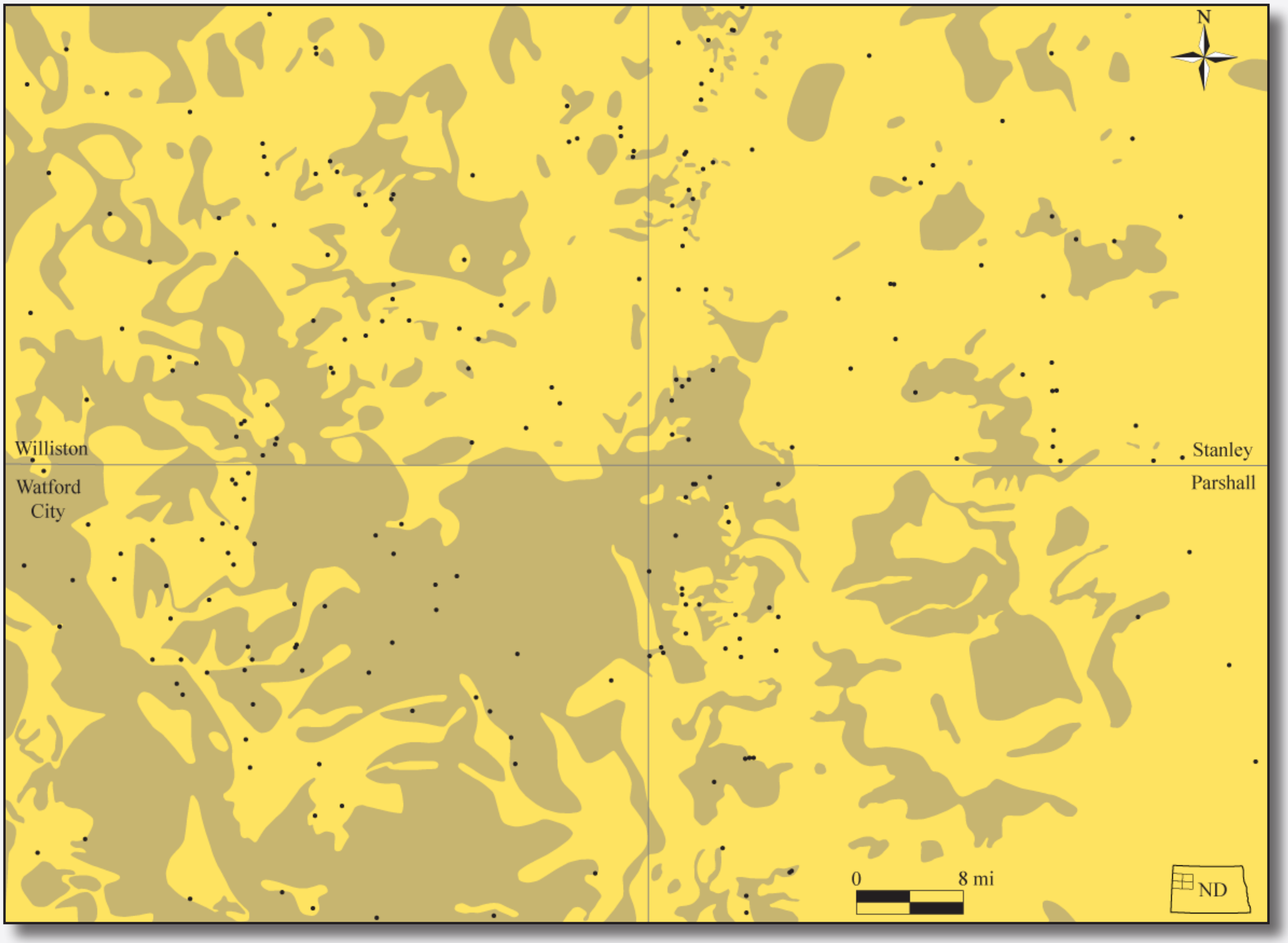

Figure 4. Generalized map showing Inyan Kara incised valley trends, Watford City 100K Sheet (Bader, 2015), Parshall 100K Sheet (Bader and Nesheim, 2016), Williston 100K Sheet (Bader and others, 2016a), and Stanley 100K Sheet (Bader and others, 2016b), North Dakota. Yellow = thicker sandstone; brown = thinner sandstone. Black dots are operating saltwater disposal wells as of January 2017.

Inyan Kara injectable sandstone bodies that can be mapped (fig. 3). Thousands of individual well logs are reviewed in a database and individual injectable sandstone bodies are identified. A consistent method with a 50% baseline is used so that each well is evaluated the same and biases are minimized. Sandstones above the 50% baseline are considered injectable sandstones (yellow zones on figure 3). Totals are computed for the entire formation and an isopach map is created for each 100K. Cross-sections are then prepared, so that sandstone trends can be accurately depicted in two dimensions. Understanding the depositional environment is critical in the mapping stage, because lack of such knowledge can easily lead to complete misinterpretation of the data. Four 100K maps (Parshall, Stanley, Watford City, and Williston) have been published to date, with another 4-6 maps planned for 2017; thus, covering the entire core area for Bakken drilling in western North Dakota.

Results

Inyan Kara sandstones deposited in incised valleys are thick, porous (20-30% porosity), and permeable (Darcy level) (fig. 3), especially along valley trends. Several distinct north-northwest-trending valleys (yellow) can be identified in the Parshall, Stanley, Watford City, and Williston, 100K Sheets, where thicker sandstones have been deposited (fig. 4). Between these valleys, in the interfluve area, sandstones are thin (brown), much less continuous, and have lower porosity/permeability than incised valley sandstones, so they are not optimal for injection of produced water. Even within the estuarine/valley-fill complex, estuarine sandstones that overlie valley-fill sandstones may have a relatively low gamma response indicating good sandstone on one log, but further correlation will show that such sandstone is not laterally continuous or porous/permeable as incised valley sandstones (fig. 3). Therefore, the use of a few logs to identify sandstones without an understanding of sequence stratigraphy principles can be risky.

There are 251 active disposal wells in the map area (fig. 4). Many saltwater disposal wells are drilled in areas of thinner to marginally thick sandstones and areas of thicker sandstones have only been locally utilized, with sandstones greater than 200 feet underutilized. This indicates that other factors such as access may have been more of an influence than geology when selecting saltwater disposal well drilling locations in the past. Although access and proximity are very important, the geology of the saltwater disposal well will obviously be the main factor in having a good injection well, and should be given careful thought because of the prodigious volumes of water being injected into the Inyan Kara. Detail of an incised valley and the interfluve area in the northern portion of the Watford City 100K is shown on figure 5. Daily saltwater disposal rates are shown for comparison. Channel sandstones within the valley take on thousands of barrels per day, whereas sandstone outside the valley in the interfluve area receives well under 1,000 barrels per day. Historically, only 10% of saltwater disposal wells have been placed in thicker channelized areas.

The production of the NDGS 100K series maps will allow operators to use sandstone thicknesses and trends, along with supporting data and road maps, to identify potential well locations for years to come. This will help minimize potential problems from developing during the injection process, such as the well not taking on water and/or development of over-pressured zones in the Inyan Kara that can have significant adverse effects on new exploration wells in the area. Accurate data generated from the mapping process is also fundamental input for developing models that simulate injection processes and volumes in three dimensions for future planning and exploration purposes.

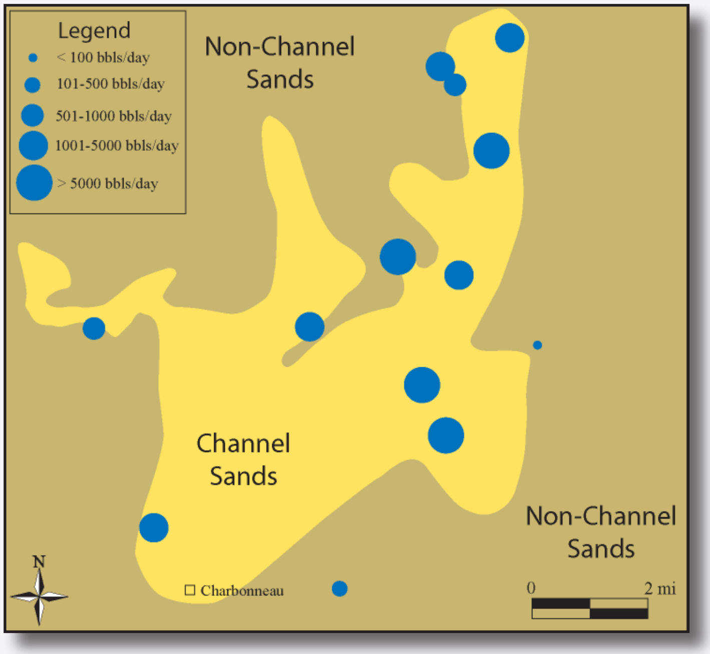

Figure 5. Detail of incised valley sandstone deposits with daily saltwater disposal rates, northern Watford City 100K. Circles are operating saltwater disposal wells. bbls = barrels.

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