North Dakota Geological Survey
Geologic Investigation No. 193
Plate I

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

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2016

Abstract

The Inyan Kara Formation of northwestern North Dakota is the lowermost unit of the Lower Cretaceous Dakota Group. The formation does not crop out within the state and limited core is available for study. The formation is the primary subsurface injection zone for produced water where over a million barrels/-day is injected. This work examines the subsurface stratigraphy of the Inyan Kara within McKenzie/Williams counties as part of a statewide investigation to identify potential areas for produced water injection. A partial core from the Amerada Petroleum Corporation, Math Iverson #1 (NDIC: #165, API: 33-105-00097-00-00) was used along with wireline logs from numerous wells to develop a working sequence stratigraphic model.

Numerous sedimentary structures and sequence stratigraphic surfaces are observed in both core and on logs. Gamma-ray signatures from well logs are characterized by a distinct, blocky pattern for coarser-grained sandstone deposits, commonly over 100 feet thick. These sandstones then grade upwards into finer-grained units of interbedded sand, silt, and clay. Based on these observations, the Inyan Kara can be subdivided into two units that reflect the overall sea-level rise of the Early Cretaceous. The lower half is interpreted to be a “fluvial” dominated, incised valley-fill complex that can be sub-divided into the following systems tracts: 1) initial incising of the lowermost valley during falling stage; 2) filling of the valley during low-stand and early transgression; 3) initial incursion of the seaway with subsequent flooding and development of estuarine deposits during transgression; and 4) progradational marine deposits of the high stand. This same depositional sequence is repeated in the upper Inyan Kara and into the overlying lower shales of the Skull Creek Formation, with the lower sequence capped by a subaerial unconformity.

The model shows coastline evolution through time and correlation of sequence stratigraphic surfaces basinward/landward from northwestern North Dakota. It can be used to predict the presence and extent of incised-valley-fill sandstone bodies for produced water disposal, as well as distinguishing such bodies from other coarser-grained units that have lesser potential for injection. Initial results indicate that sandstones of the valley-fills are well connected along valley trends (10’s of km) and within valleys (km); whereas, coarser deposits of the estuarine, marginal marine, and interfluve facies are not as laterally continuous or well connected.

Introduction

The Lower Cretaceous Inyan Kara Formation (Dakota Group) is the primary subsurface injection zone for produced water in North Dakota (Fig. 1). In support of produced water disposal operations in industry, the North Dakota Geological Survey (NDGS) is studying the Inyan Kara in detail across the entire State of North Dakota. This poster is based on initial work in northwestern North Dakota (McKenzie and Williams counties) where Inyan Kara cores are present and thousands of well logs are available for study. The focus of this report is on the Math Iverson #1 (Williams Co.) well as it has one of the few quality Inyan Kara cores in the state. Well logs from hundreds of wells were then evaluated across the state to develop a sequence stratigraphic model.

The Inyan Kara Formation consists of sandstones and shales deposited in incised valleys along the coastline of the Cretaceous Western Interior Seaway (Figs. 1, 2, 3, and 4). 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 withdrew (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 (Figs. 1 and 2).

Inyan Kara sandstones deposited in these valleys are thick, porous (20-30% porosity), and permeable (Darcy level) enough to accept the injected water. The lateral continuity of the units allows for injected water to easily move into the formation, especially along valley trends. Figure 1 shows a typical Class II injection well.

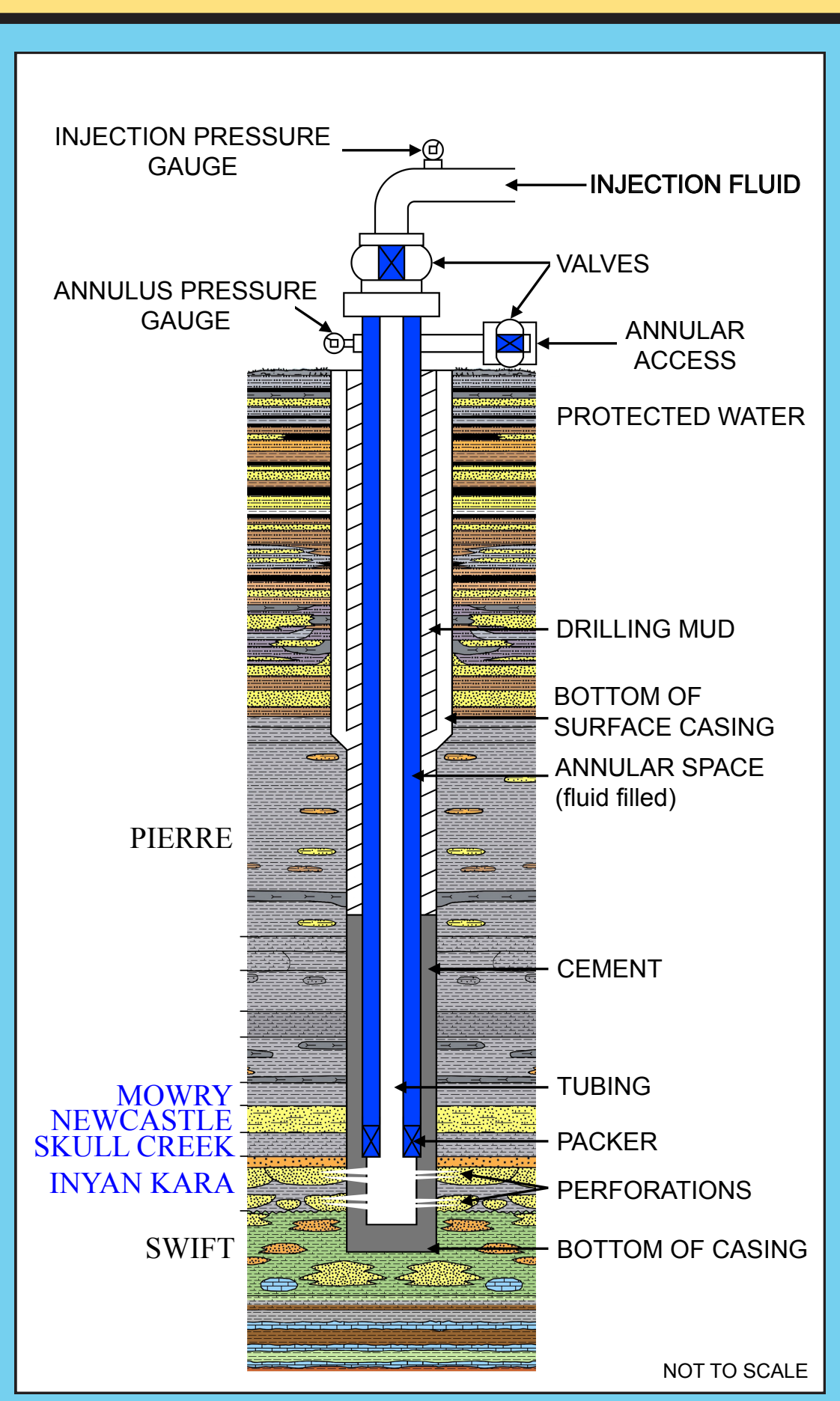


Figure 1.
Typical North Dakota Class II injection well schematic showing pertinent geologic units of northwestern North Dakota.

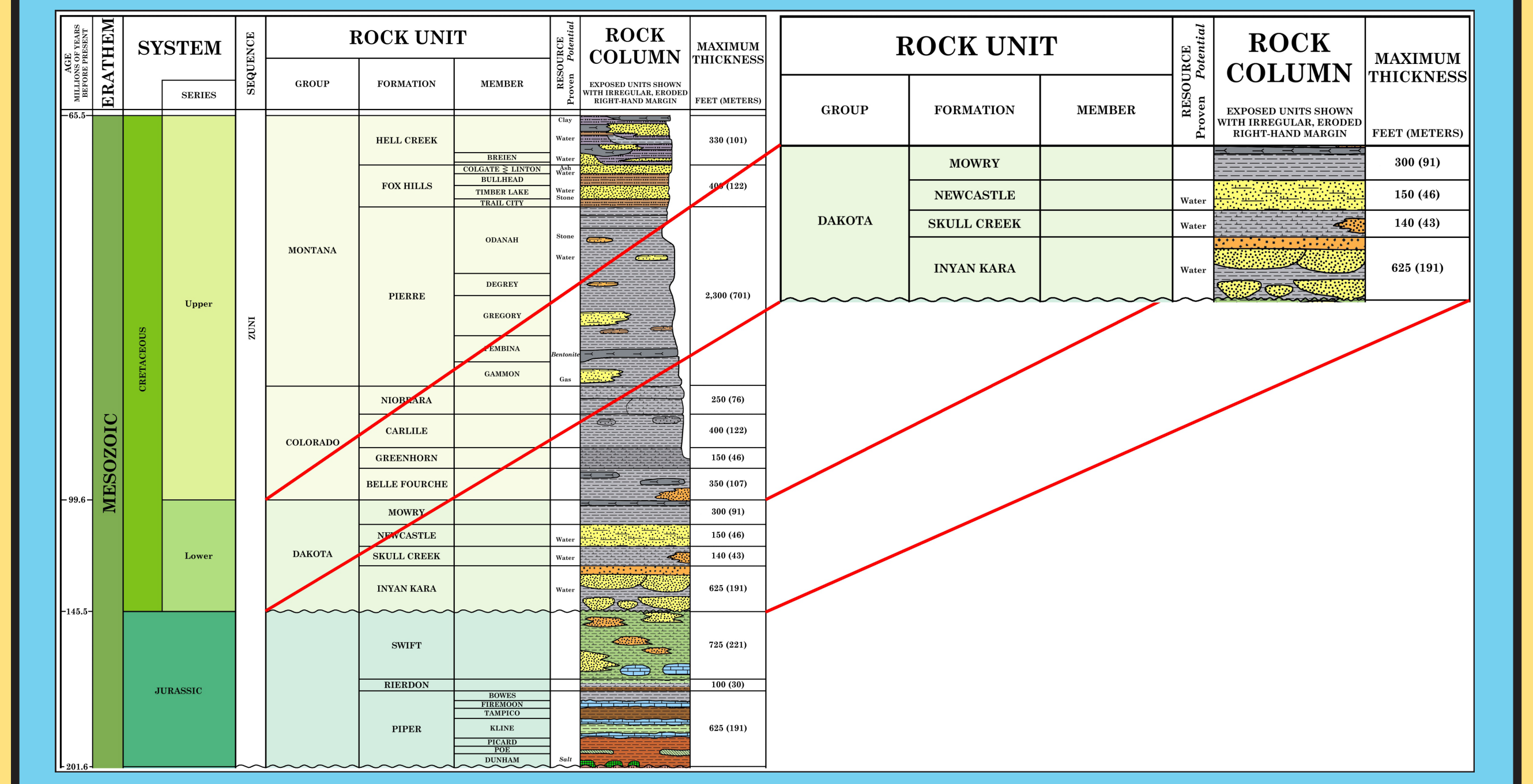


Figure 2.
North Dakota stratigraphic column showing the Lower Cretaceous Dakota Group (Murphy et al., 2009).

Figure 3.
Paleogeographic map of North Dakota area during Inyan Kara time (c.a., 106 Ma). Modified from Blakey, 2014.

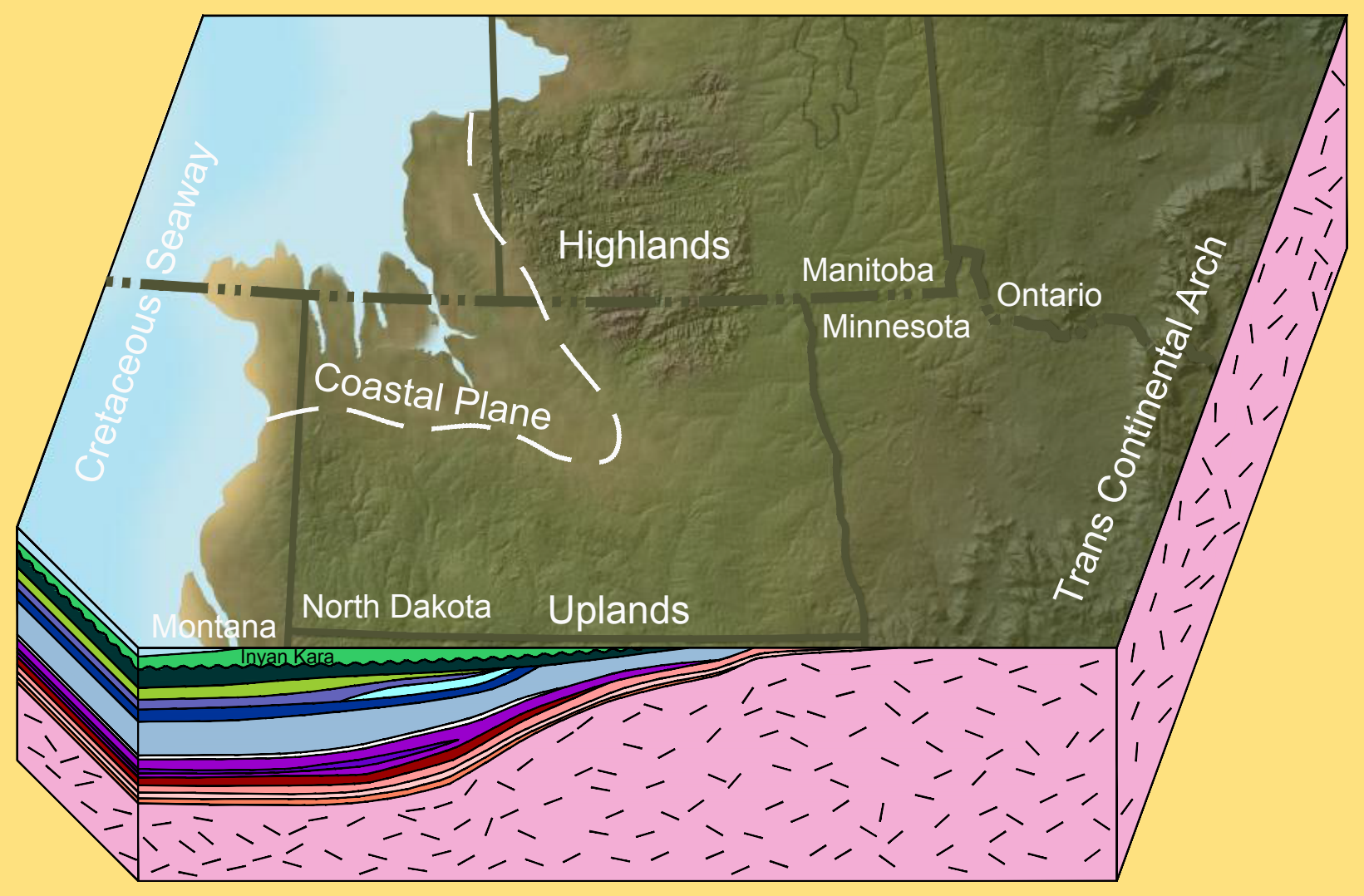
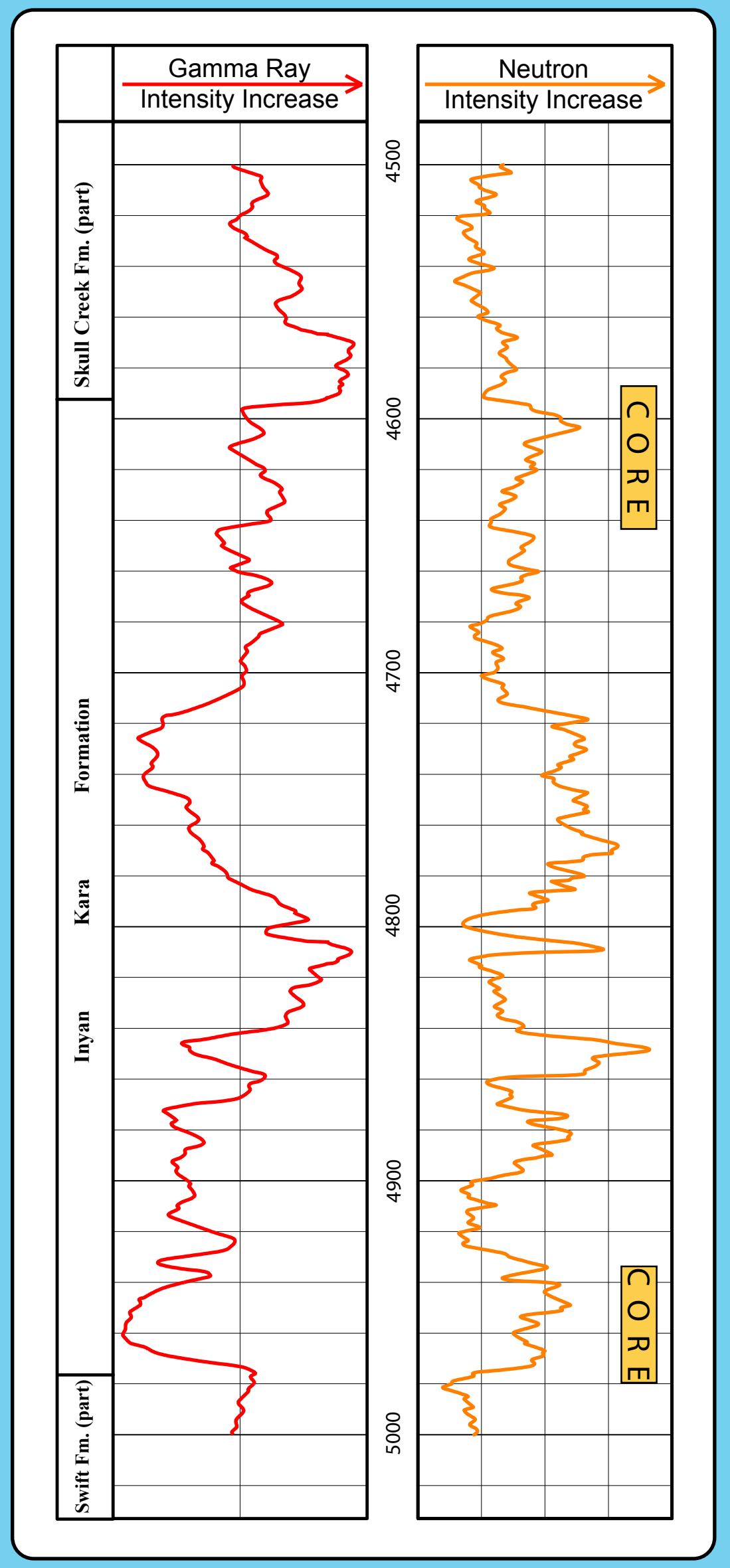


Figure 4.
Block diagram of North Dakota area showing paleogeography and geologic setting during Inyan Kara time (c.a., 106 Ma). Modified from Blakey, 2014.

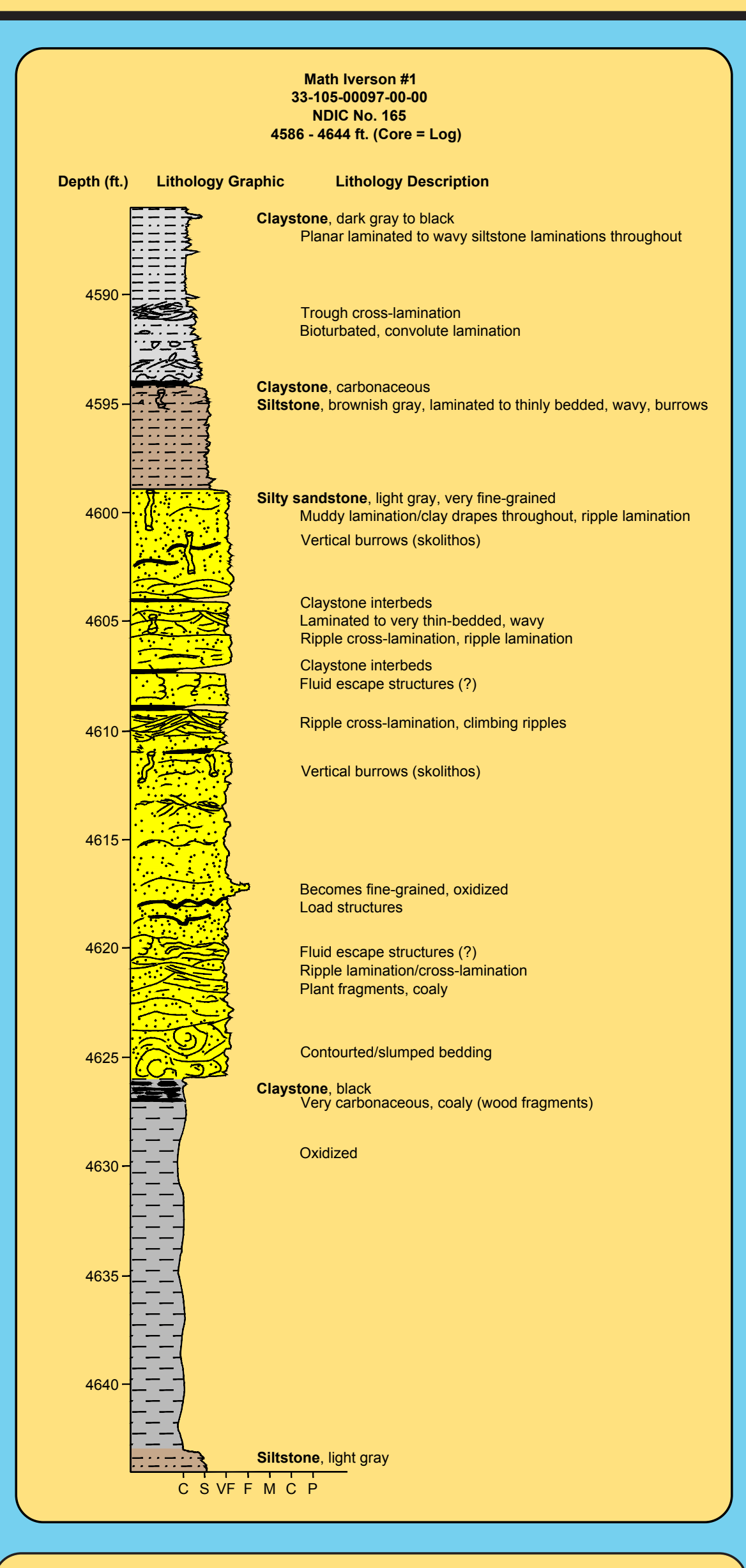
Keys to Study

- Core
  - Sedimentary structures
  - Sequence stratigraphic surfaces
- Logs
  - Over 4,000 wells in core area; hundreds across ND
  - Stacking patterns
  - Sequence stratigraphic surfaces
- Relative Sea-Level Curve (known model)
  - Sequence stratigraphic surfaces
  - Sequence stratigraphic systems tracts

Math Iverson #1
33-105-00097-00-00



- Kik @ 4,594’-4,972’
- Unconformable above Js
- Conformable below Ksc
- Core
  4,586’-4,644’
  4,937’-4,980’



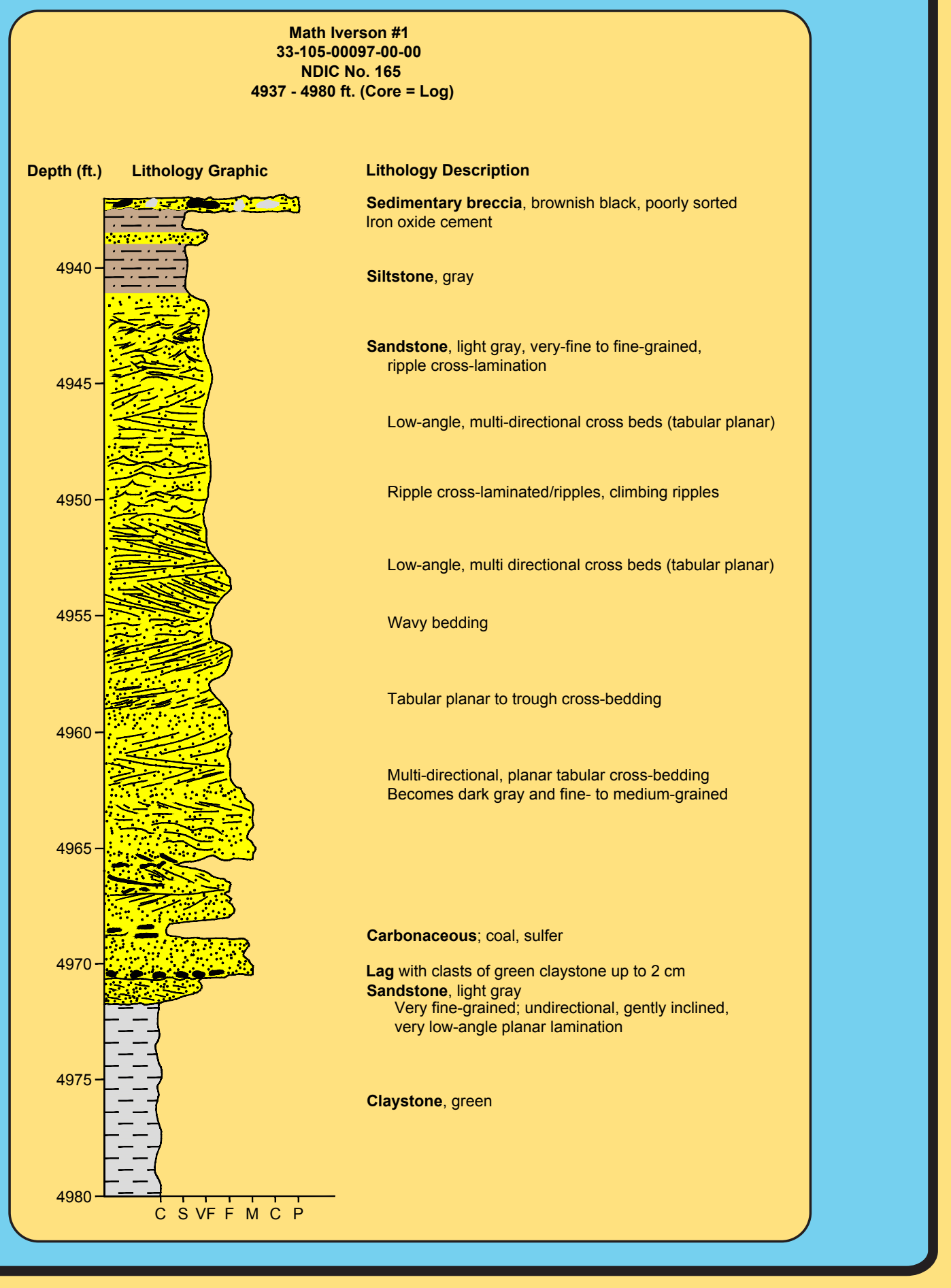


Figure 5.
Type log and core for study (Amerada Petroleum Corporation, Math Iverson #1, Williams County, SWNW Sec. 1, T.155N., R.96W.).
Js = Jurassic Swift Formation, Kik = Cretaceous Inyan Kara Formation, Ksc = Cretaceous Skull Creek Formation.

Model for Incised Valley Evolution at a Transgressive River Mouth

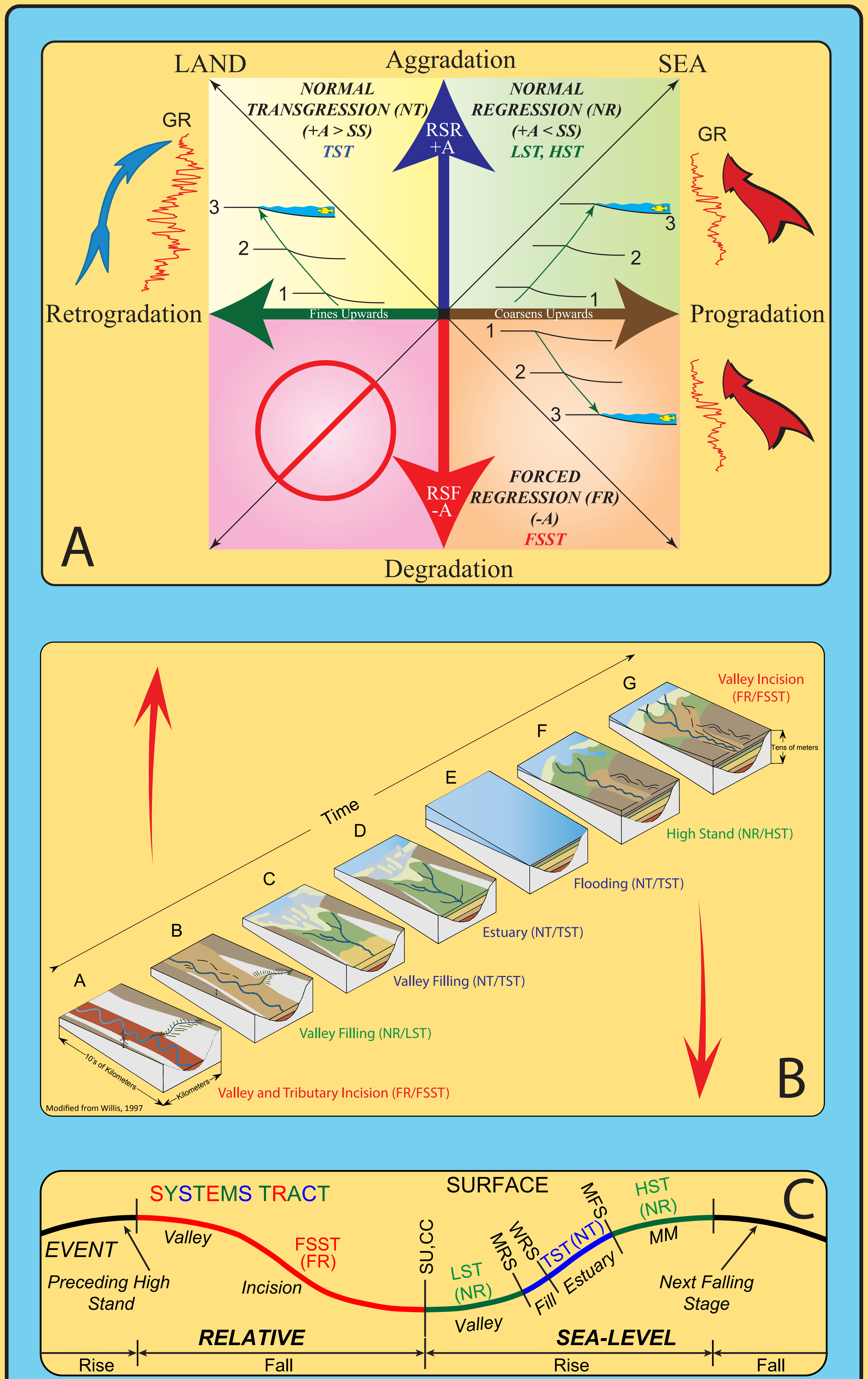


Figure 6.
Model for evolution of an incised valley at a transgressive river mouth. Figure 6A shows pertinent sequence stratigraphic principles related to sea-level rise/fall and the expected log/stacking patterns and associated systems tracts. Figure 6B shows evolution through time of incised valley system and associated system tracts/events. Figure 6C shows relative sea-level curve, systems tracts, anticipated sequence stratigraphic surfaces, and interpreted events for system. A = Accommodation Space, SS = Sediment Supply, FR = Forced Regression, NR = Normal Regression, NT = Normal Transgression, FSST = Falling Stage Systems Tract, HST = High Stand Systems Tract, LST = Low Stand Systems Tract, TST = Transgressive Systems Tract, RSR = Relative Sea-Level Rise, RSF = Relative Sea-Level Fall, CC = Correlative Conformity, MFS = Maximum Flooding Surface, MRS = Maximum Regressive Surface, SU = Subaerial Unconformity, WRS = Wave Ravinement Surface, MM = Marginal Marine.

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The Core

The Amerada Petroleum Corporation, Math Iverson #1 well was cored in the upper and lower portions of the Inyan Kara (Fig. 5). The core was accessed and described in detail at the NDGS Core Library. Lithology, sedimentary structures, and sequence stratigraphic surfaces were logged and then compared to well logs (gamma ray, resistivity, and neutron). The Inyan Kara in this well is characterized by two coarsening/fining upwards packages, as exemplified on the gamma-ray log and observed in core (Fig. 5). The deeper core (4,586-4,644 ft.) consists almost entirely of very fine- to medium-grained sandstone that unconformably overlies the Jurassic Swift Formation and represents the lower portion of the first coarsening/fining upwards package. The shallower core (4,937-4,980 ft.) shows an overall fining upwards sequence with a silty, bioturbated, very fine-grained sandstone sandwiched between finer-grained siltstone/claystone, of which the upper eight ft. is the conformably overlying Skull Creek Formation. The shallower core represents the upper portion of the second coarsening/fining upwards package.

Incised Valley Evolution

The Dakota Group of North Dakota has not been described in terms of sedimentary environments except in the most general sense, probably because the formation does not crop out in the state. However, studies by Willis (1997) of the Inyan Kara equivalent Fall River Formation in southwestern South Dakota suggest that the Inyan Kara of North Dakota may represent an incised valley complex that would have been present along the eastern margins of the Cretaceous Western Interior Seaway of South and North Dakota. The Math Iverson #1 core and log pattern are consistent with this interpretation and provide a type log/core for which a working hypothesis can be constructed and modeled (Fig.6). Because of the paralic nature of the Inyan Kara deposits, the unit presents an ideal succession of rock that can be interpreted using fundamental sequence stratigraphic principles related to relative sea-level rise/fall during the Early Cretaceous. In addition, the prodigious amounts of drilling in western North Dakota provides an unusually robust population of wells allowing for detailed stratigraphic correlation and evaluation. Utilizing sea-level curves and sequence stratigraphic principles, likely depositional environments and systems tracts can be anticipated and then compared to log stacking-patterns and core as shown on Figs. 6, 7, 8, and 9. Cores from the Math Iverson #1 show sedimentary structures and sequence stratigraphic surfaces consistent with deposition in an incised valley system. Overall, the Inyan Kara is characterized by two regressive/transgressive sequences that occurred after the initial sea-level rise in the Early Cretaceous.

Sequence Stratigraphy

Utilization of sequence stratigraphic principles is critical to understanding siliciclastic deposition and reservoir quality in paralic systems. Two full depositional sequences, from falling stage through high stand can be recognized on the Amerada Petroleum Corporation, Math Iverson #1 core/log (Figs. 8 and 9). Valley-fill deposits rest unconformably (SU) over previous high stand deposits (HST) in each sequence. The valley-fill deposits are both regressive (LST) and transgressive (TST) and separated by a maximum regressive surface (MRS) that can be seen on both log and in core. The transgressive valley-fill is capped by a transgressive lag deposit (WRS), which is in turn overlain by estuarine deposits (TST) that are capped by a maximum flooding surface (MFS). High stand deposits (HST) are at the top of each sequence and include the previously described Skull Creek deposits in the upper eight feet of the shallower core. This interpretation is consistent with sea-level curve and incised valley evolution models (Fig. 8B) and allows for a simple comparison of expected surfaces from the relative sea-level model to what is actually seen in core (Figs. 8A and 8C). In addition, major transgressive/regressive events recognized in paleogeographic models (Blakey, 2014) correspond to the various systems tracts identified in the study (Fig. 9).

Reservoir Characteristics

Permeability and porosity values for valley-fill sandstones are good to excellent as compared to other sandstone bodies (Fig. 9). Regressive valley-fill sandstones provide the best reservoir quality with Darcy level permeabilities and over 20% porosities, making them ideal for produced water disposal in North Dakota, as well as excellent oil and gas reservoirs in Canada and Wyoming.

The Model

Figure 10 presents an Inyan Kara sequence stratigraphic model that extends across the entire Williston Basin from southeast North Dakota into the Edmonton Valley of Alberta. The model uses sequence stratigraphic surfaces identified in the Amerada Petroleum Corporation, Math Iverson #1 (NDIC #165 on Fig. 10) core/log and extends them landward (SE) and basinward (NW) using sequence stratigraphic principles (shoreline and relative sea-level rise/fall diagrams) to depict evolution of the shoreline during Inyan Kara time. Select logs were reviewed in generation of the model and a few are included from SE North Dakota, where the Inyan Kara is completely fluvial in nature. Logs from Canada were also reviewed for development of the model. Two valley-fill packages can be observed on the model; the first extending nearly to Edmonton, Alberta, and the second only extending just across the U.S./Canada border. The extent of these valley fills mark the approximate extent of the maximum regressions during Inyan Kara time (Figs. 9A, 9D, and 10). Two falling stage events (I and II) are also depicted, showing both pre- and post-incision surfaces.

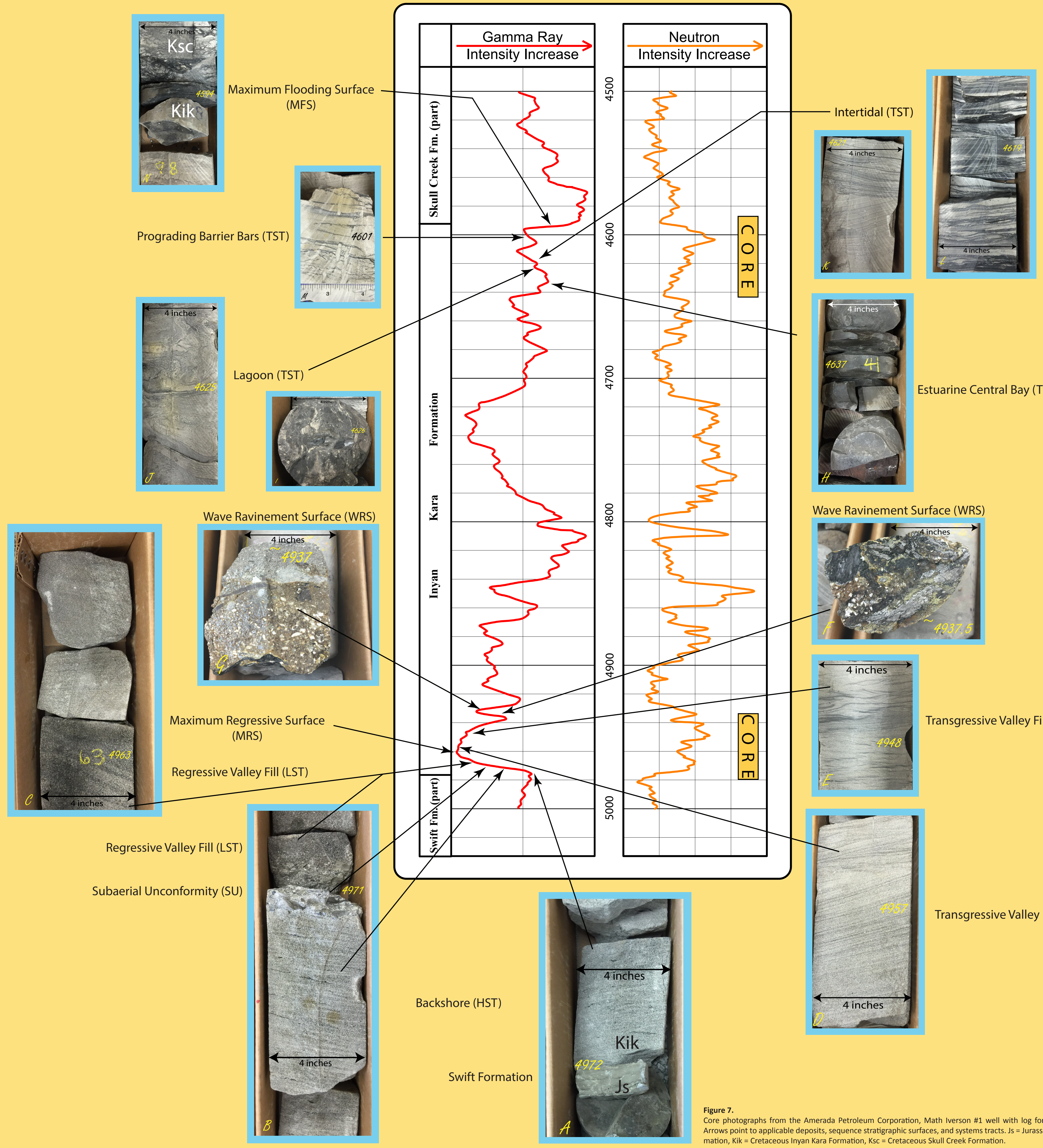

Figure 7.
Core photographs from the Amerada Petroleum Corporation, Math Iverson #1 well with log for reference. Arrows point to applicable deposits, sequence stratigraphic surfaces, and systems tracts. Js = Jurassic Swift Formation, Kik = Cretaceous Inyan Kara Formation, Ksc = Cretaceous Skull Creek Formation.

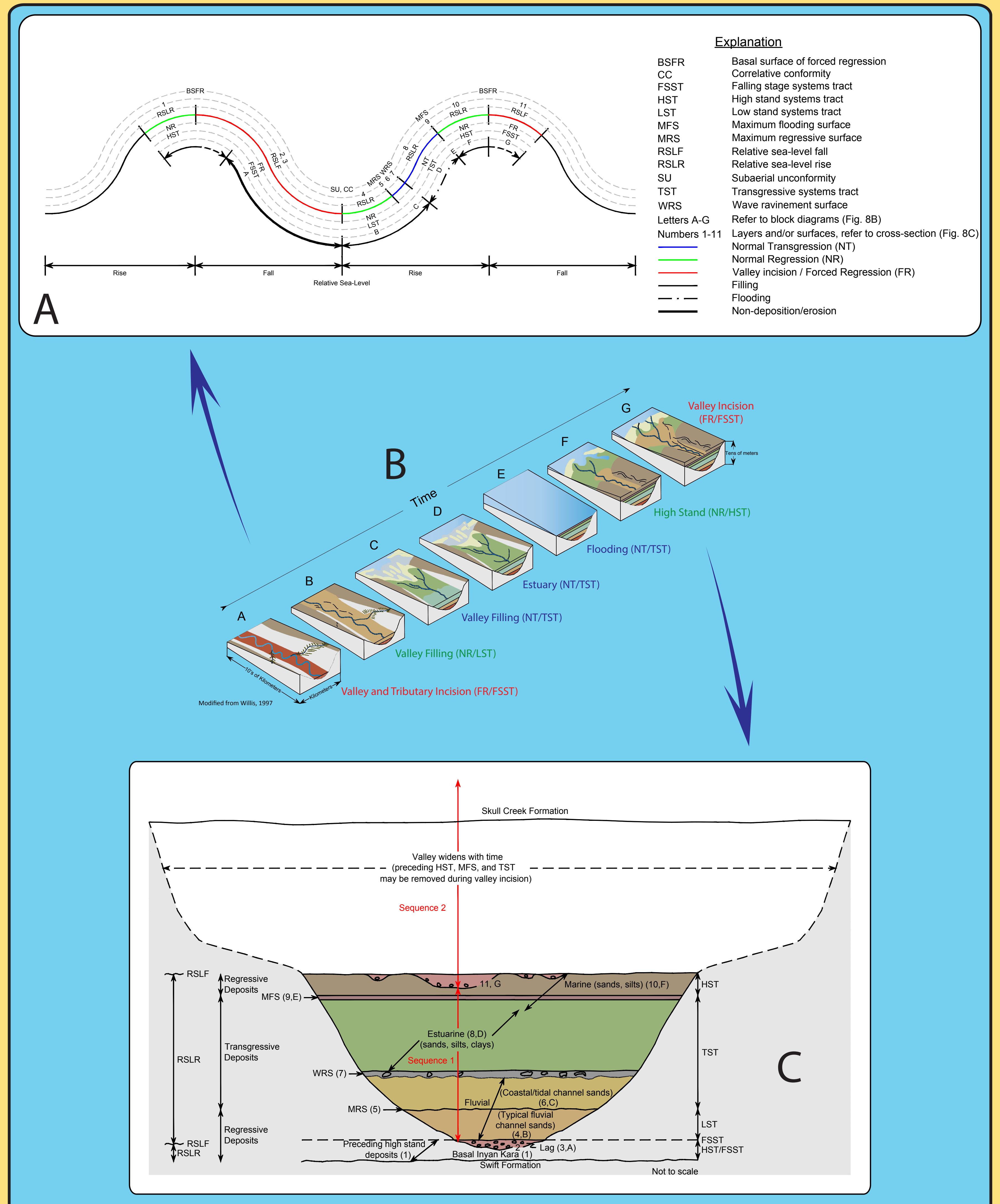

Figure 8.
Model for evolution of an incised valley at a transgressive river mouth (Fig. 8B) as compared to a detailed relative sea-level curve (Fig. 8A) and a graphic representation of the lower sequence of the Amerada Petroleum Corporation, Math Iverson #1 well (Fig. 8C). Letters A-G, refer to block diagrams (Fig. 8B); Numbers 1-11 are layers and/or surfaces, refer to relative sea-level curve (Fig. 8A).

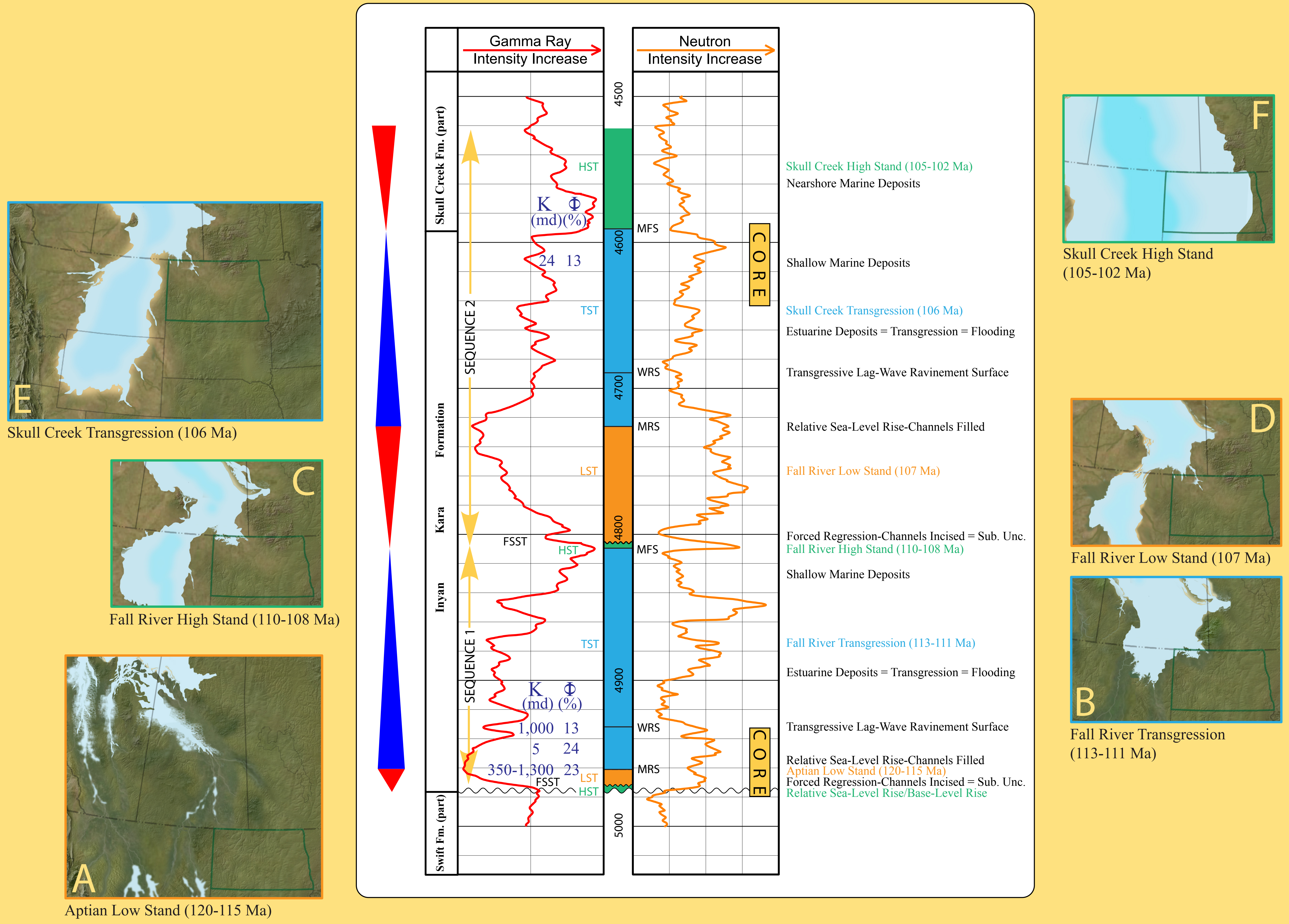

Figure 9.
Summary plate of the Amerada Petroleum Corporation, Math Iverson #1 well log showing sequence stratigraphic surfaces, system tracts, and sequence boundaries along with corresponding depositional events. Red (regression) and blue (transgression) triangle symbols are presented at the left for comparison. Paleogeographic images (Blakey, 2014) from major transgressive/regressive events (Figs. 9A-F).

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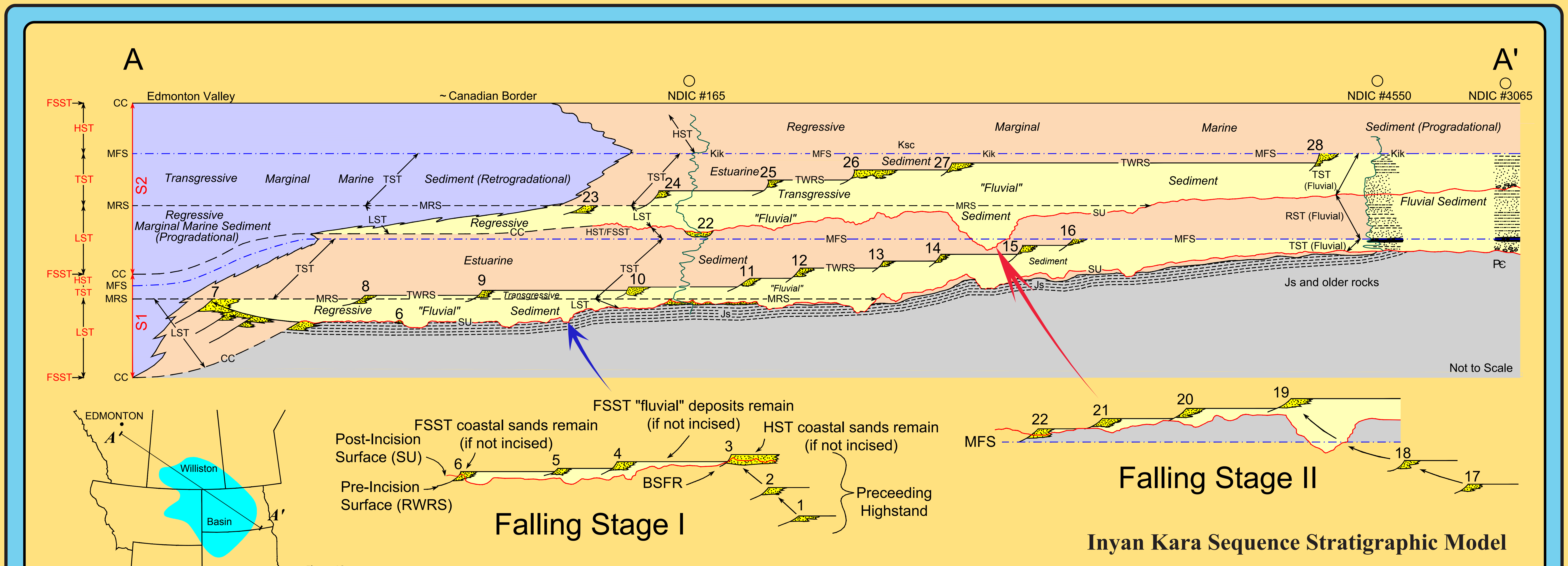


Figure 10.
Inyan Kara sequence stratigraphic model showing evolution of coastline through time (Numbers 1-28), sequence stratigraphic surfaces, systems tracts, and sequence boundaries. S1 = Sequence 1, S2 = Sequence 2, RWRS= Regressive Wave Ravinement Surface, TWRS = Transgressive Wave Ravinement Surface, 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.

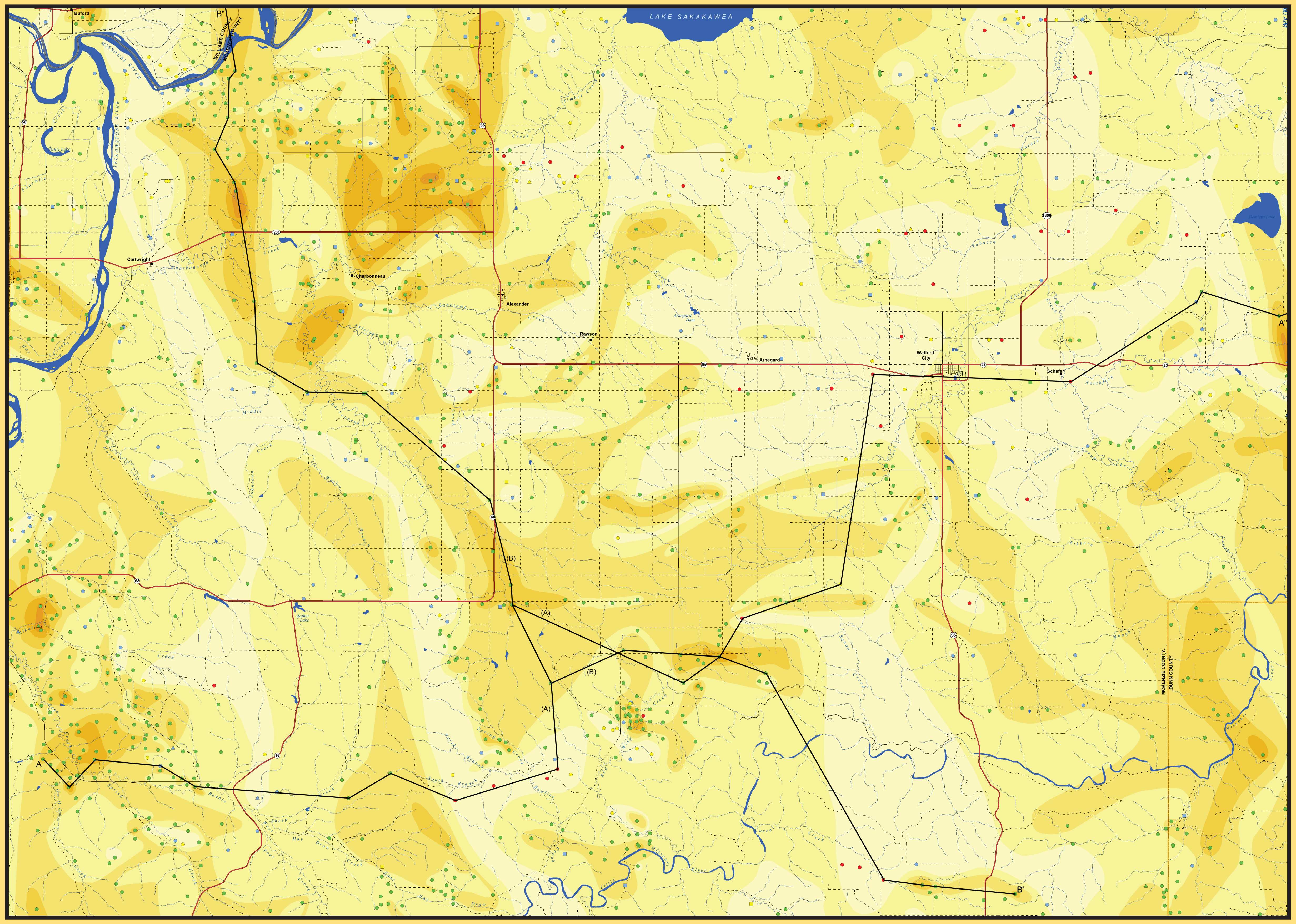
Prior to the development of hydraulic fracturing and refined horizontal drilling techniques, oil production in North Dakota was much less than it is today. During the years 1995-2005, North Dakota produced more than 320 million barrels of oil and over 670 million barrels of produced water. In 2005, 185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



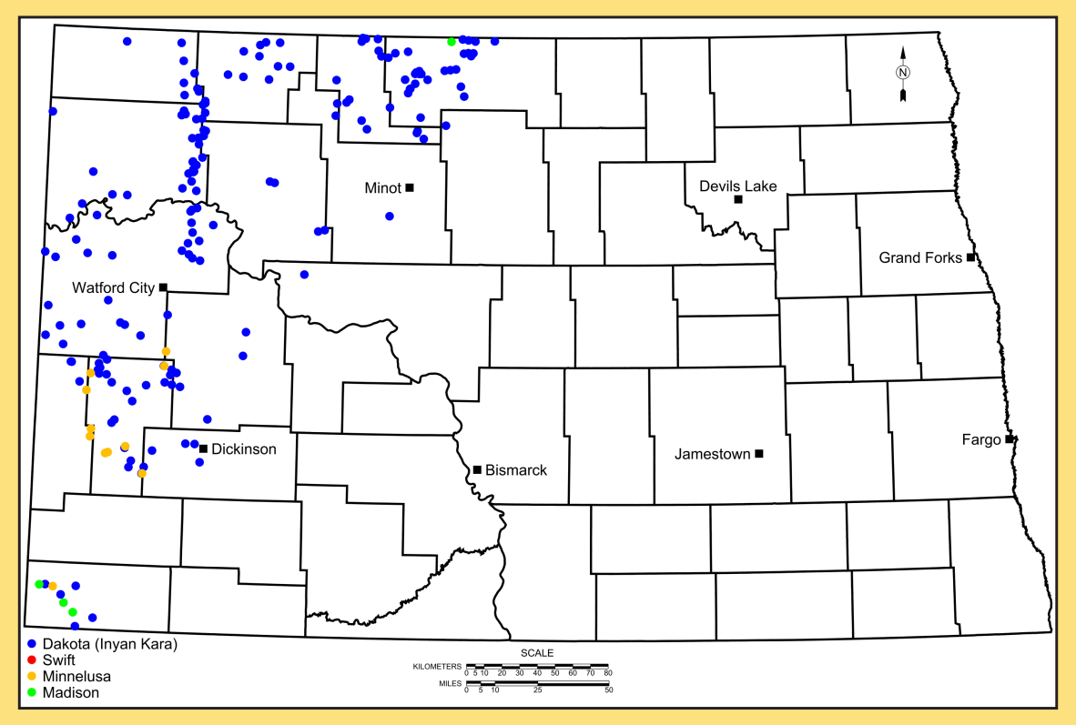


Figure 11.
Active saltwater disposal wells in North Dakota, January 2005.

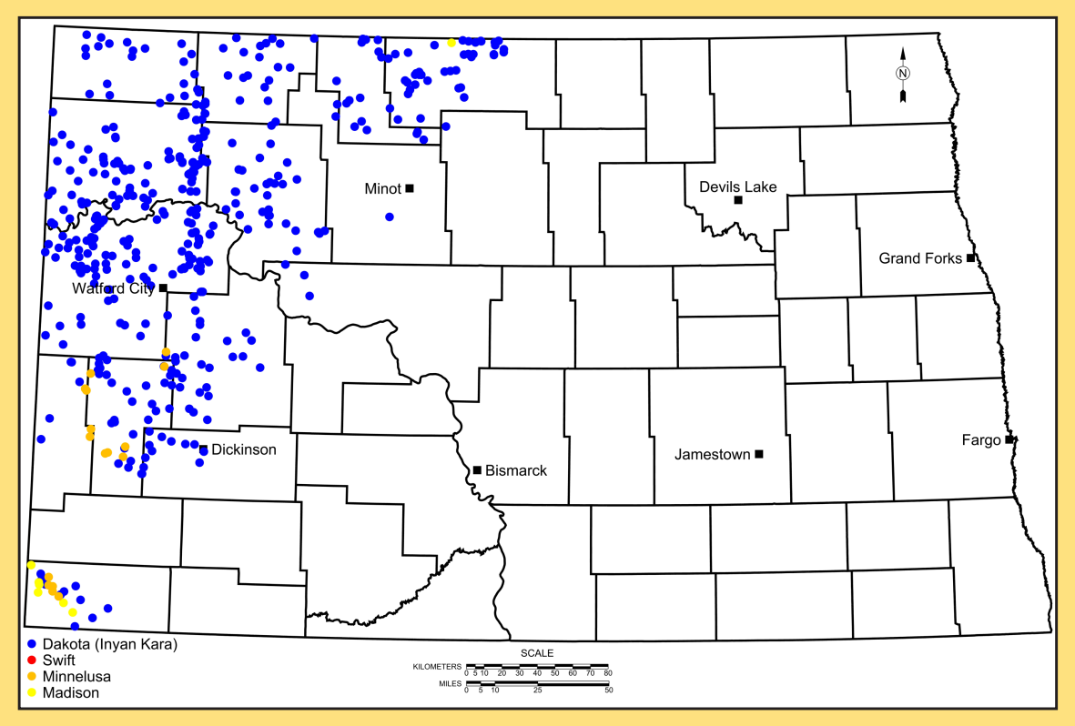


Figure 12.
Active saltwater disposal wells in North Dakota, August 2015.

INYAN KARA SANDSTONE - ISOPACH INTERVALS (feet)

300
▨
250

250
▨
200

200
▨
150

150
▨
100

100
▨
50

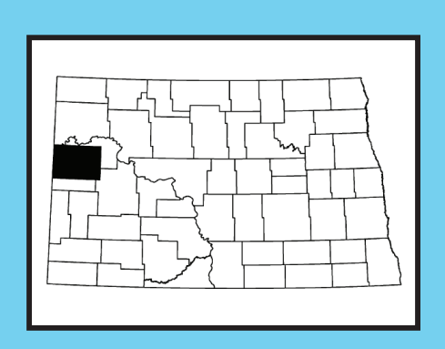
50
▨
0

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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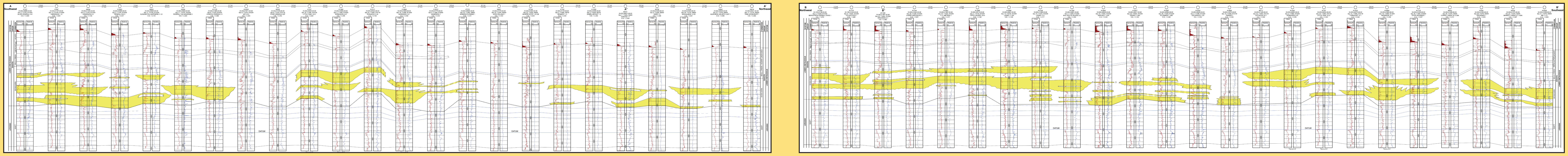

Figure 13.
Inyan Kara sandstone isopach map and cross-sections, Watford City 100K Sheet, North Dakota (Bader, 2015).