A Sequence Stratigraphic Model for the Inyan Kara Formation North Dakota

By

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ABSTRACT

The Inyan Kara Formation is the lowermost unit of the Lower Cretaceous Dakota Group. It does not crop out within North Dakota and limited core is available for study. This work examines the Inyan Kara within Williams and McKenzie counties of western North Dakota. Core from two wells, along with numerous wireline logs, were used to identify sequence stratigraphic surfaces and develop a sequence stratigraphic model.

The Inyan Kara can be subdivided into two units reflecting the overall Early Cretaceous sea-level rise. The lower half is a "fluvial" dominated, incised valley-fill complex consisting of: 1) initial valley incision during falling stage; 2) filling of the valley during lowstand and early transgression; 3) initial incursion of the seaway with subsequent flooding and development of estuaries during transgression; and 4) progradational marine highstand deposits. Gamma-ray signatures are characterized by a distinct, blocky pattern for thicker, coarser-grained sandstones. Sandstones grade upward into finer-grained, interbedded sandstone, siltstone, and claystone. The same depositional sequence is repeated in the upper Inyan Kara and the lower Skull Creek Formation but is more marginal marine dominated.

The model depicts coastline evolution and correlation of sequence stratigraphic surfaces basinward/landward. It predicts the presence and extent of valley-fill sandstone bodies and may be used to distinguish such bodies on geophysical logs from other coarser-grained units that have less potential as prospective reservoirs. Sandstones of valley-fills have excellent porosity and permeability, and are well connected; whereas, coarser deposits of the estuarine, marginal marine, and interfluve facies are not as well developed.

ACKNOWLEDGMENTS

Special thanks go to Kent Hollands, Jonathan Labonte, and Francis Nwachukwu at the Wilson M. Laird Core Library for their help in viewing and sampling of core. Also, thanks to the late Julie LeFever, who reviewed much of my early work on the Inyan Kara and provided many thoughtful and positive discussions. Dr. Stephan Nordeng provided a critical review of the paper and thought-provoking discussions with his group at the University of North Dakota, thus improving the manuscript greatly. Tim Nesheim also provided useful critiques and support for this study. Thanks to Ken Urlacher and Navin Thapa for graphics support.

INTRODUCTION

The Lower Cretaceous Inyan Kara Formation (Inyan Kara) is an important geologic unit for the oil and gas industry in North Dakota. Specifically, the Inyan Kara is the primary formation used for disposal of produced water that is generated during drilling operations across the state. Over one million barrels of produced water are generated daily requiring disposal; therefore, a thorough understanding of the geology of the formation is critical, especially as future drilling is anticipated to increase.

The Inyan Kara in North Dakota consists of fluvial, estuarine, and marginal marine units that were deposited in a paralic (coastal) setting along the Cretaceous Western Interior Seaway circa 100 Ma (Bader, 2016). The formation does not crop-out in North Dakota, with the nearest surface exposure of equivalent units being present on the flanks of the Black Hills in South Dakota and eastern Wyoming (Willis, 1997). In addition, there are also very few cores of the formation available for study even though the Williston Basin of North Dakota has had extensive drilling over the last decade during the Bakken exploration boom. Therefore, detailed investigations of the formation in North Dakota are minimal. However, because of Bakken exploration, tens of thousands of geophysical well logs are available for a subsurface study of the Inyan Kara, and particularly, the sandstone units that are the disposal reservoirs. The paralic depositional environment of the Inyan Kara is complex, with sandstone bodies that may have significant thickness changes laterally, making it difficult to place disposal wells in optimum locations. Sequence stratigraphy allows for better understanding and prediction for sandstone geometries in these nearshore settings. Therefore, western North Dakota (Fig. 1; study area) is an ideal location for applying fundamental sequence stratigraphic principles using geophysical logs to better map Inyan Kara sandstones for produced water disposal.

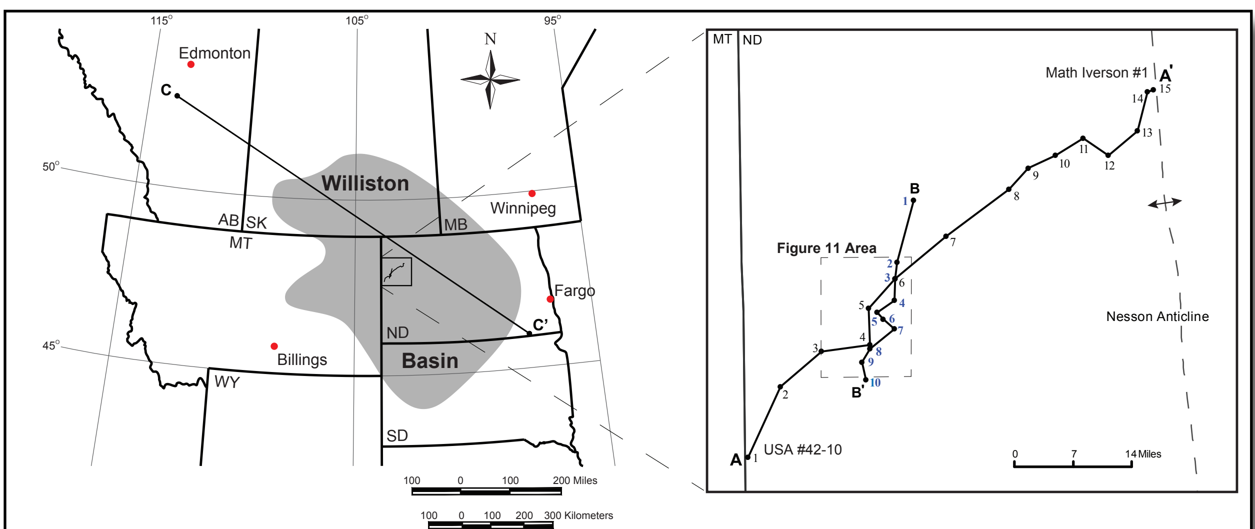

Figure 1. Index map of Williston Basin showing study area, well, cross section (A-A' and B-B'), and model (C-C') locations. State abbreviations: MT–Montana, ND–North Dakota, SD–South Dakota, WY–Wyoming. Province abbreviations: AB–Alberta, MB–Manitoba, SK–Saskatchewan.

BACKGROUND

Previous Work

The U.S. Geological Survey conducted general geologic studies on the Fall River Formation, the Inyan Kara equivalent in northern South Dakota (Ryan, 1964; Bell, III and Post, 1971). Campbell and Oaks (1973) studied the Fall River Formation on the northern flanks of the Black Hills and interpreted it as an estuarine-tidal flat-valley-fill environment of deposition. Willis (1997 and 1998) conducted outcrop studies of the Fall River Formation of southwestern South Dakota and eastern Wyoming, and also interpreted incised-valley deposition during early Cretaceous sea-level rise. Dutton and Willis (1998) and Willis' (1998) work on the valley-fill reservoirs showed that there were both vertical and lateral variations, likely related to subtle shifting depositional systems, within the valley-fill environment. Reservoirs of the Fall River produce oil in the Powder River Basin of Wyoming (Willis, 1997).

Canadian work on Inyan Kara equivalents include studies of the Lower Cretaceous Mannville Group in Alberta and Saskatchewan (Wood and Hopkins, 1989; Hayes et al., 1994; Christopher, 2003) and the McMurray Formation of Alberta, both of which are interpreted to have accumulated in an estuarine setting during the early Cretaceous (Hubbard et al., 2011; Hein et al., 2013).

Investigations of the Inyan Kara in North Dakota have been conducted by the North Dakota Geological Survey (NDGS) and include subsurface isopach mapping/correlation (Moore et al., 1987; LeFever, 2014), structure mapping (Anderson and Juenker, 2006), formation top identification (LeFever, 2007) and general formation synopses that are part of NDGS studies summarizing the entire Cretaceous stratigraphic column (LeFever and LeFever, 2007). Wartman (1982) conducted a study of the hydrogeology of the Inyan Kara and identified three informal members in northwestern North Dakota: a lower fluvio-deltaic unit "A"; a marginal-marine (transgressive tidal-flat, barrier bar) unit "B"; and a shallow marine, upper unit "C".

More recently, the NDGS has produced detailed maps (1:100,000 scale) of Inyan Kara sandstones for produced water studies in the core area of the Bakken in western North Dakota in conjunction with this study (Plate I, Figs. P1 and P2; Bader, 2015; Bader et al., 2016, a, b; Bader and Nesheim, 2016; Bader and Nesheim, 2017, a, b; Bader et al., 2017; Bader and Stolldorf, 2018, a, b; Bader et al., 2018; Bader and Stolldorf, 2019).

Geologic and Depositional Setting

The Inyan Kara is the lowermost formation of the Dakota Group (Fig. 2; Murphy et al., 2009) and the unit marks the beginning of an initial sea-level rise of the Early Cretaceous (Aptian) Western Interior Seaway. The Inyan Kara lies unconformably on the Late Jurassic (Oxfordian) Swift Formation (Langtry, 1983) and conformably beneath the Skull Creek Formation (Fig. 2). Inyan Kara sediments were deposited along a stable cratonic margin as a foreland basin developed during an overall transgression with relative low rates of subsidence and sediment input (Fig. 3A; Willis, 1997). Deposition occurred in a coastal setting and North Dakota was humid and tropical, with broad/low relief coastlines, and numerous rivers flowing across the coastal plain to the sea (Fig. 3B; Blakey, 2014). Sea-level variations caused shoreline shifts during transgressive/regressive events throughout the Cretaceous (Willis, 1997; Christopher, 2003). Inyan Kara sediments were deposited along the shoreline, possibly at transgressive river mouths, as relative sea-level fluctuated across North Dakota during two of these transgressive/regressive cycles (Fig. 4; Bader, 2016). Sedimentation along the shoreline was complex, hypothesized to consist of estuaries (drowned river valleys), that formed as the encroaching sea filled incised valleys that were cut by rivers flowing towards the retreating sea during previous relative sea-level fall, as indicated by Willis (1997) for the Inyan Kara equivalent Fall River Formation of South Dakota.

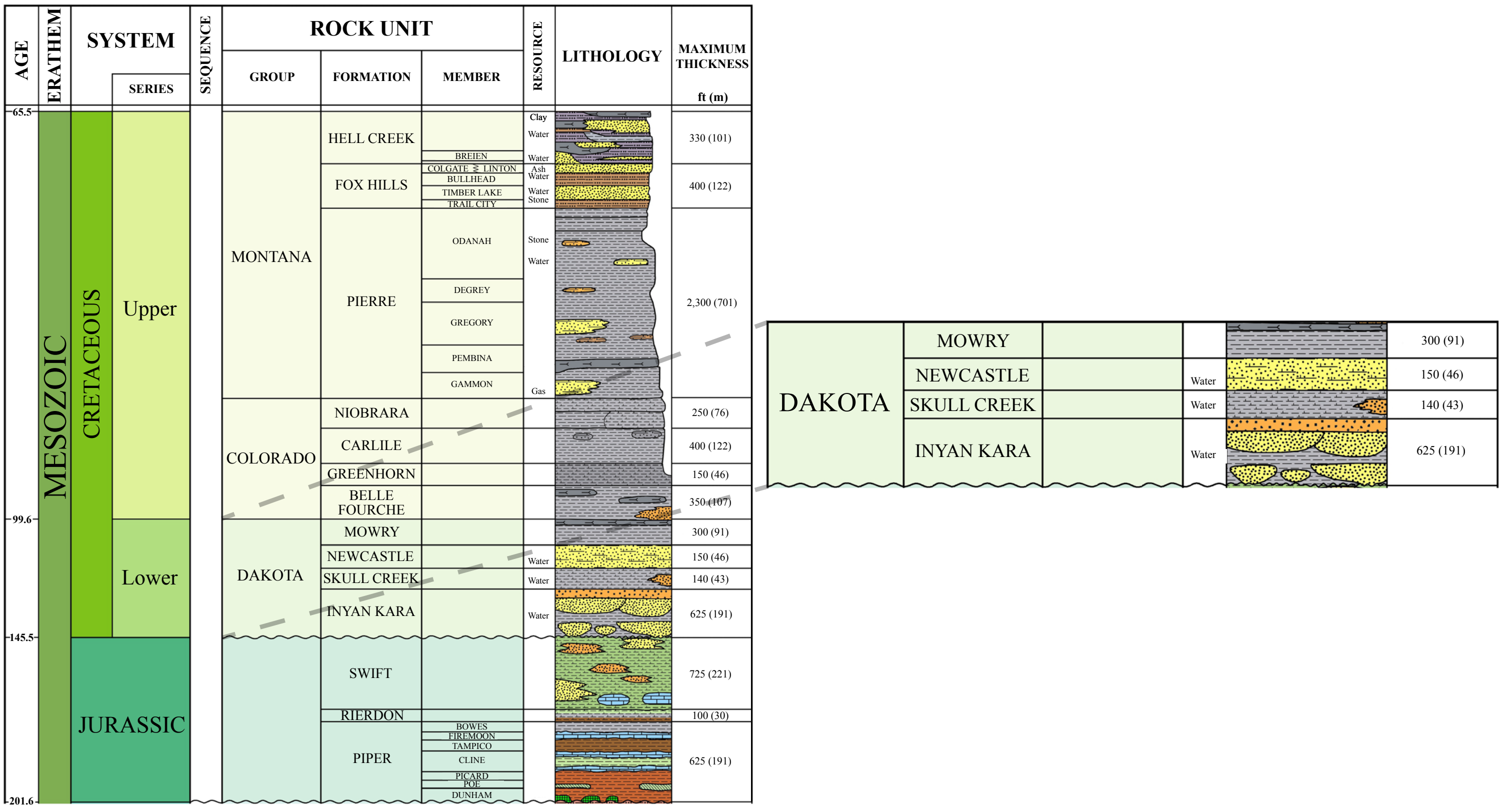

Figure 2. Stratigraphic column for Jurassic and Cretaceous rocks of North Dakota (Murphy et al., 2009).

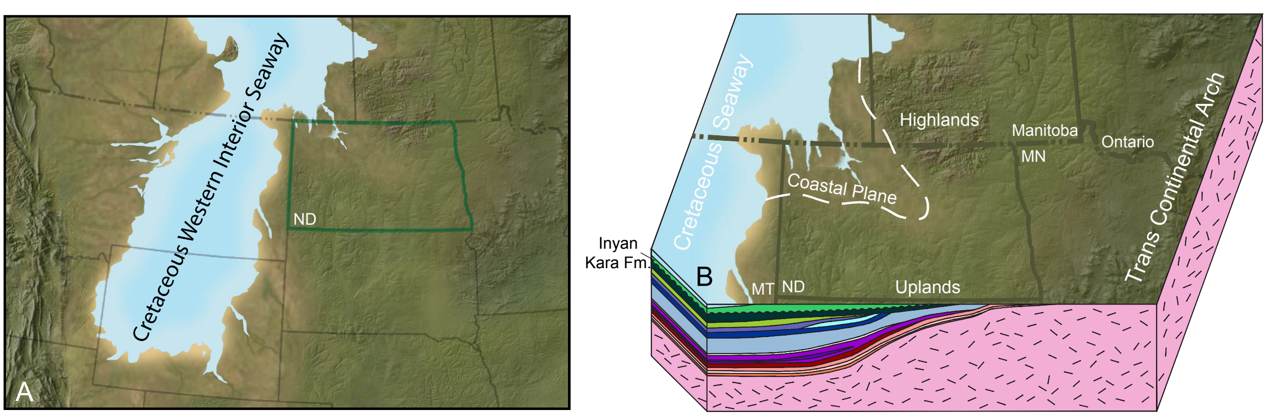

Figure 3. (A) Paleogeographic map of the North Dakota (ND) region during Inyan Kara time (c.a., 106 Ma). Modified from Blakey, 2014. (B) Block Diagram of the North Dakota (ND) area during Inyan Kara time (c.a., 106 Ma). State abbreviations: MN–Minnesota, MT–Montana, ND–North Dakota. Modified from Blakey, 2014.

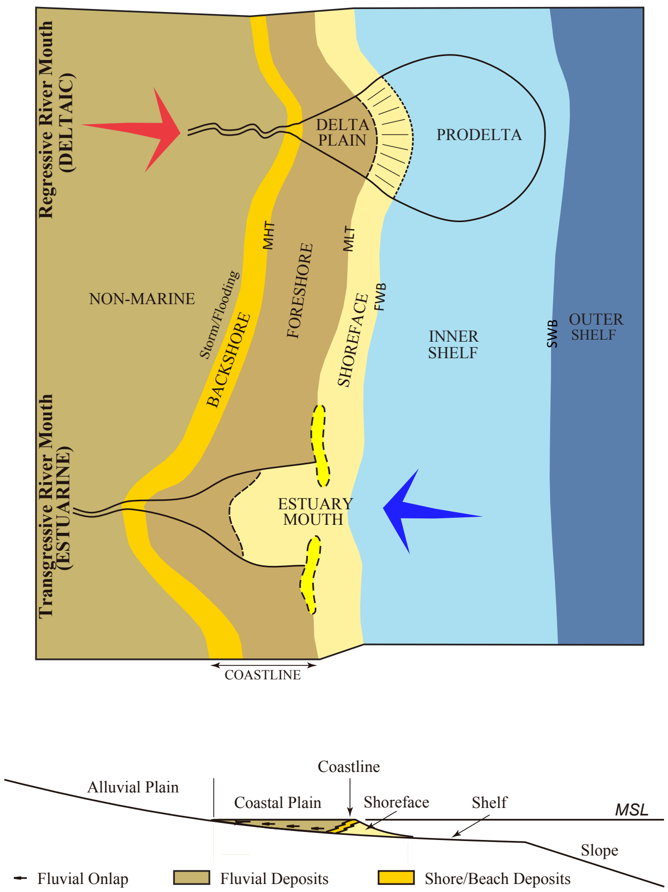

Figure 4. General setting of a marine to non-marine transition zone showing transgressive and regressive river mouths. The large arrows (red and blue) indicate the direction of coastline shift during regression and transgression. FWB–Fair-Weather Wave Base, MHT–Mean High Tide, MLT–Mean Low Tide, MSL–Mean Sea-Level, SWB–Storm Wave Base. Modified from Catuneanu, 2006.

METHODS

Based on previous work done on Inyan Kara equivalents in South Dakota (Willis, 1997) and Saskatchewan (Christopher, 2003), Inyan Kara deposition is proposed to have taken place in an incised valley/estuarine (transgressive river mouth) setting. This hypothesis was evaluated by:

- Analyzing available Inyan Kara core from two wells in western North Dakota;
- Analyzing available wireline logs to perform subsurface mapping and correlation of Inyan Kara sandstones across North Dakota;
- Identification of lithology and sedimentary structures in core;
- Identification of sequence stratigraphic surfaces in core and on logs; and
- Using results to perform comparisons to previously established sequence stratigraphic and depositional models.

Basic Sequence Stratigraphic Concepts

Sequence stratigraphy workflow first requires identification of facies and sequence stratigraphic surfaces prior to performing more detailed analysis of depositional setting and regional implications (Catuneanu et al., 2009). The Inyan Kara of North Dakota provides an excellent setting for testing this approach as well as preliminary examination of existing potential models for incised valley evolution at a transgressive river mouth (Willis, 1997). Sequence stratigraphic methodology and terminology used for this investigation is consistent with Catuneanu (2006) and Catuneanu et al. (2009).

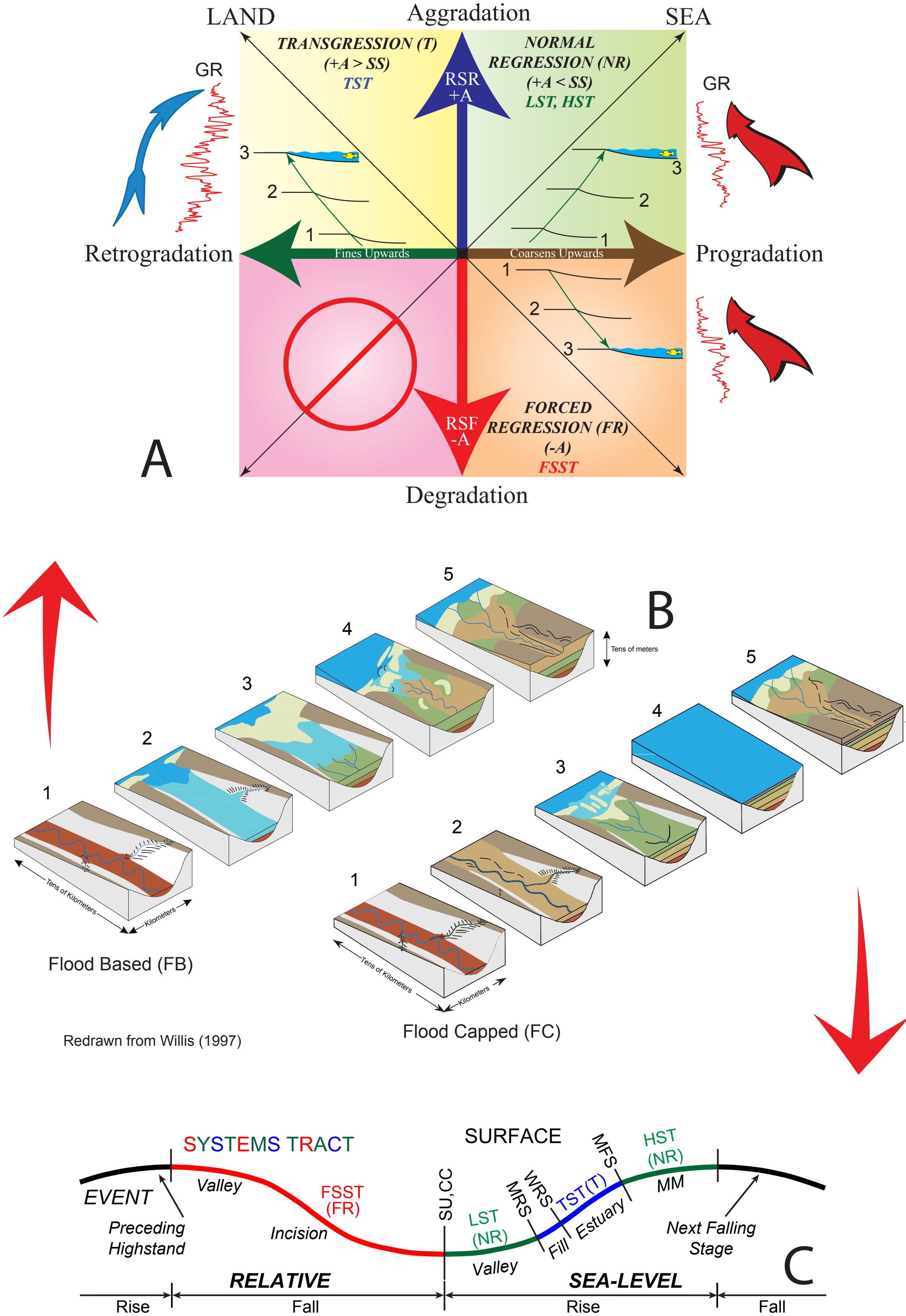

Figure 5. (A, B, C) General incised valley evolution models with diagram showing coastline evolution, stacking patterns, and sequence stratigraphic systems tracts along typical transgressive river-mouth shoreline during relative sea-level fall/rise with generalized sea-level curve model for comparison. See text for details. A–Accommodation Space, SS–Sediment Supply, FR–Forced Regression, NR–Normal Regression, T–Transgression, FSST–Falling Stage Systems Tract, HST–Highstand Systems Tract, LST–Lowstand Systems Tract, TST–Transgressive Systems Tract, RSR–Relative Sea-Level Rise, RSF–Relative Sea-Level Fall, GR–Gamma Ray, CC–Correlative Conformity, MFS–Maximum Flooding Surface, MRS–Maximum Regressive Surface, SU–Subaerial Unconformity, WRS–Wave Ravinement Surface, MM–Marginal Marine.

Sequence stratigraphy has played a major role in the recognition and development of estuarine/ incised valley (transgressive river-mouth) depositional models since the 1990s (Boyd et al., 2006). Depositional models for this type of setting were the first to use sequence stratigraphy because this approach is most easily utilized for paralic environments and makes understanding these systems much simpler. Recent advances in sequence stratigraphy, with emphasis on the evolution of depositional systems, are instrumental in preparing integrated and dynamic models, such as hypothesized here for the Inyan Kara (Fig. 5).

Stratal stacking patterns developed during cyclic and relative sea-level fluctuations on geologic time-scales are controlled primarily by tectonism and/or eustasy and are fundamental to sequence stratigraphic interpretation as shown on Figure 5A (Catuneanu et al., 2009). Figure 5B presents two models for incised valley evolution at a transgressive river mouth (Willis, 1997); flood-based and flood-capped, that along with Figures 5A and 5C, can be compared to Inyan Kara depositional models presented later in this report. Figure 5A shows a diagram for general coastline evolution, log responses for transgression/normal regression, and forced regression, stacking patterns, and systems tracts focusing on the interplay between sediment supply (SS) and accommodation space (A) during cyclic changes in base-levels (relative sea-level rise [RSR] and fall [RSF]; Fig. 5C). The area available for sediment to fill defines accommodation space; sea-level rise creates accommodation (+A), potentially leading to sedimentation; sea-level fall destroys it (-A), possibly causing downcutting and erosion. This distinction defines specific genetic types of deposits, namely, “transgressive” (T), “normal regressive” (NR), “forced regressive” (FR); and correspondingly systems tracts can be defined, “transgressive systems tract (TST), “lowstand systems tract” (LST), “highstand systems tract” (HST), and “falling-stage systems tract” (FSST). In siliciclastic, marginal marine settings, each tract is characterized by representative gamma-ray log responses related to vertical textural (grading) trends that may be used to identify sequence stratigraphic surfaces that develop based on timing of sediment supply (Catuneanu et al., 2009). Thus, transgressive packages generally fine (deepen) upwards, with lower energy deposits (e.g., clays with higher gamma) stratigraphically above higher energy deposits (e.g., silt and sand, with relatively lower gamma). Correspondingly, regressive deposits commonly coarsen (shallow) upwards, defining lowstand and highstand deposits of a normal regression. Falling-stage deposits also generally coarsen upwards but are often removed by erosion in shallow marine environment, as sea-level usually drops significantly during falling-stage creating potential for downcutting and development of incised valleys/sediment by-pass (Fig. 5A). Sequence stratigraphic surfaces, such as the maximum flooding surface and maximum regressive surface, can be identified on logs at the top of these fining- and coarsening-upwards packages (Catuneanu et al., 2009).

Sequence stratigraphic surfaces are the foundation of sequence stratigraphy in that they can be used to define boundaries between different genetic types of sequence stratigraphic deposits (e.g., forced regressive, lowstand and highstand normal regressive, transgressive) (Catuneanu et al., 2009). This allows for development of a sequence stratigraphic framework across the basin that includes these genetic units that have formed as sedimentation rates and accommodation interact in the system, irrespective of depositional setting (Fig. 5A). Stratal stacking patterns and bounding surfaces define each genetic unit contributing to the formation of a correlatable depositional system, the systems tract. Sequences can then be identified, and facies/depositional environments better defined. Ideally, integrating, outcrop, core, geophysical logs, and seismic data are optimal for a sequence stratigraphic study across an entire basin (Catuneanu et al., 2009). However, some or much of this data is usually not available, as is the case for the Inyan Kara of North Dakota, where interpretation is based almost exclusively on subsurface geophysical data. Even so, fluctuations in relative sea-level are inherently relevant to the formation of sequence stratigraphic surfaces/systems tracts and are controlled by transgressive/regressive processes at the coastline in any marine basin setting (Catuneanu et al., 2009). Therefore, sequence stratigraphic surfaces, as identified on numerous well-logs, can be utilized to develop a useful sequence stratigraphic model across the entire Williston Basin.

A transgressive river mouth hypothesis for the Inyan Kara was evaluated by performing a detailed analysis of available Inyan Kara cores along with a preliminary review of wireline logs throughout western North Dakota. A generalized sea-level curve model was also developed for predicting key sequence stratigraphic surfaces, systems tracts, and sequences of an estuarine/incised valley (transgressive river-mouth) system (Fig. 5C). Included are the expected sequence stratigraphic surfaces that should be present in core and on logs, and thus; systems tracts can be identified, and sequences defined. The generalized sea-level model was then compared to incised valley depositional models (Fig. 5B) to develop an overall sequence stratigraphic model and detailed sea-level curve for the Inyan Kara and equivalents.

Cores and Wireline Logs

Cores from the Amerada Petroleum Math Iverson #1 (NDGS #165) and the USA #42-10 (NDGS #90015) were accessed and described at the NDGS Wilson M. Laird Core and Sample Library in Grand Forks, North Dakota. These cores may be considered the informal “type” area/well/core/section for the Inyan Kara of North Dakota. Lithology, sedimentary structures, and sequence stratigraphic surfaces were identified and logged for both cores (Figs. 6A, 6B, 6C, 7, 8A, 8B, and 9).

Thousands of wells have been drilled and logged in western North Dakota, thus providing a robust data set for subsurface mapping (Bader, 2015; Bader et al., 2016, a, b; Bader and Nesheim, 2016; Bader and Nesheim, 2017, a, b; Bader et al., 2017; Bader and Stolldorf, 2018, a, b; Bader et al., 2018; Bader and Stolldorf, 2019). Geophysical logs (generally gamma ray and resistivity) from over 10,000 wells were used to identify and map/correlate sandstone bodies across the basin utilizing predictive models (e.g., incised valley, Fig. 5B; sea-level curve, Fig. 5C) and descriptions/knowledge garnered from the type wells.

This paper concentrates mainly on the geology of the two aforementioned wells with core; however, because minimal cores were available for the Inyan Kara, lithology was matched to wireline signatures for the two wells, then expanded to other wells where only wireline logs were available.

RESULTS

Core Descriptions

Math Iverson #1

The Math Iverson #1 was cored in the upper and lower portions of the Inyan Kara at depths of 4,590-4,648 feet and 4,937-4,980 feet (Figs. 6A, 6B, 6C, and 7). The deeper core consists almost entirely of very fine- to medium-grained sandstone that unconformably overlies green claystone of the Swift Formation (Fig. 6C). The contact between the Swift and the Inyan Kara is sharp, with a very fine-grained, one-foot, salt and pepper, low-angle planar-laminated sandstone at the base of the Inyan Kara (Figs. 6A, 6C, and 7).

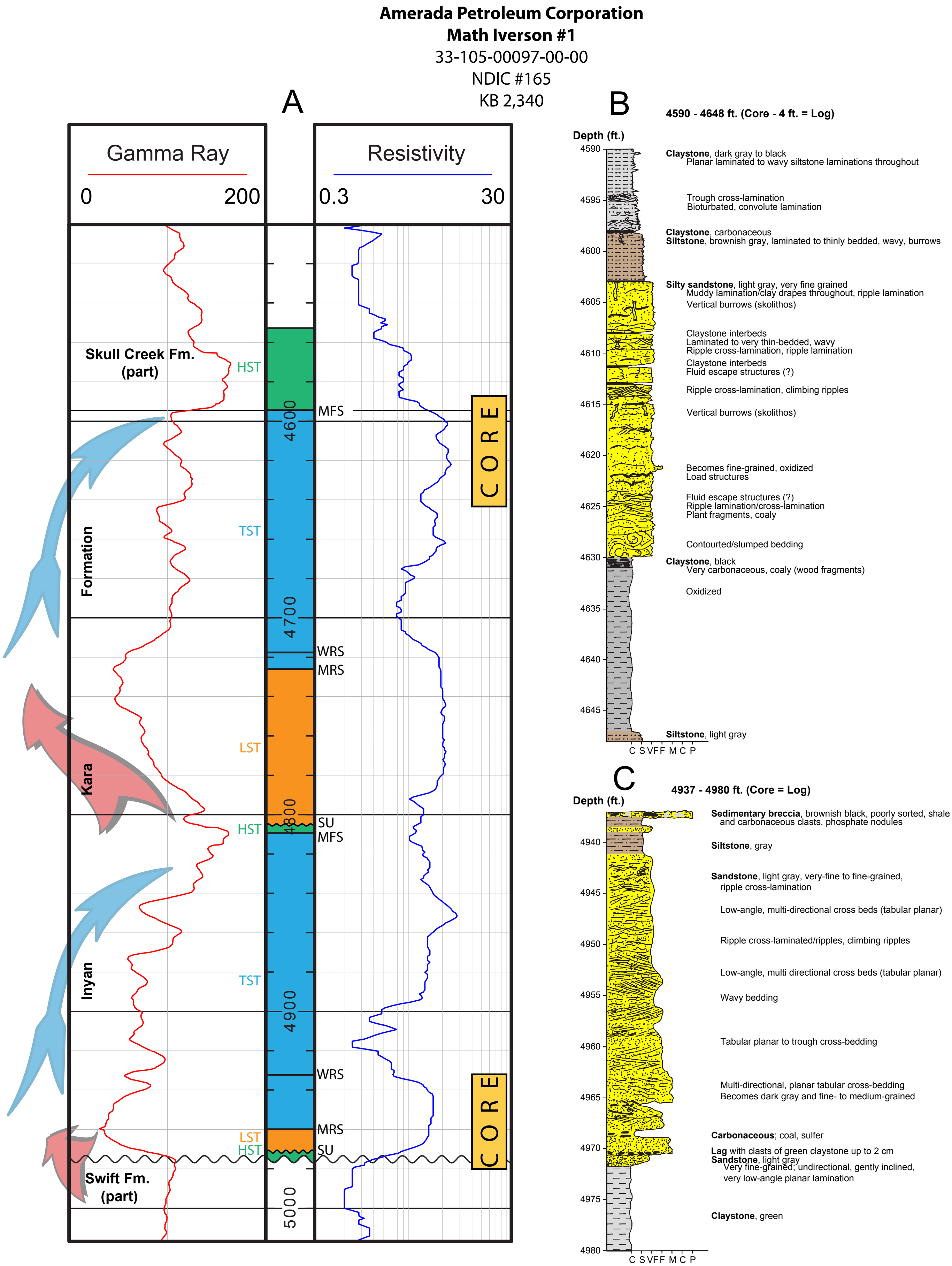

Figure 6. (A, B, C) Math Iverson # 1; log and core descriptions with sequence stratigraphic relations. Large red arrows–coarsening upwards. Large blue arrows–fining upwards. See Figure 5 for abbreviation definitions.

Amerada Petroleum Corporation
Math Iverson #1
33-105-00097-00-00
NDIC #165
KB 2,340

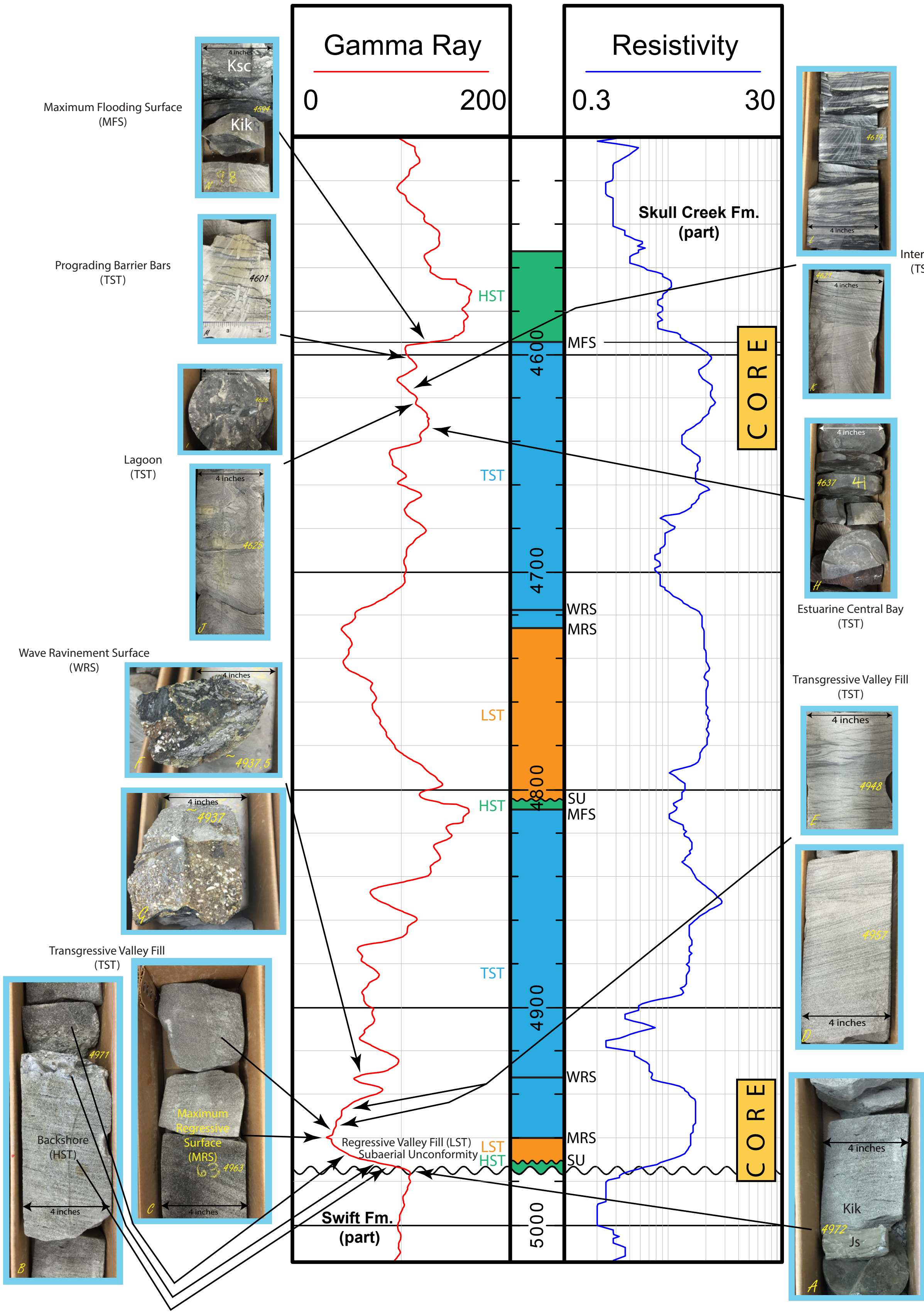

Figure 7. Math Iverson # 1; core photographs and log with sequence stratigraphic relations. Js–Jurassic Swift Formation, Kik–Cretaceous Inyan Kara Formation, Ksc–Cretaceous Skull Creek Formation. See Figure 5 for other abbreviation definitions.

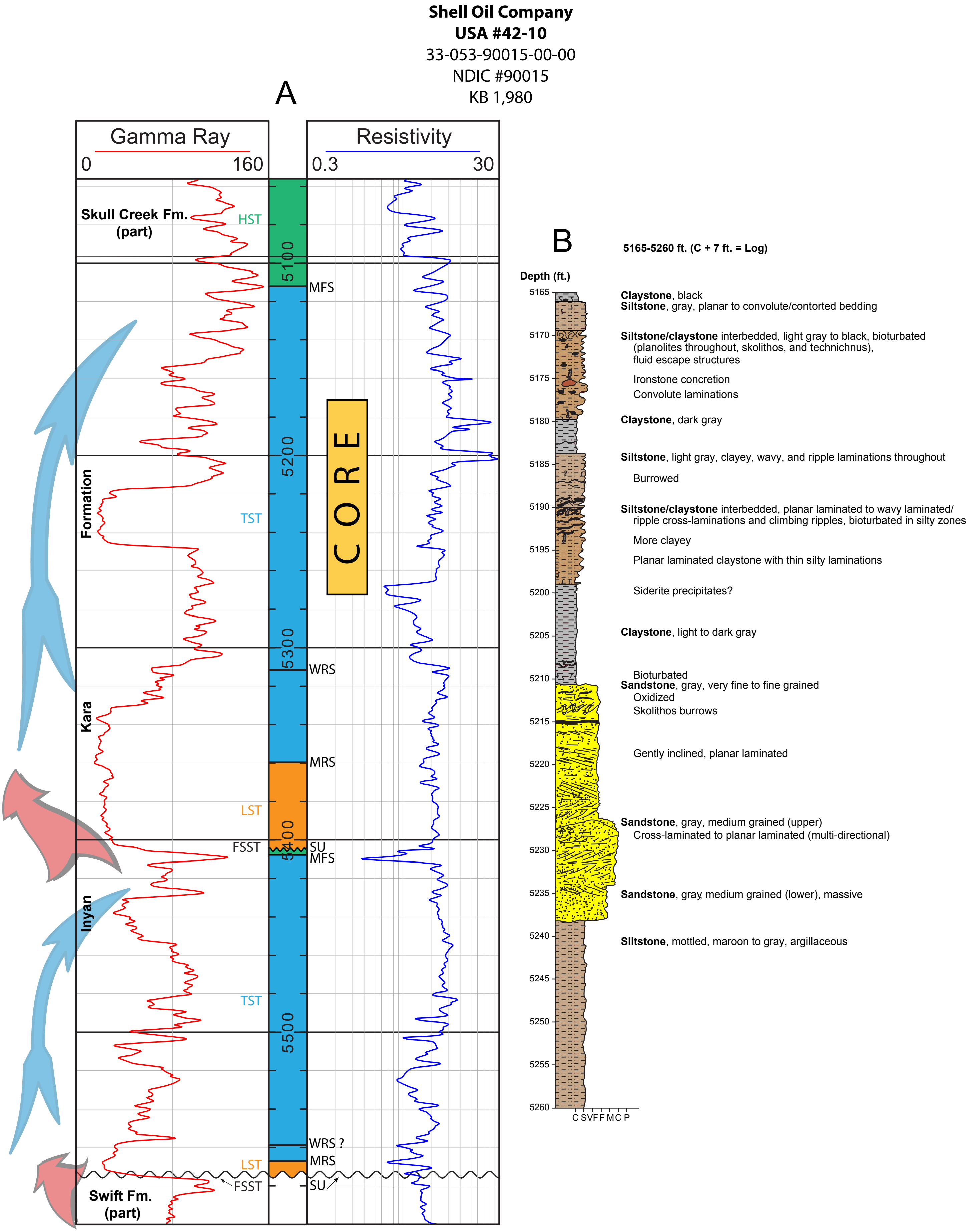

Figure 8. (A, B) USA #42-10; log and core description with sequence stratigraphic relations. Large red arrows–coarsening upwards. Large blue arrows–fining upwards. See Figure 5 for abbreviation definitions.

Shell Oil Company
USA #42-10
33-053-90015-00-00
NDIC #90015
KB 1,980

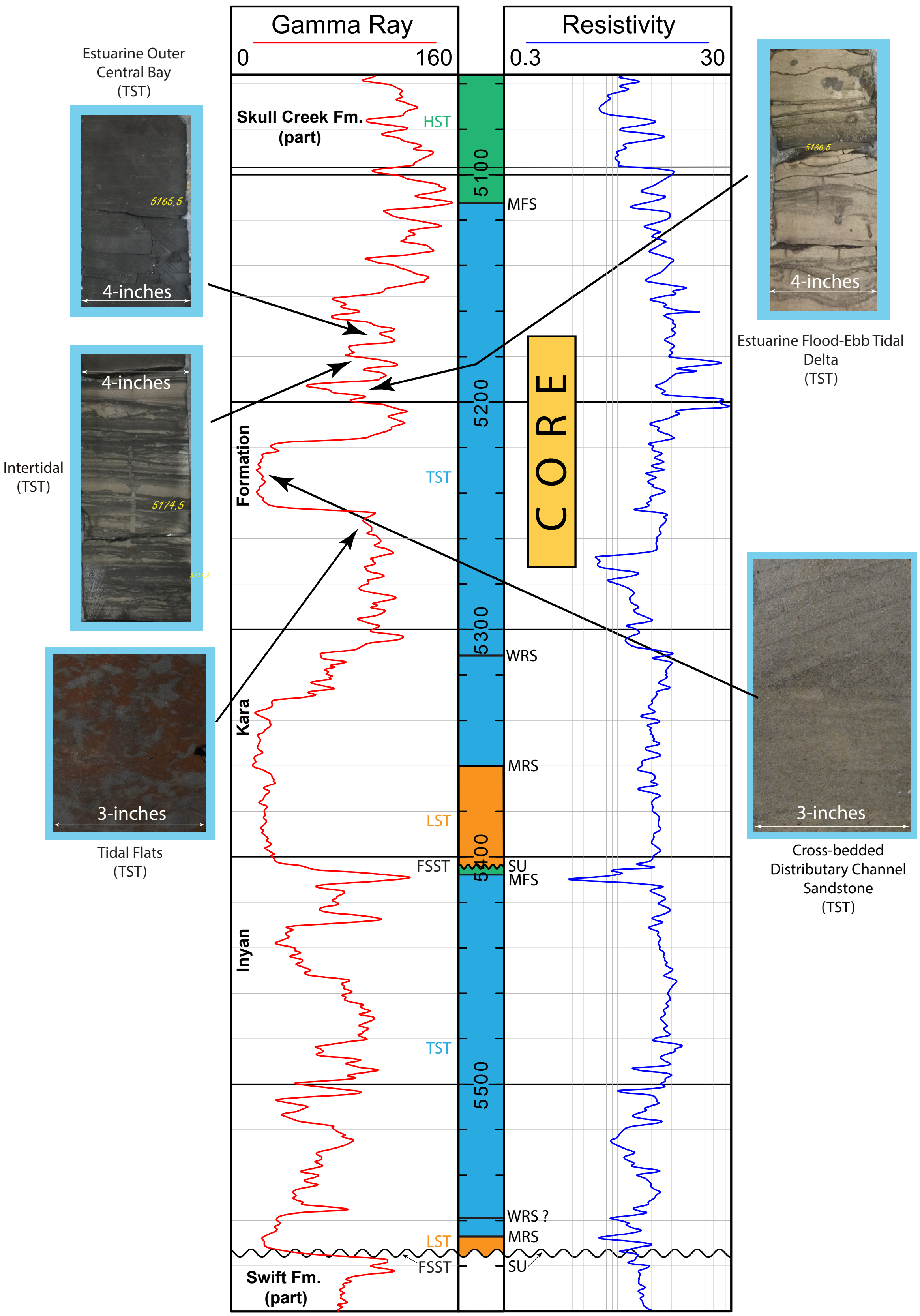

Figure 9. USA #42-10; core photographs and log with sequence stratigraphic relations. See Figure 5 for abbreviation definitions.

A 0.3 foot (9 cm)-thick, coarse-grained, salt and pepper sandstone with clasts of Swift up to 0.13 feet (4 cm) overlies the very fine-grained sandstone. This unit is overlain by an eight-foot (2.4 m)-thick, coarsening upward, fine- to medium-grained, blackish gray sandstone, where another sharp contact is present. Beds in this unit are massive to planer-tabular cross bedded. Sandstone above this contact is light brown, fine-grained, and fines upward to a depth of 4,937.5 feet where the core is capped by a 0.5 foot (15 cm)-thick, sedimentary breccia. The sedimentary breccia consists of clasts of coal, shale, and phosphate nodules supported by a coarse-grained sandy matrix. The deeper core represents the lower portion of the first of two coarsening/fining upward packages observed in the Inyan Kara Formation and contains an important transition from regressive to transgressive deposition at 4,962.8 feet (Figs. 6A and 6C).

The shallower core shows an overall fining upward sequence, with a silty, bioturbated, very fine-grained sandstone sandwiched between finer-grained siltstone/claystone of which the upper eight feet is the overlying Skull Creek Formation (Figs. 6B and 7). The lower portion of this core contains dark gray to black mudstone with some thin intervals consisting of coaly/wood fragments and convoluted bedding. The siltstones/sandstones are laminated to thinly-bedded, with climbing ripples, ripple cross-lamination, flaser beds, and tabular planar cross-sets that contain abundant skolithos-type burrows from depths of 4,602.9-4,617.0 feet. The units above the fine-grained sandstone fine upward with siltstone at a depth of 4,602.9 feet and into a 0.1 foot (3 cm)-thick, black claystone at the top of the Inyan Kara. Claystone is also present above the black claystone contact and silts upward into the lower part of the Skull Creek Formation. The shallower core represents the uppermost portion of the second coarsening/fining upward package recognized within the Inyan Kara (Figs. 6A, 6B, and 7).

USA #42-10

The USA #42-10 is cored from a depth of 5,165-5260 feet, in the middle portion of the second (upper) coarsening/fining upward package within the Inyan Kara (Fig. 8A). This core lies completely within the second overall fining upward succession; however, the sandstone unit in the middle of the core coarsens upward and transitions to fining upward (Figs. 8A, 8B, and 9). The lower part of the core consists of dark-gray clayey siltstone that is overlain by fine- to medium-grained sandstone from 5210.6 to 5238.4 feet (Fig. 8B and 9). The sandstone is massive at the base, grades upward into cross-laminated sandstone, and finally into multi-directional planer laminated sandstone in the middle of the unit. This sandstone is bioturbated (skolithos) and fine-grained from depths of 5215.0 to 5210.6 feet where it grades into interbedded siltstone and claystone to the top of the core (Figs. 8B and 9). Siltstone/claystone at the top of the core (5170.0 feet) is heavily bioturbated with abundant planolites burrows throughout, along with some technichus and skolithos traces.

Log Descriptions

Math Iverson #1

The Math Iverson #1 includes gamma-ray and resistivity logs (Fig. 6A). Gamma-ray and resistivity signatures on well-logs are characterized by a somewhat blocky pattern for coarser-grained sandstone deposits near the base of the Inyan Kara Formation. These sandstones grade upward into finer-grained units of interbedded sandstone, siltstone, and claystone near the middle of the formation (Fig. 6A). This coarsening- to fining-upward pattern repeats itself in the upper part of the formation and into the overlying Skull Creek Formation, representing the two previously discussed coarsening/fining upward packages observed in core. An order of magnitude increase in resistivity values are most useful in identifying the upper and lower contacts of the Inyan Kara, where values from the overlying Skull Creek Formation and underlying Swift Formation average much less than 3 ohm-meters, while the Inyan Kara has greater than 6 ohm-meters, possibly indicating an influx of fresher (brackish?) water during Inyan Kara time, and/or post-depositional freshwater recharge to the aquifer.

USA #42-10

Logs from the USA #42-10 include gamma ray and resistivity logs (Fig. 8A). Gamma-ray signatures on well-logs from the USA #42-10 are characterized by a very distinct blocky pattern for coarser-grained sandstone deposits in the middle and upper Inyan Kara. These sandstones grade upward into finer-grained units of interbedded sandstone, siltstone, and claystone. These finer-grained, interbedded units are also present in the lower portion of the formation (Fig. 8A). Again, an order of magnitude increase in resistivity values indicates fresh water influx during Inyan Kara time, and/or post-depositional freshwater influx into the aquifer.

INTERPRETATIONS

Sequence Stratigraphic Surfaces

Several types of sequence stratigraphic surfaces have been identified in core and subsequently on well logs. These include: subaerial unconformities, maximum regressive surfaces, maximum flooding surfaces, and wave ravinement surfaces. These surfaces, along with subsurface mapping and the sedimentologic results presented above suggest that Inyan Kara deposits fit well with an incised valley/estuarine model.

Subaerial Unconformity

Subaerial unconformities form during significant base-level fall as a result of fluvial erosion/bypass in an incised-valley setting (Catuneanu et al., 2009). They are present within the Inyan Kara, marking two forced regressions during base-level fall (Figs. 6A, 6C, 7, and 8A), one near the base of the formation that likely represents a significant and early retreat of the Cretaceous seaway well into Canada (Blakey, 2014), and a second within the formation, delineating a second sea-level fall that extends just barely across the northwest North Dakota border into Canada. The subaerial unconformity lies at the base of the valley fill and is generally represented by a thin, coarse lag and/or an erosive surface.

In the Math Iverson #1, the lower subaerial unconformity is well represented in core as a thin conglomerate with clasts of the underlying Swift Formation at approximately 4,971 feet* (Figs. 6C and 7), but due to the thinness of the unit, is not resolvable on well logs (Figs. 6A and 7). However, the upper subaerial unconformity may be recognized by a sharp, spike-like response on the gamma-ray log at approximately 4,801 feet (Fig. 6A), where the likely lag is thicker and represents coarser material than the underlying/overlying units. Lags in the USA #42-10 are not present in the core or discernable on logs (Figs. 8 and 9).

Maximum Regressive Surface

A maximum regressive surface develops during base-level rise and deposition transitions from lowstand coastal progradation (normal regression), to retrogradation (transgression) (Catuneanu et al., 2009). This surface marks the end of the regressive event where energy in the system will be highest;

** All depth references correspond to logged depths, unless otherwise noted as a core depth.*

therefore, aside from lag surfaces, the maximum regressive surface is commonly the coarsest and cleanest siliciclastic material in the sequence (e.g., sand).

The maximum regressive surface in the Math Iverson #1 was seen in both core and on well logs. Again, both regressive-transgressive events can be identified by a change in the inflection point of the gamma-ray response where values are the lowest at approximate depths of 4,728 and 4,963 feet, respectively, and corresponding to low gamma-ray readings of approximately 43 and 33 API units. The lower maximum regressive surface in core is represented by a distinct color change and a change in grain-size from coarsening upward, very-fine grained sand to fine- to medium-grained sand at a depth of 4962.9 feet (Figs. 6A, 6C, and 7).

In the USA #42-10, two likely maximum regressive surfaces are present at approximate depths of 5,360 feet and 5,564 feet; however, inflection points for gamma-ray lows are much more difficult to discern due to the very-well-sorted nature of the units creating a very 'blocky' log-character from 5,331-5,405 feet and 5,559-5,574 feet (Fig. 8A). These 'blocky' units define the well-sorted valley-fill sandstones characteristic of the Inyan Kara in western North Dakota.

Wave Ravinement Surface

Transgressive ravinement surfaces develop in coastal to upper shoreface environments because of tidal or wave scouring during transgression (Catuneanu et al., 2009), dependent on the dominant scouring mechanism, either waves or tides. Wave ravinement is the dominant erosional process affecting Inyan Kara deposition in the study area, and is commonly discernable at transgressive, wave-dominated river-mouths (Catuneanu et al., 2009). The wave ravinement surface terminates basinward, by merging with the maximum regressive surface, and landward, where it merges into the maximum flooding surface.

A wave ravinement surface is present in the Math Iverson #1 at a depth of approximately 4,937 feet. It is well characterized by a 0.5 feet (15 cm)-thick sedimentary breccia consisting of clasts of shale, carbonaceous/coaly material, and phosphate nodules supported by a sandy/silty quartzose matrix. These constituents are all consistent with erosion of coastal deposits (Figs. 6C and 7). On logs, this transgressive lag forms a sharp spike on the gamma-ray and neutron density logs. This is likely due to the coarse-grained nature and thinness of the deposit. Possible wave ravinement surfaces can also be recognized on logs in the USA #42-10 from depths of 5,310-5,311 and at 5,560 feet (Fig. 8A).

Maximum Flooding Surface

The maximum flooding surface develops during base-level rise as shoreline trajectory changes from transgression/coastal retrogradation to normal regression/progradation of the highstand (Catuneanu et al., 2009). This surface corresponds to the end-of-transgression landwards, and represents the finest/dirtiest sediment (e.g., clay) in the sequence.

An upper maximum flooding surface can be identified on the gamma-ray log from the Math Iverson #1 at approximately 4,594 feet, where gamma-ray intensity increases significantly, stabilizes, then decreases in intensity upward. This surface marks progradation/coarsening upward and deposition of the overlying Skull Creek Formation (Figs. 6A and 7). In core, the maximum flooding surface is defined by a thin, 0.5

foot (15 cm), black, claystone at 4,598.0 feet, coarsening both upward and downward from this surface, as expected for the overlying highstand deposits and underlying transgressive deposits (Figs. 6B and 7). A lower maximum flooding surface may be present at approximately 4,810 feet with a thin, highstand unit underlying a subaerial unconformity at 4,801 feet (Fig. 6A).

Two maximum flooding surfaces are also identifiable on gamma-ray logs from the USA #42-10 at approximate depths of 5,112 and 5,408 feet (Fig. 8A).

Subsurface Relations

Isopach maps of Inyan Kara sandstones are shown on Figs. 10 (Plate I, Fig. P1) and 11. The maps were developed from 100K scale maps generated by the NDGS (Bader, 2015; Bader et al., 2016 a, b; Bader and Nesheim 2016; Bader and Nesheim 2017, a, b; Bader et al., 2017; Bader and Stolldorf, 2018, a, b; Bader et al., 2018) and show interpreted regional paleovalley trends (Fig. 10; Plate I, Fig. P1) and a small, but typical incised valley in map view (Figs. 1 and 11). Thicker sandstone deposits (lighter colors) define valley trends; whereas darker colors represent interfluve areas on both Figs. 10 (Plate I, Fig. P1) and 11. Cross section A-A' (Fig. 12A; Plate II, Fig. P3) is transverse to regional incised-valley trends and includes two larger paleovalleys separated by interfluve areas. Cross-section B-B' (Fig. 13; Plate II, Fig. P4) trends across a smaller incised-valley oriented roughly north-northeast, with interfluve areas to the north and south at each end of the section. Figure 12A (Plate II, Fig. P3) includes the two wells investigated in this study.

Cross-section A-A' shows regionally how valley incision was much more prevalent to the east across the Nesson anticline and was not as significant to the west (Fig. 12A; Plate II, Fig. P3). This confirms that the Nesson was likely a positive structure in the Early Cretaceous (LeFever et al., 1987). Thinning of the entire Inyan Kara from west to east also suggests that the Nesson structure influenced Inyan Kara deposition. Because Section A-A' cuts across several interfluve areas, sandstones are not as laterally continuous (Figs. 10 [Plate I, Fig. P1] and 12A [Plate II, Fig. P3]). Note that two depositional packages can be discerned within the section, each bound by subaerial unconformities that define two sequences spanning across the entire Inyan Kara and a portion of the overlying Skull Creek Formation (Figs. 6, 7, and 12A; Plate II, Fig. P3). Sequence stratigraphic surfaces, systems tracts, and sequence boundaries have also been identified and correlated on Section A-A' (Fig. 12B; Plate III, Fig. P5).

Cross-section B-B' (Fig. 13; Plate II, Fig. P4) is constructed through a small incised-valley complex as seen on the south-central portion of A-A', but more transverse to the strike of the paleovalley than for A-A'. The section along with the isopach map again show two distinct north-northeast-trending incised-valley complexes within the Inyan Kara (Figs. 10, 11, and 13; Plate II, Fig. P4), with finer-grained interfluve deposits to the south and north. Also note that the incised valleys are much better-connected lateral to paleovalleys but may quickly pinchout transverse to valley trends. Again, two sequences can be defined on B-B', present from the base of the Inyan Kara to just into the overlying Skull Creek Formation (Figs. 8A, 9, and 13; Plate II, Fig. P4).

DISCUSSION

Stratigraphic architecture at transgressive river-mouths has been the subject of many studies (Harms, 1966; Miall, 1978; Dalrymple et al., 1992, Willis, 1997; Boyd et al., 2006; Catuneanu, 2006; Boyd, 2010).

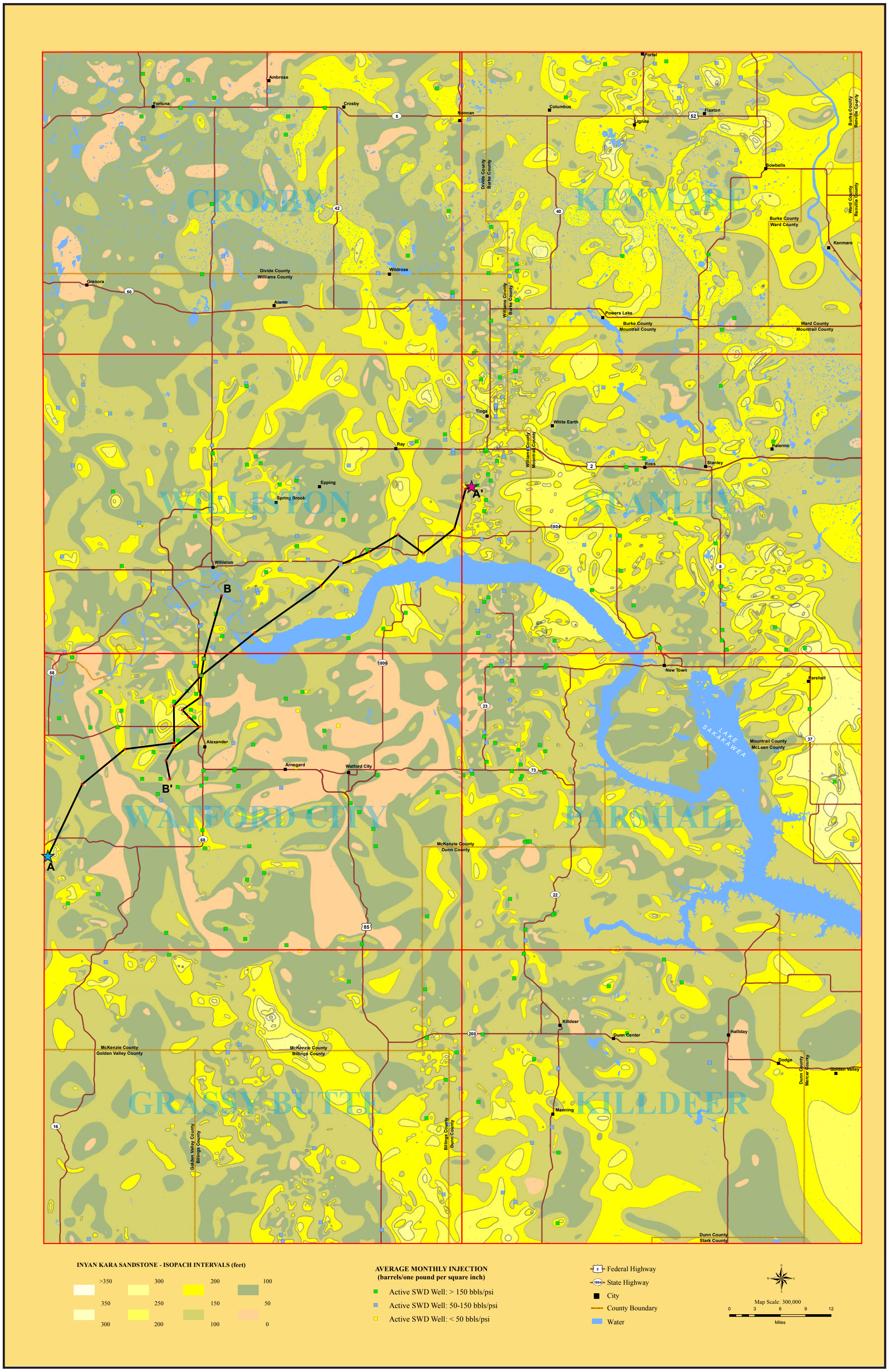

Figure 10. Inyan Kara Sandstone Isopach Map: Crosby, Kenmare, Watford City, Parshall, Williston, Stanley, Grassy Butte, and Killdeer 100K Sheets, North Dakota. Modified from Bader, 2015; Bader and Nesheim, 2016, 2017a, and 2017b; and Bader et al., 2016a, 2016b, 2017, and 2018. Math Iverson #1 well denoted by the magenta star. USA #42-10 well denoted by the blue star. See Plate I for enlarged map, average monthly injection rates, and Bakken "hot-spot" area.

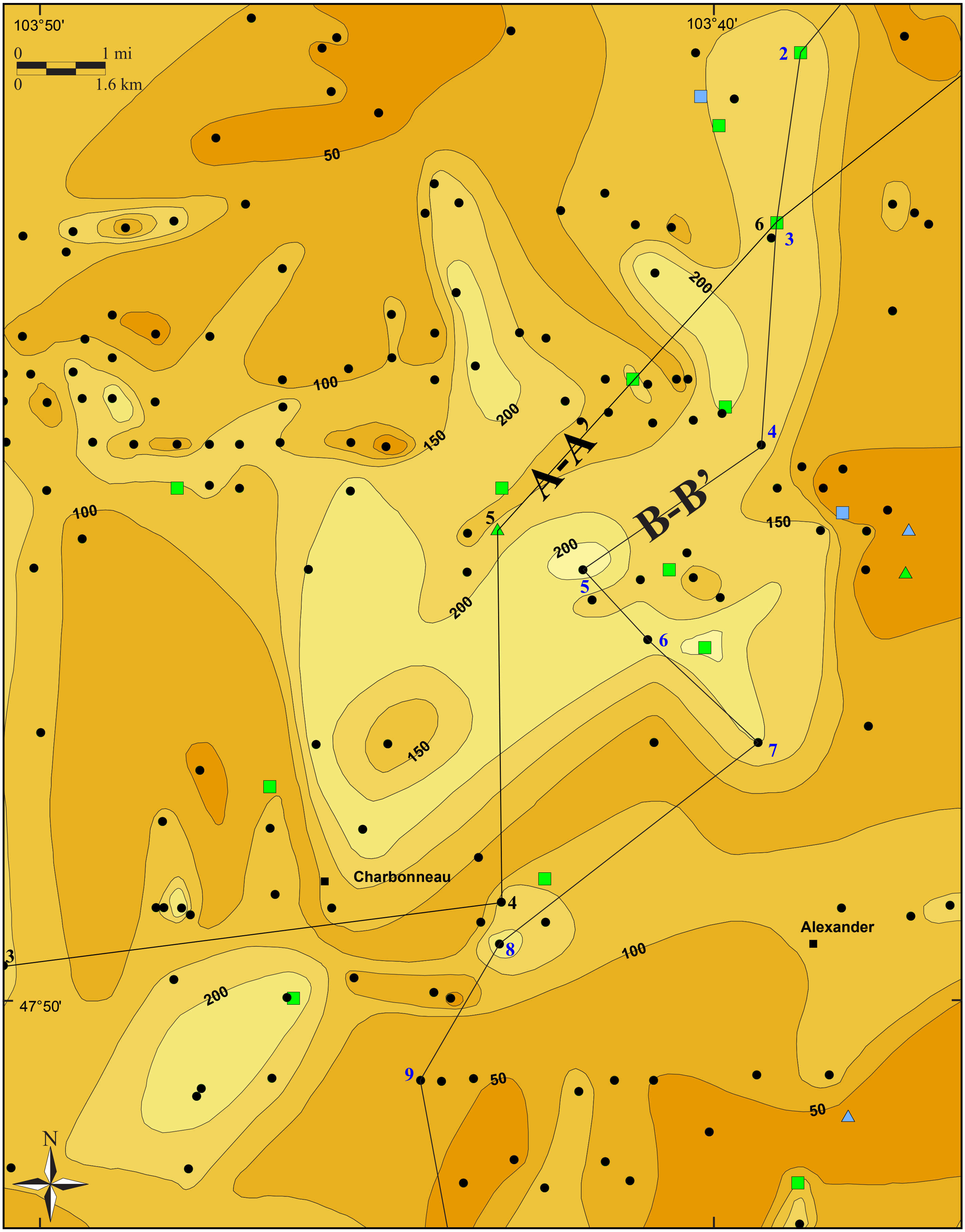

Figure 11. Generalized isopach map of Inyan Kara sandstones that define incised valleys in northwestern North Dakota. Contour interval = 50 feet. Circle–control point/well location, Square–Active saltwater disposal well, Triangle–Inactive saltwater disposal well. See Plate I, Figure P1 for average monthly injection rates.

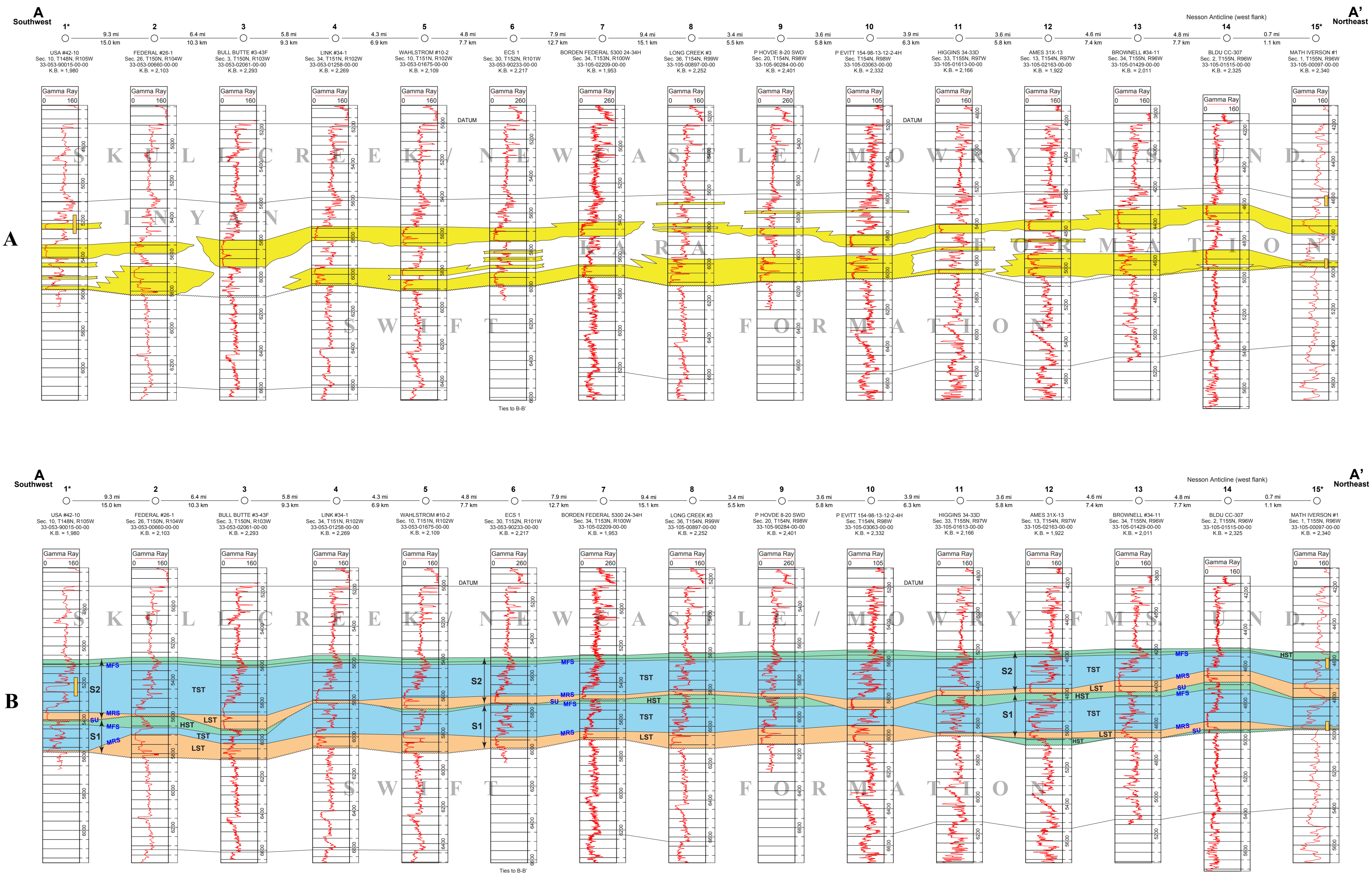

Figure 12. (A) Cross-section A-A' showing correlation of sandstones within the Inyan Kara Formation. (B) Cross-section A-A' showing sequence stratigraphic correlations for the Inyan Kara Formation. Asterisk (*) indicates key well for this investigation. See Plate II, Fig. P3 and Plate III, Fig. P5 for enlarged versions that include resistivity logs in addition to gamma-ray logs. See Figures 1, 10, and Plate I, Fig. P1 for approximate cross-section locations.

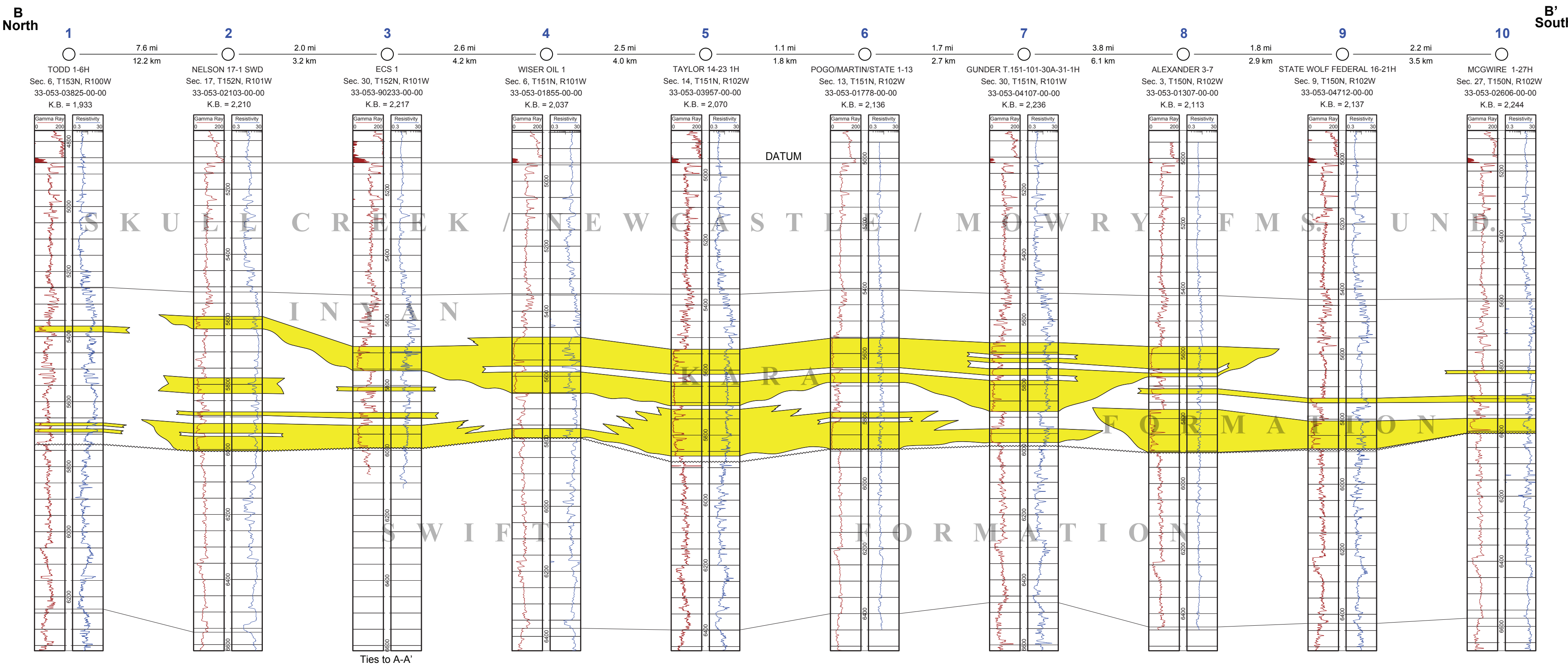

Figure 13. Cross-section B-B' showing correlation of sandstones within the Inyan Kara Formation. See Plate II, Fig. P4 for enlarged version. See Figures 1, 10, and Plate I, Fig. P1 for approximate cross-section locations.

Early studies focused on fluvial sedimentology, sedimentary structures, ichnofauna, etc. to develop facies/ depositional models. More recent work over the past few decades has included a sequence stratigraphic approach and focus on the sedimentological importance of unconformities (Boyd et al., 2006). However, study of paralic environments at transgressive river-mouths remains limited, likely due to the complex nature of these depositional systems (Dalrymple et al., 1992; Boyd et al., 2006). Such environments (Fig. 4) are ideal for sequence stratigraphic studies as they are very sensitive to fluctuating sea-level and thus provide a detailed record of shoreline shifts and associated changes in depositional trends that can be viewed both in core and on logs (Fig. 5A; Catuneanu, 2006), and thus are applicable to the Inyan Kara.

Willis (1997) presented two models for the evolution of a transgressive river-mouth system: 1) flood-based (Fig. 5B-FB); and 2) flood-capped (Fig. 5B-FC), and he concluded that Inyan Kara equivalent Fall River Formation developed in the latter environment. This suggests that the Inyan Kara may have been deposited in a similar setting lateral to the Western Interior Seaway, only slightly north along depositional strike.

The flood-based model (regression dominated) presumes a rapid relative sea-level rise as paleovalleys are quickly flooded by the marine incursion, and then gradually filled as relative sea-level begins to wane (Fig. 5B-FB). This model assumes rates of sea-level rise are much greater than rates of sediment supply (Willis, 1997), as are characteristic of many modern estuarine systems. In these systems, the valley floor is rapidly flooded resulting in a thin veneer of lowstand and transgressive valley fill overlain by a thicker sequence of highstand deposits (Willis, 1997; his Fig. 9A).

In contrast, the flood-capped model (transgression dominated) presumes that paleovalleys are largely filled during fairly slow relative sea-level rise as lowstand and transgressive fluvial sediments fill accommodation space (Fig. 5B-FC; Willis, 1997). Flooding occurs only after significant accommodation develops upstream, and downstream areas are starved of sediment (Willis, 1997; his Fig. 9B). This results in valley fills overlain by progressively more estuarine facies and ultimately marine facies deposited during transgression as sediment supply gradually decreases and new accommodation develops. These packages are often capped by maximum flooding surfaces and highstand deposits as relative sea-level rise continues to slow; however, these deposits may be removed by erosion during the subsequent sea-level fall.

Flood-Capped Model

The Inyan Kara deposits fit well with the flood-capped model of deposition (Figs. 14A, 14B, 14C, and Plate I, Fig. P1). Figure 14B is a diagram showing development of an incised valley through early Inyan Kara time starting with forced regression (Fig. 14B/A). This is followed by valley-fill deposition during normal regressive (lowstand) and transgressive phases (Fig. 14B/B-C). As transgression ramps up, accommodation greatly exceeds sediment supply and flooding occurs forming an estuary and maximum flooding (Fig. 14B/D-E). Normal regression resumes at the end of the cycle followed by subsequent relative sea-level fall and rejuvenation of valley incision in upland areas (Fig. 14B/F-G). Two of these cycles are present in the Inyan Kara and include the lower part of the overlying Skull Creek Formation. This is supported by sedimentary structures, previously described facies, and sequence stratigraphic observations from core and logs.

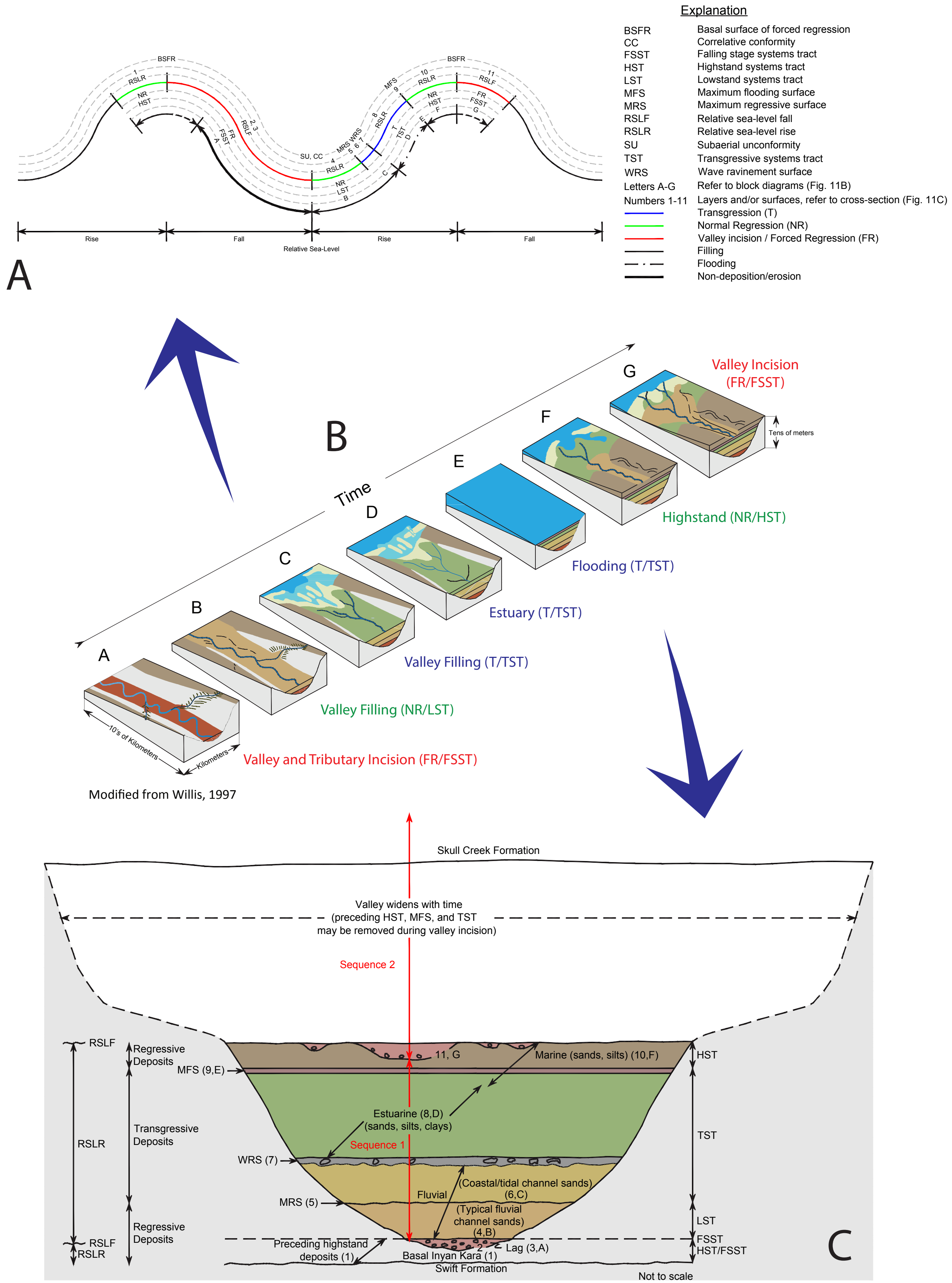

Figure 14. (A, B, C) Detailed sea-level curve (A) showing predicted systems tracts, sequence stratigraphic surfaces, and events for a typical transgressive river-mouth (flood-capped model) (B) with Math Iverson #1 deposits for comparison (C). See Figure 5 for abbreviation definitions.

A detailed sea-level curve (Fig. 14A) was developed utilizing the flood-capped depositional model (Fig. 14B) along with the generalized sea-level curve (Fig. 5C). The detailed sea-level curve pertains specifically to the Inyan Kara and deposits from the Math Iverson #1 (Fig. 14C). Figure 14C shows the stratigraphy of the Math Iverson #1 in an incised-valley setting along with relative sea-level shifts, sequence stratigraphic surfaces, and lithology/depositional environment of the lower sequence (S1).

Three regional northwest paleovalley trends may be defined across the study area in western North Dakota (Fig. 10; Plate I, Fig. P1) based on sandstone isopach-thick trends: 1) a southerly valley located well south of the Missouri River dominating the northeast Grassy Butte 100K and west-central Killdeer 100K; 2) a central valley, located just north of the Missouri in the southern Stanley 100K and north-central Watford City 100K; and 3) a valley trending across the northeast Kenmare 100K. Each valley is separated from one-another by thinner sandstone units and finer-grained siltstones and claystones. Paleovalleys are characterized by thick, very well-sorted, porous (20-30% porosity), and permeable (Darcy level) sandstone bodies that are relatively continuous along and within valleys but can quickly grade into much thinner sandstone and finer-grained deposits of the interfluve when transverse to valley trends.

Sequence Stratigraphic Model

Identification of key sequence stratigraphic surfaces allows for identification of systems tracts for the Inyan Kara. Figure 15 shows the Math Iverson #1 well-log with interpreted, sequence stratigraphic surfaces as described above. Systems tracts are identified and annotated with a description of the depositional setting as predicted by sea-level curve and depositional models (Figs. 5A, 5B-FC, and 5C).

Initial base-level rise began in the Early Cretaceous resulting in an established highstand and deposition of regressive coastal deposits at the base of the Inyan Kara (Fig. 15). The thin sandstone at the base of the Inyan Kara in the Math Iverson #1 is likely a backshore (beach) deposit representing a preserved remnant of the highstand at that location (Fig. 7). This sand was probably thicker; however, subsequent sea-level fall likely eroded much of it as rivers chased north-northwest towards the sea, eroding the exposed shelf, and resulting in a subaerial unconformity near the base of the Inyan Kara. Early Inyan Kara highstand deposits are not present at the base of the Inyan Kara in USA #42-10 (Fig. 8A), indicating that valley incision was significant in the area of these two wells during early Inyan Kara time, completely removing most or all highstand deposits and putting the subaerial unconformity at, or near the base, of the Inyan Kara.

Above the lower subaerial unconformity, coarsening upward regressive valley fills of the lowstand are readily seen in the two wells (Figs. 6A and 8A). This is consistent with the Aptian lowstand of Blakey (2014) (Fig. 15/A). These deposits are in turn overlain by fining upward packages of transgressive valley-fill sandstones and estuarine sandstone, siltstone, and claystone representing likely deltaic (bayhead delta), tidal channel, and central bay deposits of the transgressive systems tract of the Fall River transgression (Fig. 15/B). The transgressive systems tract deposits are overlain by coarsening upward Fall River highstand deposits (Fig. 15/C); with only a thin veneer in both the Math Iverson #1 (Fig. 6A) and in the USA #42-10 (Fig. 8A) wells as they are truncated by the upper subaerial unconformity. This coarsening/fining upward pattern repeats itself in the upper Inyan Kara with Fall River valley-fill lowstand deposits (Fig. 15/D) overlain by transgressive valley-fill and estuarine deposits of the Skull Creek transgression (Fig. 15/E). These are in turn overlain by Skull Creek highstand deposits of the upper Inyan Kara and lower Skull Creek Formations (Fig. 15/F; Blakey, 2014).

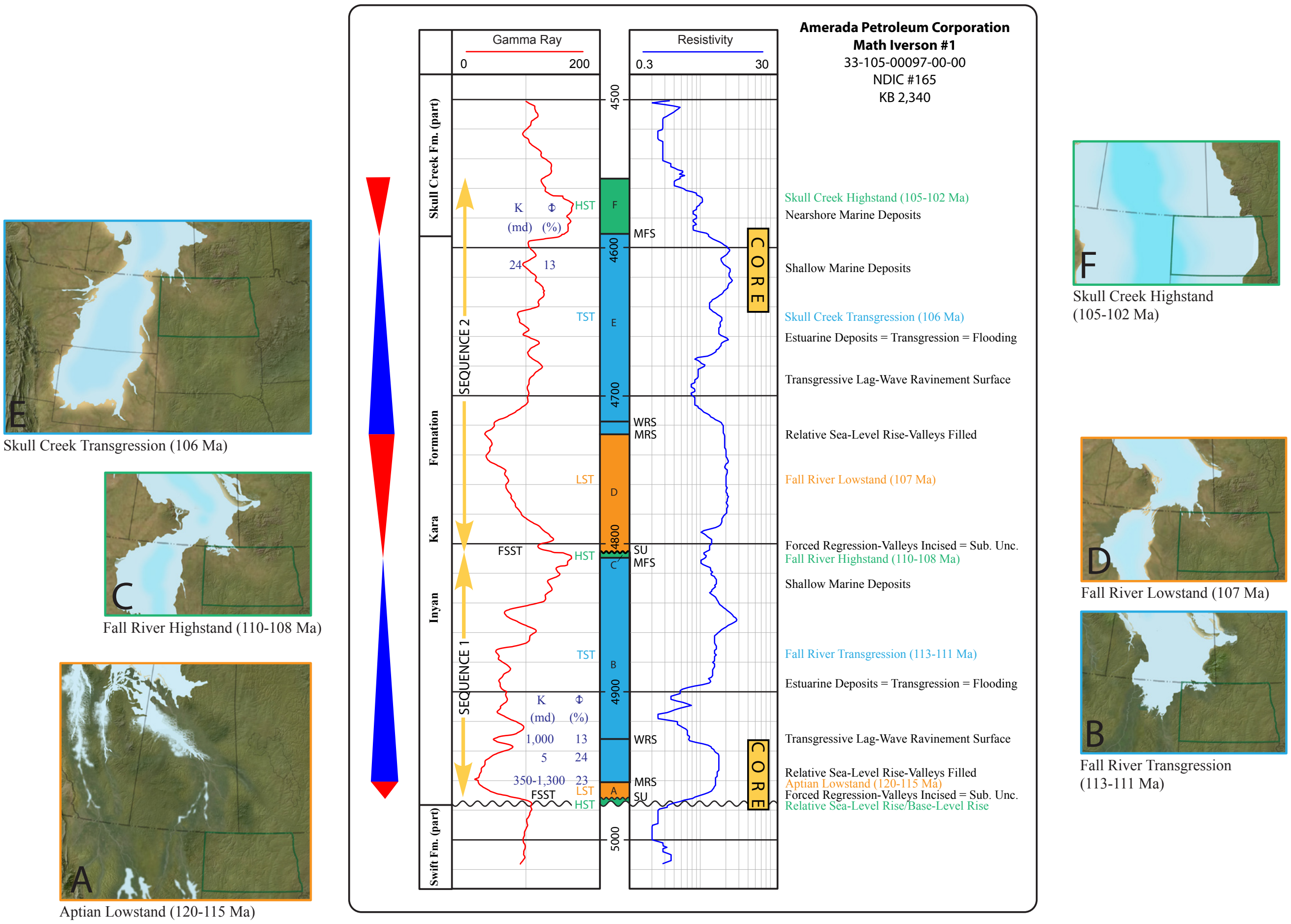

Figure 15. Summary plate of the Math Iverson #1 well log showing sequence stratigraphic surfaces, system tracts, and sequence boundaries along with corresponding depositional events. Red (regression) and blue (transgression) triangle symbols are presented at the left for comparison along with paleogeographic images (Blakey, 2014) from major transgressive/regressive events (A-F). K–Permeability, Phi symbol–Porosity. See Figure 5 for other abbreviation definitions.

Because the system is time transgressive, the Inyan Kara represents a deepening upward package. Valley-fill deposits of the lower sequence are much more fluvial (channel-form sedimentary structures) in character than the upper sequence, which is more estuarine to marine (tidal to marginal marine facies) in character (Fig. 14C). Willis (1997) had similar observations for the Fall River Formation in South Dakota, where he noted that valley fills progress upward from more fluvial to more estuarine and are capped by marine flooding surfaces. Willis (1998) also noted that permeability trends in valley fills also decreased upward and laterally. Permeability and porosity trends from the Math Iverson #1 show similar trends with the most porous and permeable sandstone in the regressive valley fills at the base of each sequence (Fig. 15).

A sequence stratigraphic model for the Inyan Kara from southeastern North Dakota to central Alberta, Canada was developed based on the results of this study and is shown as Figure 16 and Plate III, Figure P6. The Math Iverson #1 was used as a type/reference log for the model. The model is also consistent with Blakey models for the Early Cretaceous Western Interior Seaway (Fig. 15/A-F; Blakey, 2014), as well as sequence stratigraphic principles described in Catuneanu et al. (2009). Moving laterally away from the Math Iverson #1 basinwards and landwards, the model shows the proposed evolution of the system through time with emphasis on coastline trajectories during transgression (retrogradation), normal regression (progradation), and forced regression (erosion). Coastline positions are numbered sequentially from 1 (oldest) to 28 (youngest) and reflect aggradation/degradation during sea-level rise/fall (Fig. 5A). Using the aforementioned sequence stratigraphic surfaces, systems tracts can be identified and correlated laterally to equivalent marine/non-marine environments. Two depositional sequences, S1 and S2, can be identified. Pre-falling stage surfaces are shown as Falling Stages I and II, in order to show the pre-incision nature of shoreline progression from the previous highstand through each falling stage. On these insets, note that pre-incision surfaces such as falling stage deposits, regressive surface of erosion, possibly portions of previous highstand and even transgressive system tracts, may be completely removed during valley incision (e.g., Falling Stage II).

Valley-fill deposits extend into central Alberta in the lower sequence, but only just across the US/Canada border in the upper sequence (Hayes et. al, 1994), marking the initial transgressions of the Cretaceous seaway to the southeast (Figs. 15/A-F and 16). Within the valley-fill wedges, regressive and transgressive sediment packages can be identified by sequence stratigraphic surfaces. In western North Dakota, the valley-fill deposits are generally very-well sorted, fine- to medium-grained sands with 20-30% porosity and permeabilities up to Darcy level, making them ideal reservoirs (Fig. 15). Based on the model, these sandstone bodies become more marine and likely thin to the northwest into Canada (Hayes et al., 1994). To the southeast, the sandstones become more fluvial in nature before completely pinching-out against the Precambrian unconformity in southeast North Dakota (Fig. 16; Plate III, Fig. P6).

CONCLUSIONS

Incised-valley deposits have been described for Lower Cretaceous rocks of the Western Interior Seaway in South Dakota northwards into Canada. However, prior to this study, similar studies have not been performed in western North Dakota. Results of this study indicate that incised valleys were common in North Dakota during deposition of the Inyan Kara Formation based on the following core and wireline-log observations:

- The Inyan Kara is characterized by two coarsening/fining upward packages in both type cores and logs;
- Presence of basal well-sorted sandstones that fine upwards into finer-grained sandstones, siltstones, and claystones;
- Presence of distinct sequence stratigraphic surfaces in core that can be confidently matched with wireline-log signatures;
- Sequence stratigraphic surfaces and systems tracts define two depositional sequences within the Inyan Kara;
- Flood-capped transgressive river mouth deposits (incised valley/estuarine) dominate across western North Dakota;
- Incised valley-fill sandstones contain significant net-sand with lateral continuity parallel to valley trends;
- Valley-fill sandstones have significant thickness, porosity, and permeability, ideal for saltwater disposal reservoirs.

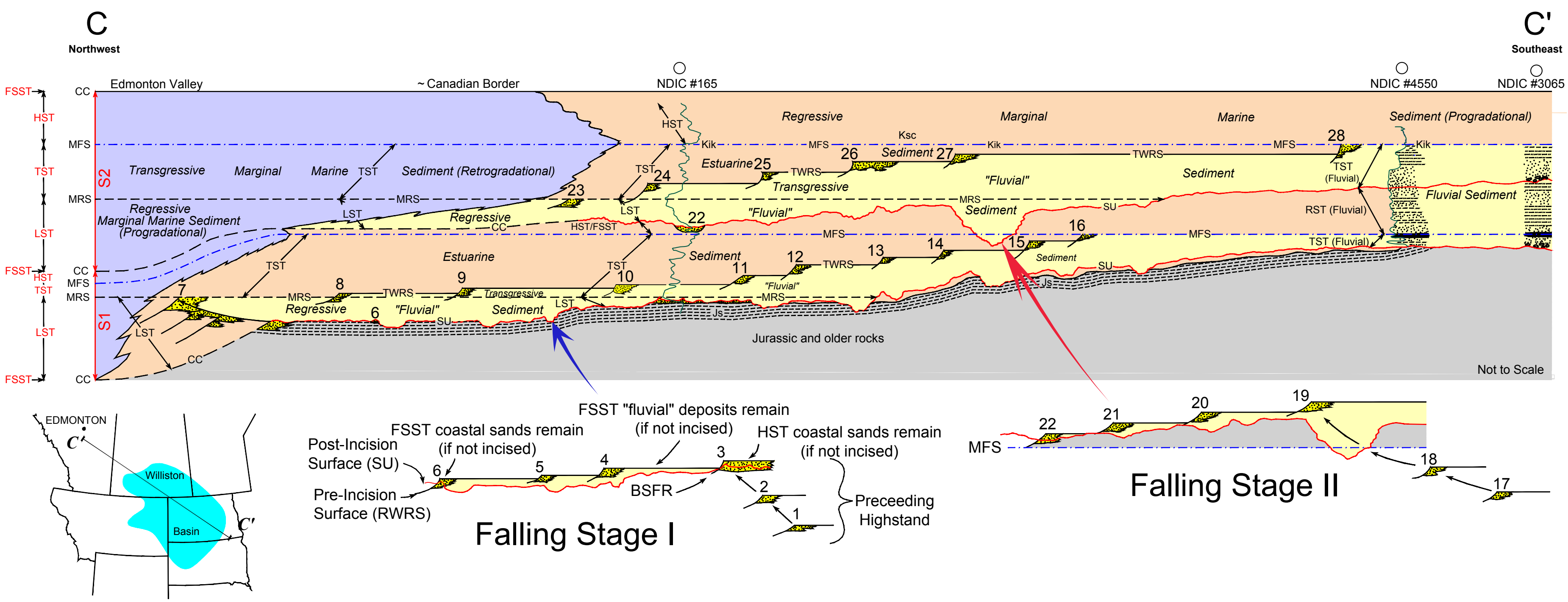

Figure 16. Inyan Kara sequence stratigraphic model showing evolution of coastline through time (Numbers 1-28), sequence stratigraphic surfaces, systems tracts, and sequence boundaries. See Plate III, Fig. P6 for enlarged version. See text for details. S1–Sequence 1, S2–Sequence 2, RWRS–Regressive Wave Ravinement Surface, TWRS–Transgressive Wave Ravinement Surface, Js–Jurassic Swift Formation, Kik–Cretaceous Inyan Kara Formation, Ksc–Cretaceous Skull Creek Formation; see Figure 5 for other abbreviation definitions.

In addition, identification of sequence stratigraphic surfaces, log-based stacking patterns, and core analysis allows for preparation of a sequence stratigraphic model across the depositional dip of the Inyan Kara from southeastern North Dakota to central Alberta, Canada. This model may be used in evaluating sandstone reservoirs for produced water disposal in North Dakota/Canada, and petroleum reservoirs in deeper portions of the Williston and Powder River basins of Montana and Wyoming. In addition, the model may be used/refined for investigations of similar depositional systems.

Understanding and recognition of the proper paleoenvironmental and depositional setting is critical for prediction of reservoir heterogeneity in transgressive river-mouth systems. The development of a regional stratigraphic framework using the principles of sequence stratigraphy allows for accurate regional mapping of reservoirs and, along with geophysical and petrophysical characteristics obtained from cores and logs, facilitates accurate reservoir modeling. This regional stratigraphic network developed by the NDGS is being used by industry and academia to assess applications for produced water production in North Dakota.

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