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Cover

Drone photograph of the north side of Vermillion Creek. The Upper Cretaceous Rock Springs Formation is centered in the photograph. The top of the Rock Springs Formation is just right of center within a prominent valley. Above the Rock Springs Formation is the gray-colored Trail Member of the Ericson Sandstone, followed by the brown colored Rusty zone of the Ericson Sandstone. The Rusty Member also forms a prominent valley. The Canyon Creek Member of the Ericson Sandstone is in the upper right-hand corner of the photograph. The horizontal distance across the center of the photograph is approximately 500 m.

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The Upper Cretaceous Rock Springs Formation of Northwest Colorado—A Previously Undescribed Key Deltaic Outcrop

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ABSTRACT

The Upper Cretaceous Rock Springs Formation of the Mesaverde Group in northwestern Colorado, southwestern Wyoming, and northeastern Utah is composed of fluvial, deltaic, and marine sediments that record the regression of the Western Interior Seaway during the Early to Middle Campanian. Contemporaneous deposits are present along the eastern and southeastern margins of the Greater Green River Basin in Wyoming, but correlation across the basin is challenging. Analysis of a small (1-km-long), understudied outcrop in northwestern Colorado assists in bridging that gap. The outcrop consists of distal and proximal deltaic deposits, overlain by distributary-channel complexes within delta-plain deposits. Correlation panels based on subsurface wireline logs and outcrop gamma-ray profiles show that the deposits are younger than lithostratigraphically equivalent strata of the Rock Springs Formation in Utah and Wyoming. Regional nomenclature is introduced for the area, and it is shown that these deposits differ from better-documented, older Rock Springs Formation deposits in Utah and Wyoming by having a higher net sandstone percentage due to the presence of substantial distributary-channel complexes. This study benefits subsurface exploration efforts in the Greater Green River Basin by providing outcrop analogs of reservoir distribution and quality.

INTRODUCTION

The Upper Cretaceous Rock Springs Formation of the Mesaverde Group in northwestern Colorado, southwestern Wyoming, and northeastern Utah records an overall regression of the Cretaceous Western Interior Seaway during the Early to Middle Campanian (e.g., Roehler, 1993; Plink-Björklund, 2008, 2019; Rudolph and others, 2015). It represents an early-stage sedimentary wedge sourced from the Sevier orogenic fold and thrust belt (Armstrong and Oriel, 1986) and is composed of fluvial, deltaic, shallow marine, and deep marine deposits (e.g., Roehler, 1993; Plink-Björklund, 2008, 2019; Rudolph and others, 2015). The Rock Springs Formation has been studied in detail via outcrops around the Rock Springs uplift and along the northern flank of the Uinta Mountains (e.g., Roehler, 1993; Plink-Björklund, 2008, 2019; Rudolph and others, 2015). Outcrop of the Rock Springs Formation is also present in a small, tectonically complex exposure in northwest Colorado along Vermillion Creek (Sears, 1924, 1925; Hale, 1950) (figure 1). This outcrop has never been studied in detail and its relationship to other outcrops has not been well-established. It is commonly

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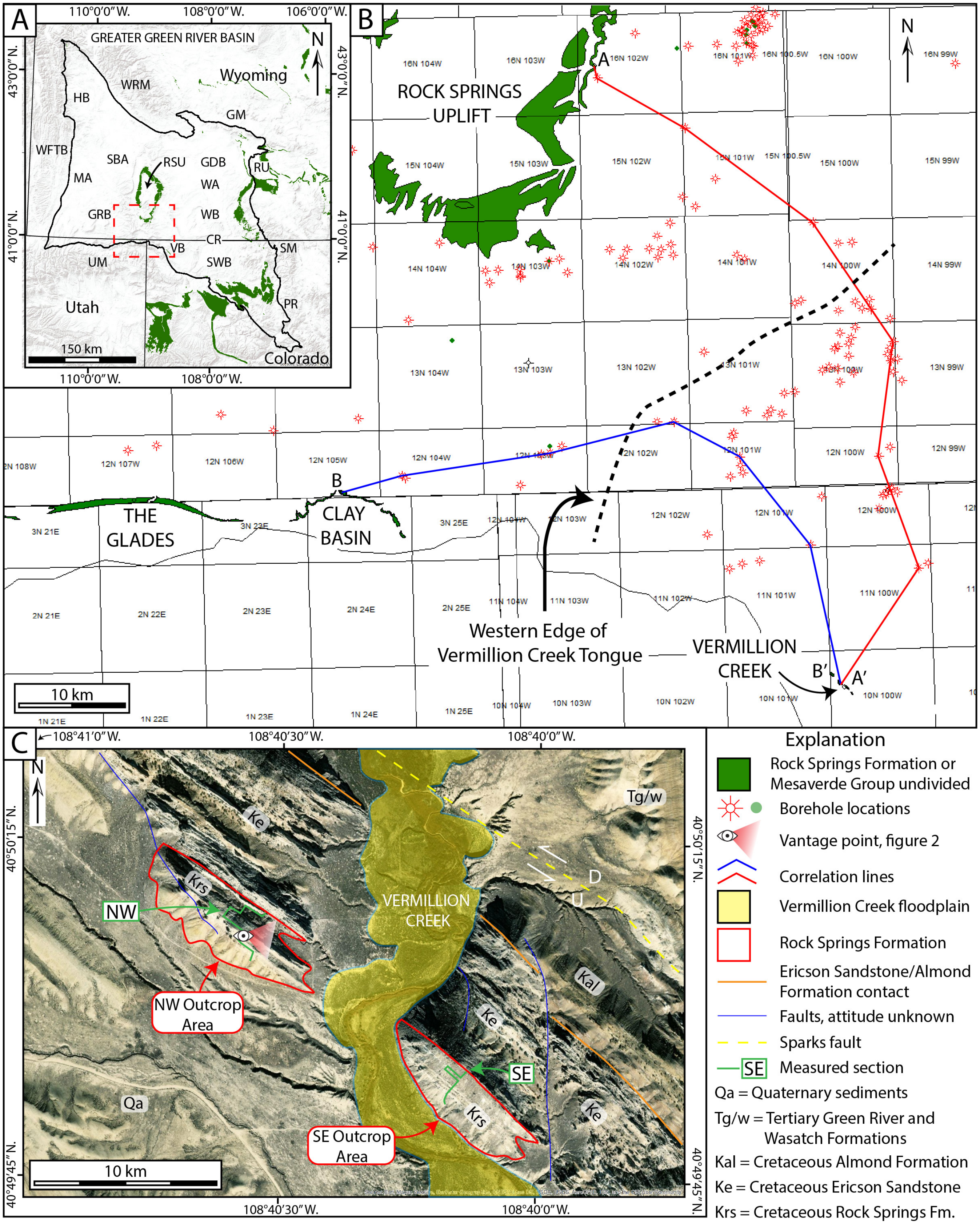

Figure 1. Caption is on the following page.

Figure 1 (figure is on the previous page). Location maps of various scales. (A) Map of the Greater Green River Basin showing the location of the Rock Springs Formation and equivalent rocks. Red dashed box indicates the extent of map shown in B. Basemap attribution: ESRI, USGS, and NOAA. Abbreviations: WFTB = Wyoming fold and thrust belt, HB = Hanna Basin, WRM = Wind River Mountains, SBA = Sandy Bend arch, GM = Granite Mountains, MA = Moxa arch, RSU = Rock Springs uplift, VB = Vermillion Basin, GRB = Green River Basin, UM = Uinta Mountains, GDB = Great Divide Basin, WA = Wamsutter arch, WB = Washakie Basin, CR = Cherokee Ridge, SWB = Sand Wash Basin, RU = Rawlins uplift, SM = Sierra Madre, PR = Park Range. Outcrop pattern in Wyoming is from Love and Christainsen (1985). (B) Map of the study area showing the extent of the Rock Springs Formation outcrop, available well data, and surface to subsurface correlation lines for figure 8. The location of C is also indicated. (C) Satellite image of the Vermillion Creek area showing the location of the Rock Springs Formation outcrop examined in the study. Satellite imagery attribution: ESRI, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community. Cross section is shown on figure 9.

bypassed via subsurface correlation panels that tie the Rock Springs uplift to outcrops on the edge of the Sand Wash Basin, Colorado, even though it represents a strategic tie-point along that transect (Hale, 1955; Douglass and Blazzard, 1961; Keith, 1965; Miller, 1977; Kiteley, 1983; Roehler, 1987; Luo and Nummedal, 2010). The aims of this paper are to present a detailed description of the sedimentology and architecture of the outcrop, interpret depositional settings based on that description, and utilize this information to facilitate a comparison to subsurface geophysical data. Additionally, this paper aims to utilize this information to enable comparisons between outcrops on the north flank of the Uinta Mountains and the east flank of the Rock Springs uplift (figure 1).

A better understanding of the depositional history of this outcrop can inform future studies that utilize subsurface correlation and sequence stratigraphic interpretation. Future paleogeographic reconstructions will also benefit from a better understanding of shoreline position of the Rock Springs Formation deposits through time. Additionally, the Rock Springs Formation has a rich history of economic significance, mainly through the mining of coal in the Rock Springs uplift (e.g., Andrew, 1965; Roehler, 1986; Scott and others, 1995). However, oil and gas accumulation within the Rock Springs Formation is potentially significant, yet unknown, largely because of sparse testing in much of the Greater Green River Basin (Finn and Johnson, 2005; Johnson and others, 2005). This work can inform future exploration efforts through detailed description of facies distribution and reservoir geometry/connectivity in the subsurface of the Washakie and Sand Wash Basins.

GEOLOGIC SETTING

Study Area

The Rock Springs Formation is present in a small tectonically complex exposure on the southern edge of the Vermillion Basin in northwestern Colorado (e.g., Sears, 1924; Hale, 1950; Burger, 1965; Ritzma, 1965, 1971) and is divided into two key outcrop areas by Vermillion Creek—the NW outcrop area and the SE outcrop area (figure 1C). In total, the outcrop stretches for less than 5 km in a northwest-southeast direction with about 1 km of high-quality outcrop (figure 1). The Vermillion Basin is a modern-day basin or topographic low drained by Vermillion Creek and its tributaries (e.g., Nightingale, 1930; Gras, 1955) and is located within the Greater Green River Basin (Rigatti and others, 2007) (figure 1). The Greater Green River Basin is further divided into several sub-basins and uplifts (figure 1).

The outcrop area is located along a northern bounding fault of the Uinta Mountains called the Sparks fault (figures 1 and 2). The Sparks fault is a thrust fault with a sinistral component (Weber, 1971; Johnson and Andersen, 2009) and a history of movement during the late Paleocene to early Eocene (Ritzma, 1965, 1971; Weber, 1971; Bradley, 1995). Faulting and associated folding was followed by erosion and the unconformable deposition of younger Eocene deposits above older rocks (Ritzma, 1965; Bradley, 1995). This is highlighted in the Vermillion Creek area by an angular unconformity that juxtaposes shallowly dipping (2°to 10°) deposits of the Wasatch and Green River Formations against vertical to nearly vertical Cretaceous rocks (Sears, 1924; Ritzma, 1965) (figure 2).

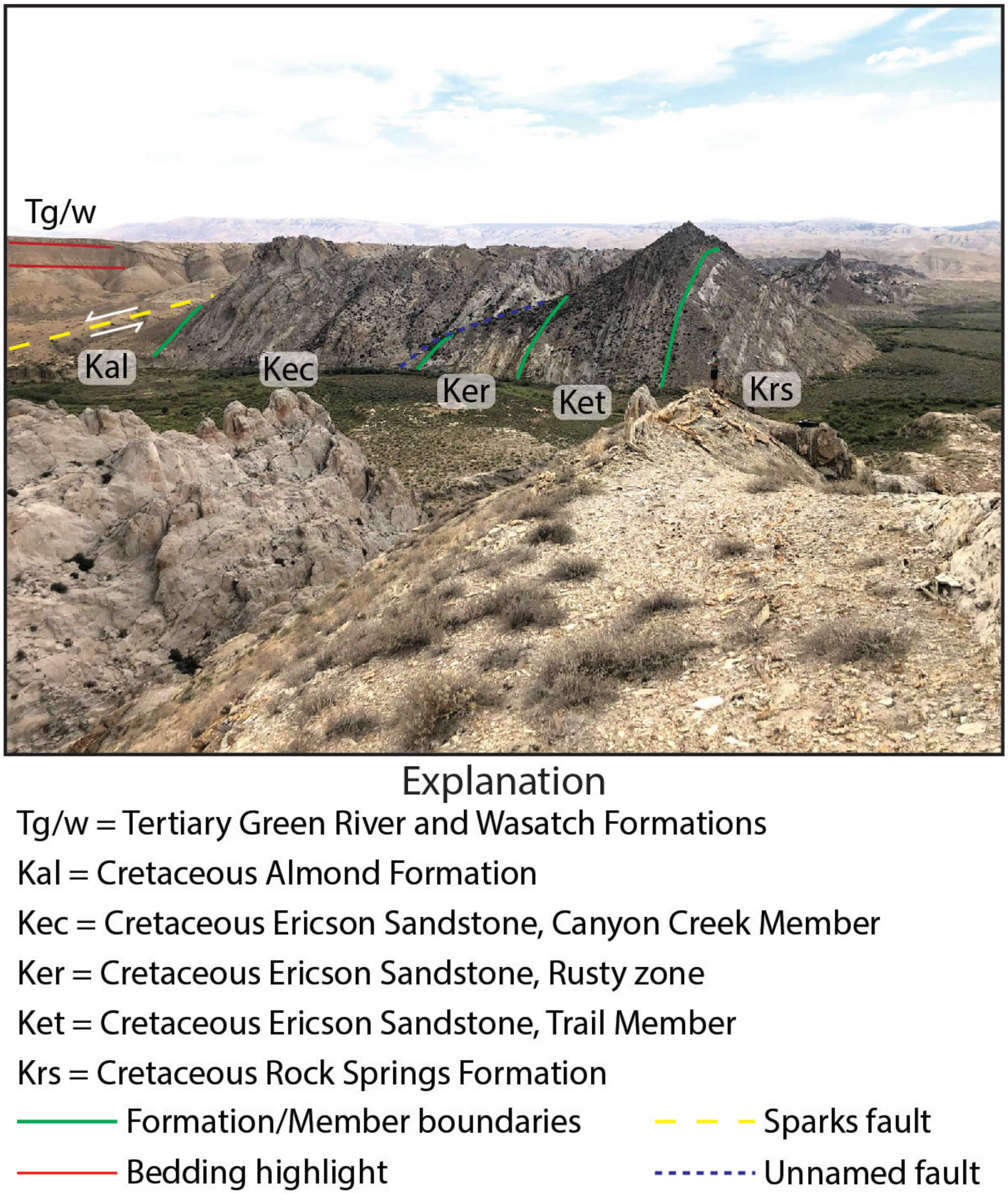

Figure 2. Overview photo of the southeast outcrop (vantage point is from the northwest outcrop). The nearly vertical Cretaceous rocks are annotated as well as the Sparks fault and the nearly horizontal Tertiary Green River and Wasatch Formations.

Additional outcrops of the Rock Springs Formation are located in three distinct areas from the Vermillion Creek area in the Vermillion Basin: Clay Basin is 45 km to the northwest, the Glades is 60 km to the northwest, and the Rock Springs uplift is 50 km to the north (figure 1). Rocks of a similar age, but different lithostratigraphic nomenclature, are also present 105 km east of the Vermillion Creek area on the east edge of the Washakie Basin (Lynds and Slattery, 2017) (figure 1).

The Laramide-age Rock Springs uplift began to form around 79 Ma (Lynds and Xie, 2019). The center of the uplift is cored by the older Baxter and Blair Formations (Schultz, 1920) and the Rock Springs Formation is present around this anticlinal structure in beds that dip away from the center of the uplift (Yourston, 1955) (figure 1). The Glades and Clay Basin outcrops are located on the north flank of the Uinta Mountains and dip northward into the subsurface (Roehler, 1986) (figure 1). Additional data for the Rock Springs Formation is available in the subsurface between these outcrop areas via borehole geophysical logs from oil and gas wells (figure 1).

Stratigraphy

The name "Rock Springs Formation" has its origins in a report by Schultz (1920) where coal-rich continental deposits of the Rock Springs uplift were termed the "Rock Springs coal group." Sears (1925) first used the name "Rock Springs Formation" and Burger (1965) established the eastern flank of the Rock Springs uplift as the type locality for the formation. The Rock Springs Formation has since been subdivided into a series of members or tongues named after various ranches and physiographic features in the Rock Springs uplift. In ascending order, these members are: the Chimney Rock Tongue (Hale, 1950), Black Butte Tongue (Hale, 1950), Brooks Sandstone Tongue (Smith, 1961), Coulson Shale Tongue (Smith, 1961), McCourt Sandstone Tongue (Smith, 1961), and Gottsche Tongue (Roehler, 1965; Smith, 1965) (figure 3). We propose a new member, the Vermillion Creek Tongue, for the Rock Springs Formation. The Vermillion Creek Tongue overlies the Gottsche Tongue and unconformably underlies the Trail Member of the Ericson Sandstone. The McCourt Sandstone and Gottsche Tongues are also present in the Vermillion Creek area. The Rock Springs Formation is underlain by the Blair Formation and unconformably overlain by the Trail Member of the Ericson Sandstone (Sears, 1925; Roehler, 1965; Miller, 1977) (figure 3). Together, the Blair Formation, Rock Springs Formation, Ericson Sandstone, and younger Almond Formation make up the Mesaverde Group in the Rock Springs uplift area (Yourston, 1955) (figure 3).

Chimney Rock Tongue

The basal member of the Rock Springs Formation is called the Chimney Rock Tongue and consists of an upward coarsening, sandy marine wedge that pinches out into marine mudstone to the southeast of the Rock Springs uplift. It also transitions into continental deposits to the northwest. The Chimney Rock Tongue has been interpreted as a wave-dominated deltaic system by many workers (Hale, 1955; Roehler, 1978; Hendricks, 1983; Levey, 1985; Løseth and others, 2006; Plink-Björklund, 2008). The main sandstone wedge consists of proximal and distal delta-front deposits that grade into prodeltaic deposits in a basinward direction (Hale, 1955; Roehler, 1978; Hendricks, 1983; Levey, 1985; Løseth and others, 2006; Plink-Björklund, 2008). Landward of the main sandstone wedge, delta-plain deposits are composed of various depositional environments such as fluvial, lagoonal, bay, estuarine, lacustrine, and swamp (Hale, 1950, 1955; Douglass and Blazzard, 1961; Jacka, 1970). Other workers have favored a shoreface

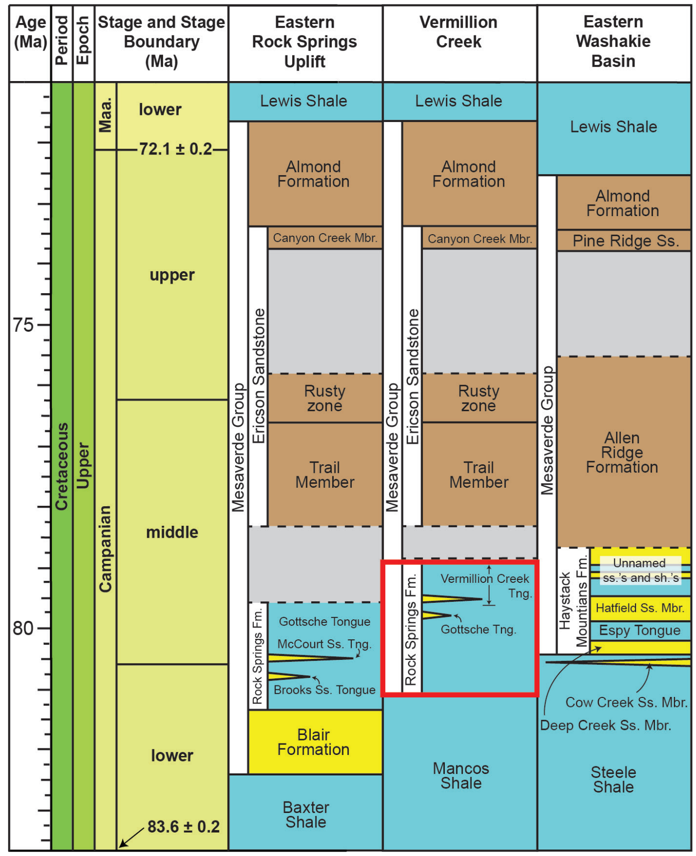

Figure 3. Stratigraphic columns for the eastern Rock Springs uplift, Vermillion Creek area in the Vermillion Basin, and the eastern Washakie Basin. The study interval is highlighted with a red box. Columns and age data are modified from Lynds and Slattery (2017) except for the Vermillion Creek column. Absolute ages for the Vermillion Creek Tongue are not known, therefore, this column is simply placed in its relative position based on stratigraphic relationships.

centric terminology (Roehler, 1990; Purwanto, 2002; VanHolland, 2005; Rudolph and others, 2015).

Black Butte Tongue

The Chimney Rock Tongue is overlain by, and transitional with, marine mudstone deposits of the Black Butte Tongue (Hale, 1950). The Black Butte Tongue weathers recessively forming distinct valleys between the Chimney Rock Tongue and overlying sandy tongues of the upper Rock Springs Formation. It is generally interpreted as a marine prodeltaic deposit (Roehler, 1965, 1978; Kirschbaum, 1985, 1986) or lower shoreface to offshore deposits (Rudolph and others, 2015). These sediments are thought to have been deposited within an embayment bordered by swampy deltaic plains (Hale, 1955). The tongue forms an important subsurface marker that can be correlated over great distances (more than 100 km) and is used to subdivide the lower sandy parts (Chimney Rock Tongue) from the upper sandy parts (Brooks and McCourt Sandstone Tongues) of the Rock Springs Formation (Hale, 1955; Douglass and Blazzard, 1961; Weichman, 1961; Miller, 1977; Hendricks, 1983; Kiteley, 1983; Roehler, 1985, 1987; Luo and Nummedal, 2010; Rudolph and others, 2015).

Brooks Sandstone Tongue

The Brooks Sandstone Tongue is one of two major upward-coarsening marine sandstone units of the upper Rock Springs Formation that pinch out into marine mudstone in a southeastward direction. Deposits of the Brooks Sandstone Tongue transition into continental deposits in a northwestward direction, and the member is not recognized in the far north of the Rock Springs uplift. Equivalent rocks in the north remain undivided. It has not been studied individually, but has been considered in larger scale studies of the Rock Springs Formation and Mesaverde Group (e.g., Roehler, 1965; Hendricks, 1983; Rudolph and others, 2015). It is interpreted as a wave-dominated deltaic system by some authors (Hale, 1955; Douglass and Blazzard, 1961; Roehler, 1978; Hendricks, 1983; Kirschbaum, 1985; Levey, 1985; Uroza, 2008) and as a shoreface system by others (e.g., Rudolph and others, 2015).

Coulson Shale Tongue

The Brooks Sandstone Tongue is overlain by, and transitional with, marine mudstone deposits of the Coulson Shale Tongue. The Coulson Shale Tongue weathers recessively despite having thin sandstone beds, including a regional sandstone marker bed that lies just above the Brooks Sandstone Tongue on the east flank of the Rock Springs uplift, southern Green River Basin, and Clay Basin (Rudolph and others, 2015). The Coulson Shale Tongue has been interpreted as offshore marine (Roehler, 1978; Rudolph and others, 2015) or prodeltaic (Roehler, 1983, 1985, 1986). Similar to the Black Butte Tongue, it forms an important subsurface marker that can be correlated over great distances (more than 100 km). The Coulson Shale Tongue is used to separate sandy deposits of the Brooks and McCourt Sandstone Tongues in the subsurface (Hale, 1955; Douglass and Blazzard, 1961; Weichman, 1961; Miller, 1977; Hendricks, 1983; Kiteley, 1983; Roehler, 1985, 1987; Luo and Nummedal, 2010; Rudolph and others, 2015).

McCourt Sandstone Tongue

The McCourt Sandstone Tongue is the second (upper) of two major upward-coarsening marine sandstone units of the upper Rock Springs Formation that pinch out into marine mudstone in a southeastward direction. Deposits of the McCourt Sandstone Tongue transition into continental deposits in a northwestward direction, and the member is not recognized in the far north of the Rock Springs uplift. Equivalent rocks in the north remain undivided. The McCourt Sandstone Tongue has been studied in detail (Roehler, 1986; Uroza, 2008) as well as in larger-scale studies of the Rock Springs Formation and Mesaverde Group (e.g., Roehler, 1965; Hendricks, 1983; Kirschbaum, 1986, 1989; Rudolph and others, 2015). It has been interpreted as both a deltaic system (Roehler, 1983, 1986; Uroza, 2008) and a shoreface system (Roehler, 1986; Rudolph and others, 2015) on the east flank of the Rock Springs uplift and in the Glades area. In the vicinity of the city of Rock Springs, Wyoming, it has been interpreted as a mixture of wave-dominated deltaic and shoreface deposits (Kirschbaum, 1986, 1989).

Gottsche Tongue

The uppermost member of the Rock Springs Formation on the Rock Springs uplift is the Gottsche Tongue because the upper part of the Rock Springs Formation has been cut out by an unconformity (see figure 3). It is chiefly composed of mudstone with varying amounts of lenticular sandstones and isolated coal beds (Roehler, 1983, 1990). Though early workers commonly combined the Gottsche Tongue with the Ericson Sandstone (e.g., Hale, 1955; Douglass and Blazzard, 1961), they are easily differentiated because the Ericson Sandstone has nearly 100% sandstone and conglomerate, and is generally coarser in grain size than the Gottsche Tongue. The Gottsche Tongue is interpreted as being deposited in freshwater marshes and swamps developed on coastal plains (Roehler, 1983, 1990). Small distributary-channel and splay deposits are locally present and soils are generally poorly drained due to permanent saturation (Roehler, 1990). Between the Rock Springs uplift, Clay Basin, and Vermillion Creek area, the deposits of the Gottsche Tongue transition into fully marine delta-front deposits.

Nomenclatural Issues

Due to lithologic and environmental changes in a northwestward direction, the nomenclature as outlined becomes problematic. Moving landward, sandstone tongues (Chimney Rock, Brooks, and McCourt Sandstone Tongues) transition into rocks of continental origin that lack significant marker beds, and mudstone tongues (Black Butte and Coulson Shale Tongues) pinch out completely. In this northernmost area, workers commonly refer to these rocks as “the main body of the Rock Springs Formation,” as “continental deposits,” as “the coal bearing facies,” or something similar (Hale, 1950; Douglass and Blazzard, 1961; Roehler, 1965).

Some workers have interpreted the outcrops in the Vermillion Creek area as part of the Rock Springs Formation (Burger, 1965; Kiteley, 1983). However, the nomenclature from the Rock Springs uplift has not been introduced to the Vermillion Creek area, possibly due to correlation issues. Historically, most workers have tended to focus on outcrop to the west, north, and east of Vermilion Basin and neglect to include outcrop information from this locality (Hale, 1955; Douglass and Blazzard, 1961; Keith, 1965; Weichman, 1961; Miller, 1977; Kiteley, 1983; Roehler, 1987; Luo and Nummedal, 2010). We introduce a new nomenclatural scheme for the Vermillion Creek area in the Vermillion Basin based on correlation and facies analysis.

Vermillion Creek Tongue

The Vermillion Creek Tongue (a new member and stratotype) is named for Vermillion Creek, which flows through the outcrop area on the southern edge of Vermillion Basin. The type section begins at 40°50'5.84" N., 108°40'34.94" W., and ends at 40°50'7.22" N., 108°40'29.43" W. However, the entire outcrop area, which stretches from approximately 40°50'13.58" N., 108°40'44.04" W. to 40°49'47.13" N., 108°40'1.76" W., can be considered as a type locality. Due to the limited surface exposures of the outcrop belt, a type log (Shell Creek Unit 6, API no. 0508106438) is presented alongside the type measured section for subsurface reference (figure 4). Additionally, the landward extent of the unit is shown on figure 1. The eastward extent of the unit beyond the outcrop is unknown due to sparse well-log data, and uncertain correlation in that direction.

The Rock Springs Formation in the Vermillion Creek area consists of only two tongues: the Gottsche Tongue and the newly named Vermillion Creek Tongue. The Gottsche Tongue can be readily distinguished from the Vermillion Creek Tongue by color and bioturbation. The Gottsche Tongue has a distinct brown color and contains iron-stained burrows and concretions. The Vermillion Creek Tongue is colored various shades of gray to white at its base. The specific sedimentological characteristics of this new tongue are presented in following sections of this paper, and a type section is located to the northwest of Vermillion Creek (figure 4). In short, the Vermillion Creek Tongue differs from the Gottsche Tongue by being composed of a single sand-rich progradational package of deltaic and nearshore delta-plain deposits, whereas the Gottsche Tongue is composed of more landward mud-dominated delta-plain deposits. It is also clearly a younger progradational package separated from the Gottsche Tongue by a flooding surface in the Vermillion Creek area (figure

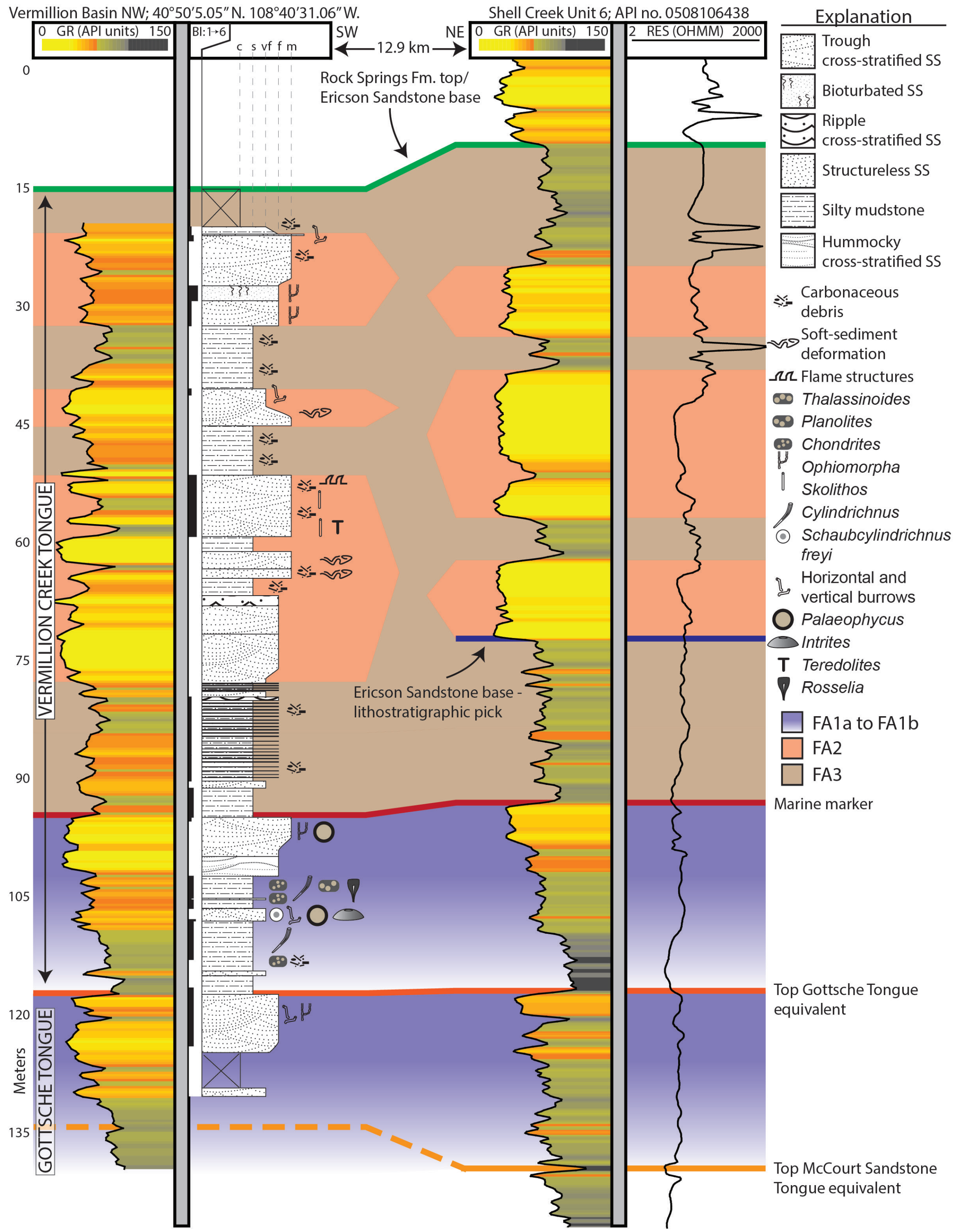

Figure 4. Comparison between the Vermillion Basin NW measured type section from the NW outcrop area and outcrop gamma-ray curve (measurements every 0.5 m) with the nearest along-strike (northeast) subsurface well log. Both coarsening-upwards successions that are present at the outcrop are also present in the subsurface. Additionally, a typical (incorrect) gamma-ray/lithostratigraphic pick for the base of the Ericson Sandstone is shown in blue. The true base of Ericson pick should be made much higher in the well log based on comparison with the outcrop gamma-ray curve. This highlights the usefulness of surface to subsurface ties in the vicinity of the Vermillion Creek area.

4). The Vermillion Creek Tongue's westward extent is limited by erosion prior to deposition of the Ericson Sandstone as well as the transition from nearshore deposits to more landward facies, characteristic of the Gottsche Tongue.

Age Constraints

The Rock Springs Formation was deposited during the Campanian (Roehler, 1986) from 81.71 Ma (*Scaphites hippocrepis* II zone) at its base to approximately 80 Ma (*Baculites maclearni* zone) at the upper erosional unconformity (Luo and Nummedal, 2010) (figure 3). Parts of the Haystack Mountains Formation at the eastern edge of the Washakie Basin are time-equivalent to the Rock Springs Formation, including parts of the Rock Springs Formation that were eroded prior to deposition of the Ericson Sandstone (Luo and Nummedal, 2010) (figure 3). Lynds and Slattery (2017) published a helpful correlation of Upper Cretaceous strata from Wyoming that summarizes radiometric ages and ammonite biozones. The entire marine part of the Rock Springs Formation in the Rock Springs uplift is younger than the Hatfield Sandstone Member of the Haystack Mountains Formation (Lynds and Slattery, 2017); however, some older sandstone units of the Haystack Mountains Formation (Cow Creek Sandstone, O'Brien Spring Sandstone, Bolten Ranch, and Tapers Ranch Sandstone Members) are equivalent to the marine tongues of the upper Rock Springs Formation (Lynds and Slattery, 2017) (figure 3). No age data is available for the Vermillion Creek area.

Surface to Subsurface Correlation

Several workers have attempted subsurface correlation to try and tie outcrops of the Rock Springs uplift with outcrop on the edges of the Greater Green River Basin (Hale, 1955; Hallock, 1960; Douglass and Blazzard, 1961; Weichman, 1961; Keith, 1965; Miller, 1977; Hendricks, 1983; Kiteley, 1983; Roehler, 1985, 1987; Irwin, 1986; VanHolland, 2005; Luo and Nummedal, 2010; Rudolph and others, 2015). Several of these correlations pass very near outcrops of the Rocks Springs Formation in the Vermillion Creek area (Miller, 1977; Kiteley, 1983; Irwin, 1986; Roehler, 1987; Luo and Nummedal, 2010). In spite of the close proximity, these correlations did not incorporate the outcrop data.

Tectonic Setting

The Rock Springs Formation was deposited in a foreland basin (Wiltschko and Dorr, 1983; DeCelles, 1994; Liu and Nummedal, 2004; Luo, 2005). The thrust belt was active in the Campanian causing rapid subsidence in the foreland basin and the creation of significant accommodation (Wiltschko and Dorr, 1983). However, subsidence was not only controlled by flexure near the thrust front, but must also have had a dynamic mantle flow component (Liu and Nummedal, 2004; Liu and others, 2005) as evidenced by rapid and widespread subsidence all across Wyoming, not just in the foredeep depozone (Liu and others, 2005).

The boundary between the Rock Springs Formation and the overlying Ericson Sandstone is a widespread angular unconformity (Smith, 1961; Roehler, 1965; Miller, 1977). The length of time represented by the unconformity is approximately 1.5 million years (Miller, 1977; Kiteley, 1983) (figure 3). During a cessation of thrusting, isostatic rebound and associated erosion took place prior to deposition of the Ericson Sandstone (Liu and Nummedal, 2004; Liu and others, 2005). Deformation progressed eastward through time resulting in the incorporation of foredeep sediments within the thrust belt and erosion of older foredeep sediments, including part of the Rock Springs Formation (DeCelles, 1994; Liu and Nummedal, 2004; Liu and others, 2005).

While it is clear that a foreland basin was present, the basin was likely subdivided or broken by Laramide deformation, which complicates the standard foreland basin model (DeCelles, 2004; Rudolph and others, 2015). Laramide deformation probably began after deposition of the Rock Springs Formation (as early as 79 Ma; Gosar and Hopkins, 1969; Lynds and Xie, 2019), but a pre-Laramide deformational history may have had a local positive effect on subsidence (Hagen and others, 1985).

The overall highly progradational nature of the Rock Springs Formation is generally controlled by high sediment supply derived from the growth and erosion of the thrust belt, coupled with lower accommodation due to slowing subsidence rates (Gill and Cobban, 1973; Hendricks, 1983; Kiteley, 1983; DeCelles, 1994; Hudson and others, 2019). Generally, sedimentation rates were equal to or higher than rates of subsidence (Hendricks, 1983; Kirschbaum, 1986; Devlin and others, 1993; Rudolph and others, 2015). However, during deposition of the transgressive Black Butte and Coulson Shale Tongues, subsidence either increased briefly, or eustatic sea level rose, causing widespread flooding and the deposition of significant marine mudstone over more proximal facies (Hendricks, 1983; Kiteley, 1983; Roehler, 1990; Rudolph and others, 2015).

METHODS

To better understand the variability of deposits in the field area, field data were collected from outcrops on both sides of Vermillion Creek (NW outcrop area and SE outcrop area; figure 1), including photographs and two measured sections. Measured sections include a graphic log with observations of texture, sedimentary structure, bedding, bioturbation, and geomorphic expression. Sections were located based on accessibility. Facies were then defined by grain size, sedimentary structure, and/or bioturbation (table 1; figure 5) and subsequently grouped into associations. Additionally, one scintillometer (Radiation Solutions Inc. RS-230 BGO Super-Spec handheld gamma-ray spectrometer) survey was undertaken to measure the natural radioactivity of the rock along the same path as the measured section in the NW outcrop area (figures 1 and 4) . Measurements were taken every half meter. The resulting gamma-ray profile was then used to correlate units from the outcrop with subsurface gamma-ray curves from boreholes north of the outcrop. Additional outcrop gamma-ray profiles and measured sections were obtained for the east flank of the Rock Springs uplift and for Clay Basin to facilitate correlations between major outcrop areas (figure 1). A gamma-ray cutoff of 65 API units was used for net sandstone calculations on well-log data using IHS Petra.

To map the vertical and lateral architectural element organization within the outcrop, additional photographs were taken using a DJI Phantom 4 Pro drone and used to create a photogrammetric model of the main part of the outcrop (figure 6). Agisoft Metashape Professional was used to develop the photogrammetric model, and interpretations were made using LIME software (Buckley and others, 2019).

Finally, to aid environmental interpretations, samples were collected from mudstone beds throughout the section for pyrolysis. Fresh samples were obtained by digging holes beyond the surface exposure. Whole rock pyrolysis was performed using the HAWK Workstation (Wildcat Technologies). Samples were crushed with a mortar and pestle to 40 mesh size, then combusted to measure evolved hydrocarbons, CO, CO_2, and total carbon (table 2). A standard total organic carbon/carbonate carbon (TOC+CC) method was used where the sample was heated from 300°C to 850°C at a rate of 25°C per minute during the pyrolysis stage, and from 300°C to 850°C at a rate of 25°C per minute during the oxidation stage (Espitalié and others, 1977; Peters and Cassa, 1994).

FACIES ANALYSIS

Facies Association 1 (FA1) – Delta Front

FA1a Distal Delta Front – Description

FA1a deposits are composed of heterolithic very fine grained sandstone and silty shale (10% to 60% sandstone) (figure 5A). Sandstone beds increase in thickness from laminated (< 1 cm) to thick bedded (30 to100 cm) upsection. They are structureless, low to high-angle cross-stratified, planar cross-stratified, hummocky cross-stratified, or wave-rippled (figure 5B) and contain ubiquitous terrestrial organic matter. Laminated parts (both sandstone and mudstone) of the association have no discernible burrowing. When beds reach cm-scale, *Chondrites* (figure 7A), *Planolites, Schaubcylindrichnus freyi,* and *Cylindrichnus* (figure 7B) burrows are present with a maximum bioturbation index (BI) of 3 (Reineck 1963; Taylor and Goldring, 1993). Bioturbation intensity is highly variable on the bed scale. Thicker sandstone beds may contain *Palaeophycus* (figures 7C and 7D), *Thalassinoides*, *Chondrites*, *Planolites*, *Rosselia rotatus* (figure 7E), *Cylindrichnus, Neonereites multiserialis* (figure 7F), *Intrites* (cf., Menon and others, 2017) (figure 7C), and tool marks (figure 7C), especially along both basal and

Table 1. Facies in the Rock Springs Formation.

Facies Code	Facies Name	Sedimentary Structures, Textures, and Additional Notes	Bedding	Facies Association
Ss1	Trough cross-stratified sandstone	Very fine to medium grained; variable cementation; commonly contains carbonaceous debris; *Ophiomorpha*, *Thalassinoides*; high and low-angle foresets	Thin to medium	FA1 FA2 FA3
Ss2	Asymmetric ripple cross-stratified sandstone	Fine to medium grained; variable cementation; *Skolithos*	Very thin to thin	FA2
Ss3	Symmetric ripple cross-stratified sandstone	Very fine to fine grained; variable cementation; commonly contains carbonaceous debris; *Skolithos*	Very thin to thin	FA2
Ss4	Planar cross-stratified sandstone	Very fine to fine grained; variable cementation; indistinct horizontal burrows	Thin to medium	FA1a
Ss5	Hummocky to swaley cross-stratified sandstone	Fine grained; variable cementation; contains carbonaceous debris; *Ophiomorpha*	Medium	FA1a
Ss6	Bioturbated or rooted sandstone	Very fine to medium grained; variable cementation; bioturbation has nearly to completely destroyed original bedding and sedimentary structures; *Ophiomorpha*, *Thalassinoides*, *Planolites*, *Chondrites, Chondrites, Schaubcylindrichnus freyi, Cylindrichnus, Paleophycus, Rosselia rotatus, Neonereites multiserialis*	Medium or obscured	FA2
Ss7	Soft-sediment deformed sandstone	Medium grained; variable cementation; commonly contains carbonaceous debris	Very thin to thick	FA1 FA2
Ss8	Structureless sandstone	Very fine to medium grained; variable cementation; *Ophiomorpha*	Medium or obscured	FA1 FA2 FA3
M	Silty mudstone	Structureless to laminated; nodular or chippy to fissile; *Chondrites*	Laminated	FA1 FA3
L	Pebble lag	Pebbles are composed of mud clasts that typically weather leaving voids along basal surfaces; *Apectoichnus longissimus* in woody debris	NA	FA2
C	Coal and carbonaceous mudstone	Contains carbonaceous debris; true coal exhibits well-developed cleats	Laminated to medium	FA3

upper bedding planes (figure 7B; BI up to 3). Minor (cm-scale) load features are common on the base of sandstone beds. The shale beds are laminated and fissile to chippy. The association is recessive, but locally, exceptionally well exposed due to the vertical attitude of the bedding. Where exposed, beds appear to maintain thickness laterally.

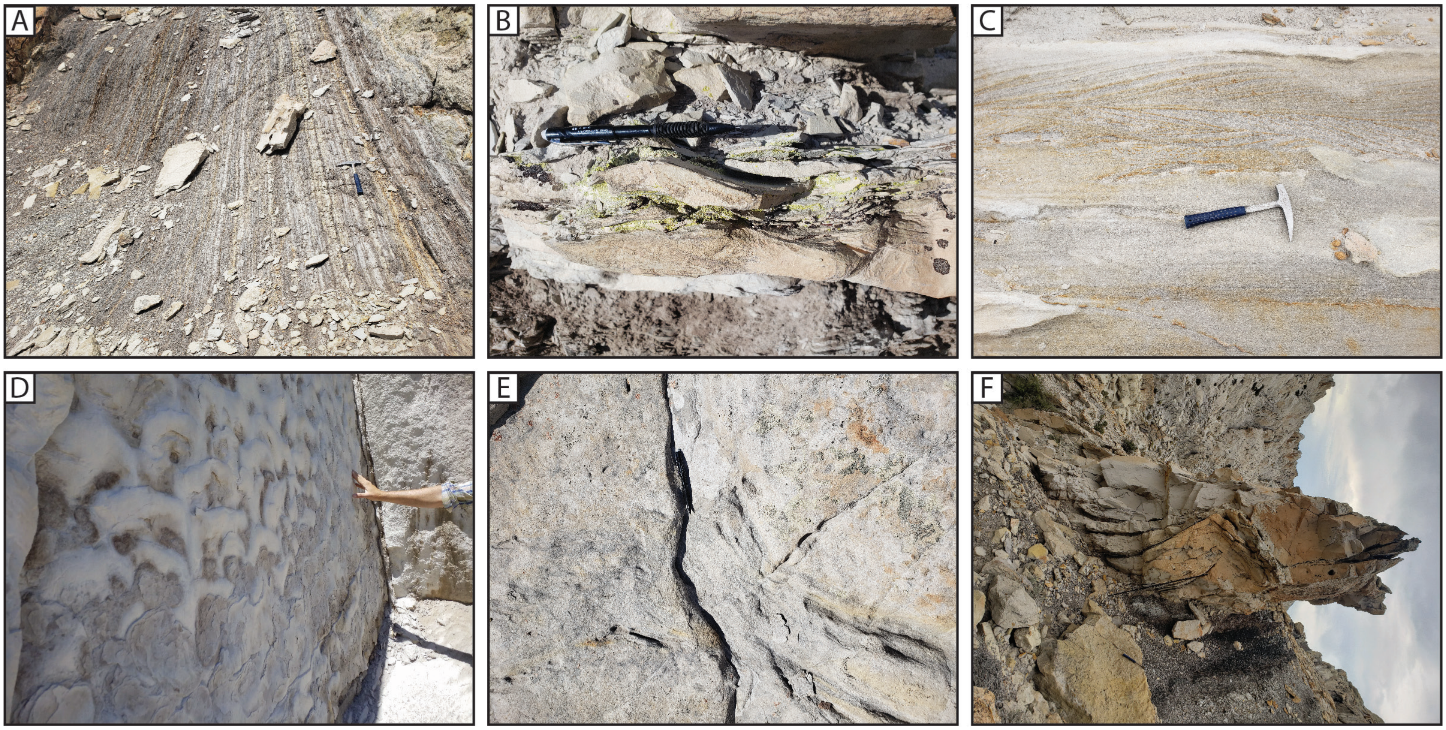

Figure 5. Selected facies from the Vermillion Creek area. (A) Interbedded sandstone and silty mudstone which includes facies M, Ss1, Ss3, Ss4, and Ss7. (B) Symmetrical rippled sandstone (Ss3). (C) Trough cross-stratified sandstone (Ss1). (D) Asymmetrical rippled sandstone (Ss2). (E) Small-scale soft-sediment deformed sandstone (Ss6). (F) Large-scale soft-sediment deformed sandstone (Ss6) within distributary channel deposits. Note that F has been rotated to horizontal (top is to the right) to highlight that this slump feature occurred at the base of the sandstone.

FA1b Proximal Delta Front – Description

FA1b deposits are composed of very fine to medium grained, medium bedded (10 to 30 cm), low- to high-angle trough cross-stratified, structureless, or soft-sediment deformed sandstone. Bioturbation is composed of locally abundant, but typically sparse, *Ophiomorpha* (figure 7G) or *Palaeophycus* burrows (BI = 1 to 2). Both basal and upper contacts are sharp. The unit is laterally continuous across the entire outcrop.

Interpretation and Depositional Setting

We interpret the deposits of FA1 as marine-deltaic. Several key criteria for a deltaic deposit are outlined in the literature: (1) a direct link to feeding rivers can be identified, (2) significant progradation occurred indicating a fluvial sediment source, (3) deposits are upward-shallowing, (4) seaward-dipping clinoforms are present, and (5) the deposit is lobate or elongate as a shoreline protuberance (e.g., Kirschbaum, 1989; Roehler, 1990; Bhattacharya, 2006, 2010). No direct link to feeding rivers could be established for the lowermost deposits exposed in the Vermillion Creek area possibly due to wave reworking of the delta front, and also possibly due to limited spatial outcrop exposure. However, these deposits are overlain by delta-plain and distributary-channel deposits (figure 6), which do indicate a direct link to a fluvial source, at least for younger deposits (e.g., Bhattacharya, 2006, 2010). The abundance of terrestrial organic matter is also likely derived from a fluvial source on or near a delta. Additionally, the presence of *Intrites* structures and soft-sediment deformation indicate high sedimentation rates potentially associated with fluvio-deltaic sedimentation (e.g., Bhattacharya, 2006, 2010; Menon and others, 2017). Progradation can be established to be at least 15 km downdip

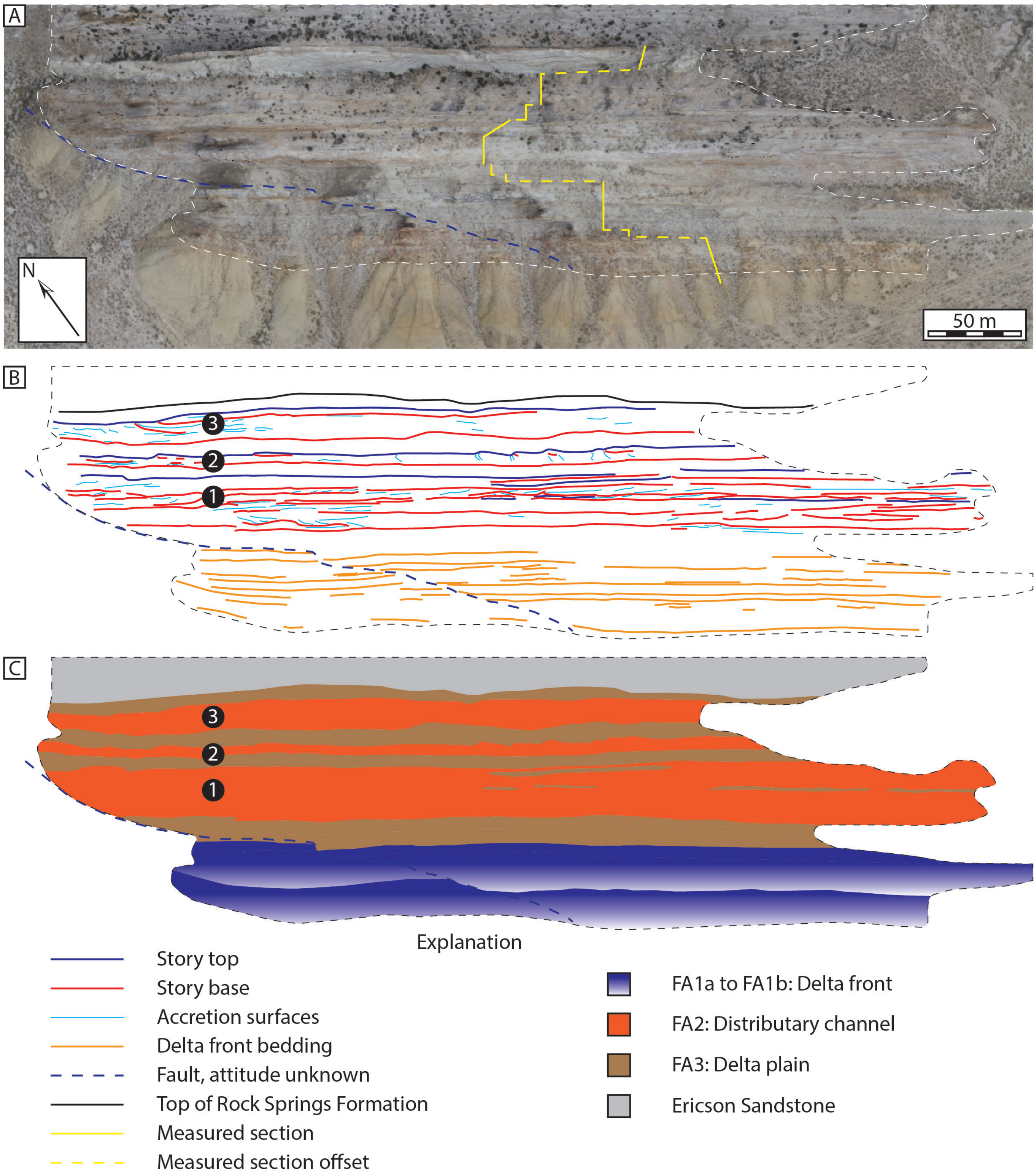

Figure 6, part 1. Virtual outcrop interpretations for the NW outcrop area northwest of Vermillion Creek. (A) Aerial view of the NW outcrop looking straight down from above. Solid yellow line represents measured section segments and dashed yellow line represents section offsets. (B) Line drawings of the NW outcrop indicating important surfaces and channel complexes (1 through 3). (C) Facies map of the NW outcrop indicating various depositional environments. Refer to figure 1 for location of outcrop area.

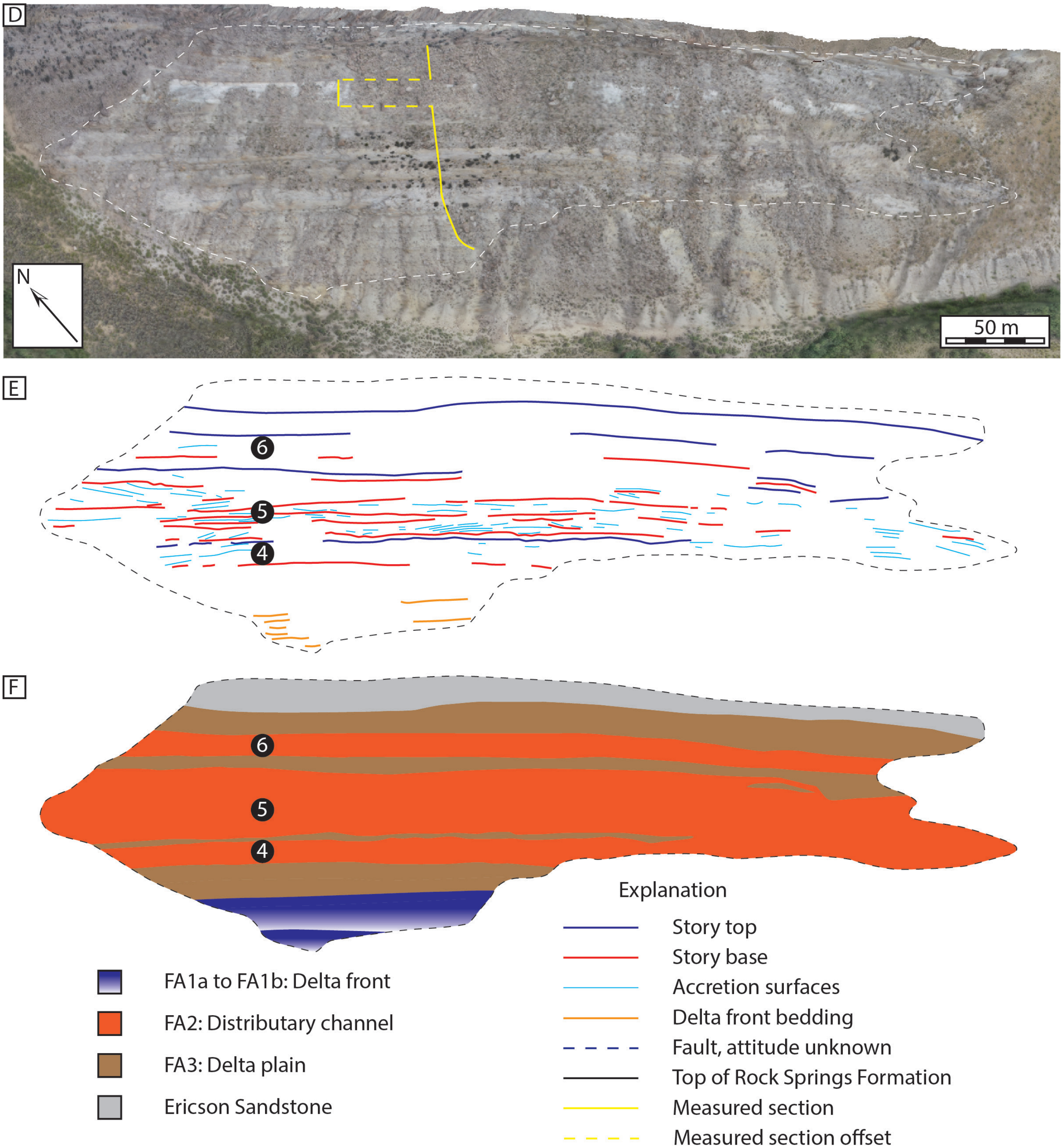

Figure 6, part 2. Virtual outcrop interpretations for the SE outcrop area southeast of Vermillion Creek. (D) Oblique aerial view of the SE outcrop. Solid yellow line represents measures section segments and dashed yellow line represents section offsets. (E) Line drawings of the SE outcrop indicating important surfaces and channel complexes (4 through 6). (F) Facies map of the SE outcrop indicating various depositional environments. Refer to figure 1 for location of outcrop area.

Table 2. Pyrolysis data in stratigraphic order with sample DP-L near the top of the Rock Springs Formation and sample PS1-1 near the base. See figure 8 for sample locations.

Sample ID	S1 (mg/g)	S2 (mg/g)	S3 (mg/g)	PI	TOC (%)	Tmax (°C)	HI	OI	Kerogen Type	Facies Association
DP-L	3.33	51.04	11.24	0.06	10.26	424	497	109	II	FA3
DP-K	1.1	16.17	4.59	0.06	5.96	425	271	77	II/III	FA3
DP-J	0.77	14.95	5.93	0.05	5.89	423	253	100	II/III	FA3
DP-I	0.38	1.01	0.69	0.28	0.87	412	115	79	III	FA3
DP-H	0.73	1.1	0.75	0.4	1.06	409	103	71	III	FA3
DP-G	0.24	0.43	0.75	0.36	0.72	409	59	103	III	FA3
DP-F	7.84	110.72	19.02	0.07	17.02	423	650	111	I	FA3
DP-E	3.52	27.77	8.51	0.11	10.1	418	274	84	II/III	FA3
DP-D	1.84	45.93	23.35	0.04	15.28	425	300	152	II	FA3
DP-C	2.06	10.89	1.93	0.16	3.58	425	303	53	II	FA3
DP-B	0.3	1.26	0.6	0.19	0.74	429	169	80	III	FA3
DP-A	2.99	17.2	2.77	0.15	4.41	426	390	62	II	FA3
DP-A-EQ	1.37	19.61	4.45	0.07	6.1	430	321	72	II	FA3
DP-7	0.44	0.43	0.56	0.51	0.59	363	71	94	III	FA3
DP-6	0.46	0.45	0.55	0.51	0.58	394	78	95	III	FA3
DP-5	0.36	0.45	0.58	0.45	0.71	417	62	81	III	FA3
DP-4	0.33	0.36	0.34	0.48	0.35	316	102	97	III	FA3
DP-3	0.65	1.01	0.96	0.39	1.32	418	76	72	III	FA3
DP-2	0.35	0.39	0.5	0.47	0.49	369	79	102	III	FA3
DP-1	0.36	0.77	0.62	0.32	0.94	412	81	65	III	FA3
PS2-7	0.28	1.62	0.94	0.15	1.49	427	108	62	III	FA1a
PS2-6	1.18	1.92	1.31	0.38	1.65	415	116	79	III	FA1a
PS2-5	0.33	0.98	0.92	0.25	1.16	415	84	79	III	FA1a
PS2-4	0.52	1.49	1.24	0.26	1.49	417	99	82	III	FA1a
PS2-3	0.46	1.32	0.98	0.26	1.38	416	95	70	III	FA1a
PS2-2	0.44	1.19	0.82	0.27	1.28	423	92	64	III	FA1a
PS2-1	0.21	1.35	1.05	0.14	1.15	428	116	91	III	FA1a
PS1-4	0.15	0.27	0.32	0.35	0.33	428	80	97	III	FA1a
PS1-3	0.25	0.49	0.44	0.33	0.45	427	109	97	III	FA1a
PS1-2	0.09	0.19	0.29	0.32	0.27	434	71	105	III	FA1a
PS1-1	0.19	0.77	1.02	0.2	0.84	428	92	121	III	FA1a

(southeast) via subsurface correlation, but to the east and southeast of the outcrop, well data is too sparse for confident correlation. Progradation may be up to 27 km based on available well data. For comparison, the McCourt Sandstone Tongue can be correlated at least 70 km in the subsurface with outcrop control over much of that distance. The McCourt Sandstone Tongue has been interpreted as deltaic by many authors, and meets all of the aforementioned criteria for deltaic deposits (Roehler, 1983, 1986; Uroza, 2008). The deposits of FA1 do meet the criteria that the deposits be upward-shallowing. This is evidenced by the increase in more proximal facies over more distal facies. However, other systems also exhibit upward shallowing of facies such as shore-

Figure 7. Selected photographs of trace fossils. (A) *Chondrites* burrows (Ch). (B) *Cylindrichnus* burrow (Cy). (C) *Palaeophycus* burrows (P), tool marks (T), and *Intrites* (i). (D) *Palaeophycus* burrows (P) and *Ophiomorpha* burrows (O). (E) *Rosselia rotatus* burrow (R). (F) *Neonereites multiserialis* traces (N). (G) *Ophiomorpha* burrows (O) within the proximal delta-front sandstone. (H) *Apectoichnus longissimus* borings (A). (I) Heavily bioturbated distributary channel sandstone. All traces are *Ophiomorpha* (O).

face systems and bayhead deltas. The outcrop is not extensive enough to identify any clinoformal surfaces, and we cannot prove deltaic geometry with available data.

Deltaic environments are commonly stressed due to high turbidity and lowered salinity (e.g., Howard and Frey, 1973; Wightman and others, 1988; Pemberton and Wightman, 1992; Bhattacharya, 2006, 2010). The relatively low BI in the Vermillion Creek area more closely matches the expectations for deltaic shorelines rather than shoreface systems that are distant from active deltaic processes. Furthermore, the trace fossil assemblage for deposits of FA1 (*Rosselia rotatus, Planolites, Schaubcylindrichnus freyi, Cylindrichnus, Thalassinoides*, and *Chondrites*) are referable to the *Rosselia* ichnofacies of sandy delta-front deposits (MacEachern and Bann, 2020). The variable, and generally low, BI are characteristic features of this ichnofacies (MacEachern and Bann, 2020). The variable bioturbation intensity at the bed scale is another feature common to the *Rosselia* ichnofacies, and may indicate variable physico-chemical stresses common in deltaic environments (MacEachern and Bann, 2020). The presence of *Neonereites multiserialis* is a noteworthy departure from expectations for deltaic sediments. Examples from the literature suggest that these traces are confined to deep water flysch (e.g., Pickerill, 1991; Cherif and Naimi, 2021) or lower shoreface to offshore transition deposits (e.g., Bouchemla et al., 2021). The noted presence of *Neonereites multiserialis* may be the first instance of that trace in delta-front sediments.

Architecture

FA1a deposits are overlain by FA1b deposits, and there are two repeated successions of this stacking pattern (figure 6). The lowermost succession is obscured at its base by Quaternary sediments (figure 6), so its association with underlying sediments cannot be ascertained at the outcrop. However, correlations to subsurface boreholes via wireline logs indicate relatively high gamma-ray readings suggestive of shale deposits (figure 4). The second succession is overlain by deposits of FA3 (delta plain; figure 6).

Facies Association 2 (FA2) – Distributary Channel

Description

FA2 deposits are dominantly composed of fine to medium grained sandstone with minor interbeds of mudstone. Beds range from thin to thick bedded. The dominant sedimentary structure is unidirectional trough cross-stratification (figure 5C), but asymmetrical rippled (including climbing ripples; figure 5D) and soft-sediment deformed sandstone (figures 5E and 5F) is common. Sandstone can sometimes appear structureless. Symmetrical ripples are present at the tops of some units. Internal mud-clast lags are also present and carbonaceous debris is common throughout. *Apectoichnus longissimus* (figure 7H) and *Skolithos* burrows are present as well as locally abundant *Ophiomorpha* (figure 7I). The BI is highly variable from 0 up to 4. Basal contacts are sharp and scoured. Master bedding surfaces extend from the top to the base of each unit (figure 6). Individual sandstone bodies pinch out laterally and have a lensoidal geometry except in cases where the edges of the bodies are obscured. The association can be underlain or overlain by additional FA2 (distributary channel) deposits or by FA3 (delta plain) deposits (figure 6).

Interpretation and Depositional Setting

These deposits are interpreted as distributary-channel deposits near and behind the delta front. Master bedding surfaces that extend from the top to the base of individual channel bodies are interpreted as accretion surfaces and may include lateral and/or downstream components (figure 6). The lensoidal geometry of these deposits coupled with the presence of distinct accretion surfaces suggests a fluvial origin (e.g., Miall, 2010). However, the presence of *Ophiomorpha* and brackish-water *Apectoichnus* (previously *Teredolites*) burrows suggests close proximity to marine conditions in distributary channels (e.g., Bromley and others, 1984; Gingras and others, 2004, 2005; Donovan, 2018; King and others, 2020).

Architecture

FA2 deposits (distributary channel) are arranged in multistory and multilateral channel complexes with intervening FA3 deposits (delta plain). There are a total of six complexes, and no attempt has been made to correlate complexes between the northwest and southeast outcrops. Complexes 1, 2, 3, and 5 exhibit both multistory and multilateral architectures (figure 6). Individual complexes range from 2 to 6 stories. Complex 4 and 6 suffer from poor exposure making identification of story surfaces difficult (figure 6). However, for complex 4, variable dip directions for interpreted master bedding surfaces indicates higher complexity than what is apparent from the virtual outcrop data (figure 6). It is likely that all six complexes are multistory and multilateral.

Facies Association 3 (FA3) – Delta Plain

Description

FA3 deposits are composed of silty mudstone, silty carbonaceous mudstone (figure 5F), coal (figure 5F), and isolated, very thin (1 to 3 cm) to medium (10 to 30 cm) beds of very fine to fine-grained carbonaceous sandstone. Sandstone beds can be trough cross-stratified or structureless. Carbonaceous debris and wood fragments are common throughout. The association is usually overlain and underlain by FA2–distributary channel deposits (figure 6). However, it also overlies deposits of FA1b–proximal delta front (figure 6).

Interpretation and Depositional Setting

These deposits are interpreted collectively as deposits of the delta-plain environment. The abundance of carbonaceous material, coal beds, and lack of marine bioturbation suggests a continental origin. Thin sandstone deposits are likely crevasse splays (e.g., Allen, 1964; Miall, 2010) and coal beds indicate the presence of swampy conditions on the delta plain (Roehler, 1983, 1990).

PYROLYSIS

Thirty-one samples were collected from mudstone beds along the measured section in the NW outcrop area in order to better understand kerogen types within various units (figure 8). Pyrolysis data shows variability in organic matter type and richness throughout the section. Data from samples representing delta-front strata (FA1) indicate a relatively low hydrogen index (HI; 50 to 200) typical of type III, terrestrially sourced kerogen (table 2; figure 8). All samples contain coal flecks that are sometimes visible with the naked eye, and always visible with the aid of a hand lens (10x). Low HI values in delta-front deposits are likely due to significant terrestrial input from fluvial point sources on a delta (e.g., Meilijson and others, 2020).

Samples taken from delta-plain strata (FA3) exhibit a wider range of HI (59 to 650; table 2; figure 8). Samples with the highest HI values correspond with the highest TOC (table 2). These samples contain significant carbonaceous material, that is visible to the naked eye, yet have HI values that indicate a mixed type II/III kerogen. This suggests that FA3 deposits consist of a mix of humic and algal kerogens. While not common, coal-bearing strata can contain mixed kerogen types (e.g., Fleet and Scott, 1994). Peat swamps can contain algal matter via marine flooding (Bagge and Keeley, 1994) or non-marine lacustrine facies variation (Parnell, 1988; Powell and Boreham, 1994; Thompson and others, 1994). Both scenarios are possible for the FA3 deposits in the Vermillion Creek area. With HI values as high as 650 (sample DP-F), there is also the possibility that some samples contain some type I kerogen. Type I kerogens are algal and distinctly lacustrine in origin, suggesting lacustrine influence. Coal and lacustrine deposition often take place in close proximity to each other, with ponded waters commonly occurring in a poorly drained delta-plain environment, and can be gradational through time forming two separate end members of a depositional continuum (Fleet and Scott, 1994).

CORRELATION

Two correlation panels have been created to tie the sections in the Vermillion Creek area to the Rock Springs uplift and Clay Basin (figure 9). In attempting to correlate between these outcrops, it was first necessary to determine how the section in the Vermillion Creek area compared to the closest available borehole wireline data along depositional strike (figure 4). Of interest is the interpretation of the basal contact of the Trail Member of the Ericson Sandstone. This contact has historically been located at the base of a significant increase in net sandstone and grain size, as determined by the abundance of low gamma-ray response in wireline logs (e.g., Kiteley, 1983; Roehler, 1987) (figure 4); a purely lithostratigraphic interpretation. Our outcrop gamma-ray measurements indicate that the uppermost Rock Springs Formation deposits also have this same log response, and we have interpreted the basal erosional unconformity of the Ericson Sandstone as much higher in the section than previous workers (Kiteley, 1983; Roehler, 1987) (figure 4).

Correlation between major outcrops was aided by the use of high-confidence picks that could be matched to outcrop gamma-ray curves (figure 9). These high-confidence picks include the Rock Springs Formation/Ericson Sandstone contact, the flooding surface of the Coulson Shale Tongue, and minor flooding surfaces within and above the McCourt Sandstone Tongue (figure 9). We also make the assumption that the Ericson Sandstone members are relatively isopachous over short distances (about 10 km or less). Over larger distances (many tens of km), the Ericson Sandstone thickens gradually eastward (figure 9). Thicknesses of the Ericson Sandstone in the Vermillion Creek area were measured from satellite imagery with the assumption that the deposits are nearly vertical, similar to the Rock Springs Formation in the area.

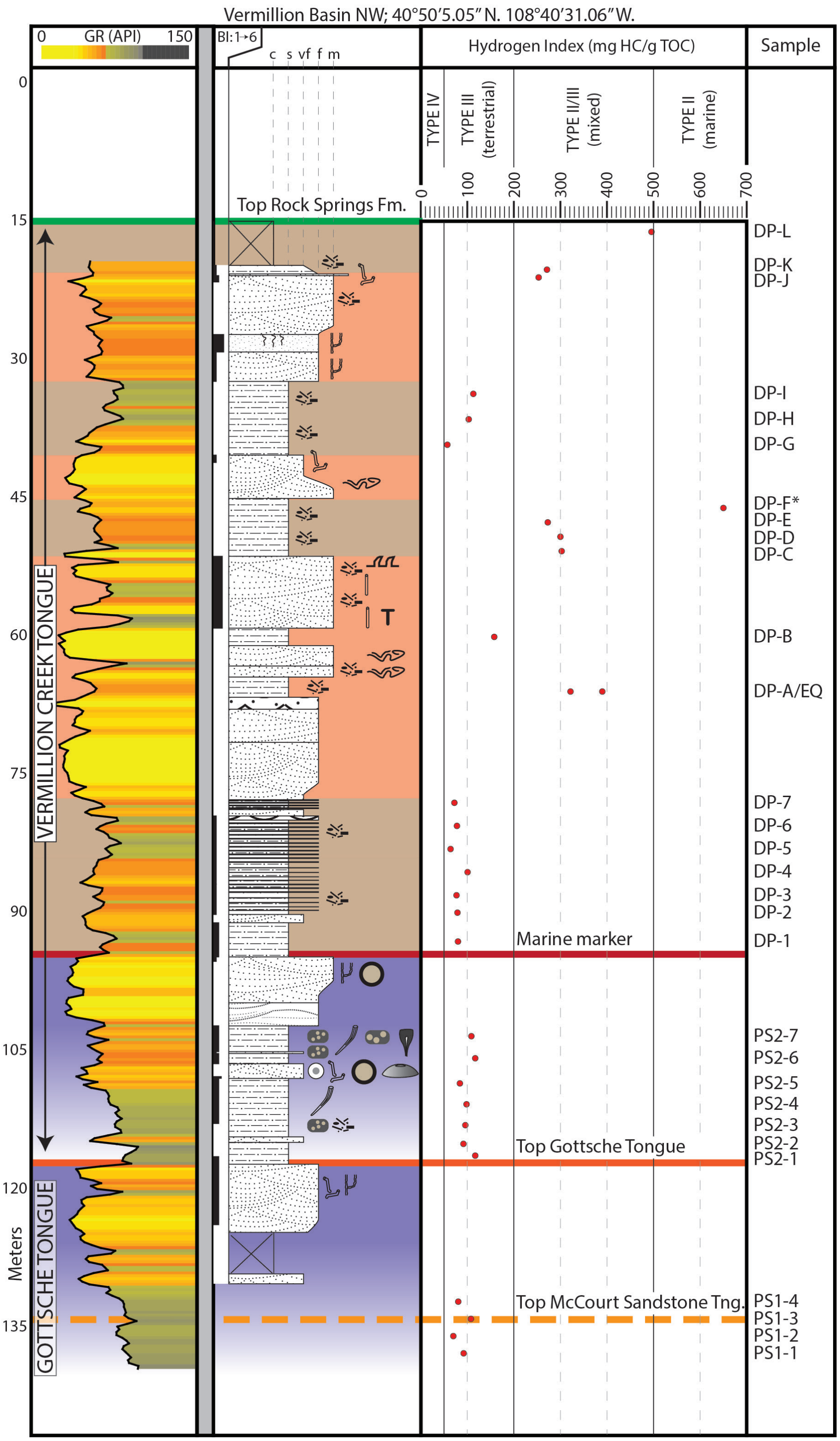

Figure 8. Hydrogen Index (HI) shown with the Vermillion Basin NW section from the NW outcrop area. HI values are typically indicative of type III, terrestrial kerogen or type II/III mixed terrestrial/marine or possibly lacustrine kerogen*. The abundance of type III kerogen suggests a heavy fluvial source common in deltaic settings. Note that measured section data does not extend as low as gamma-ray data due to outcrop quality. Holes were dug through cover to obtain the lowermost gamma-ray measurements. Refer to figure 4 for explanation of symbols.

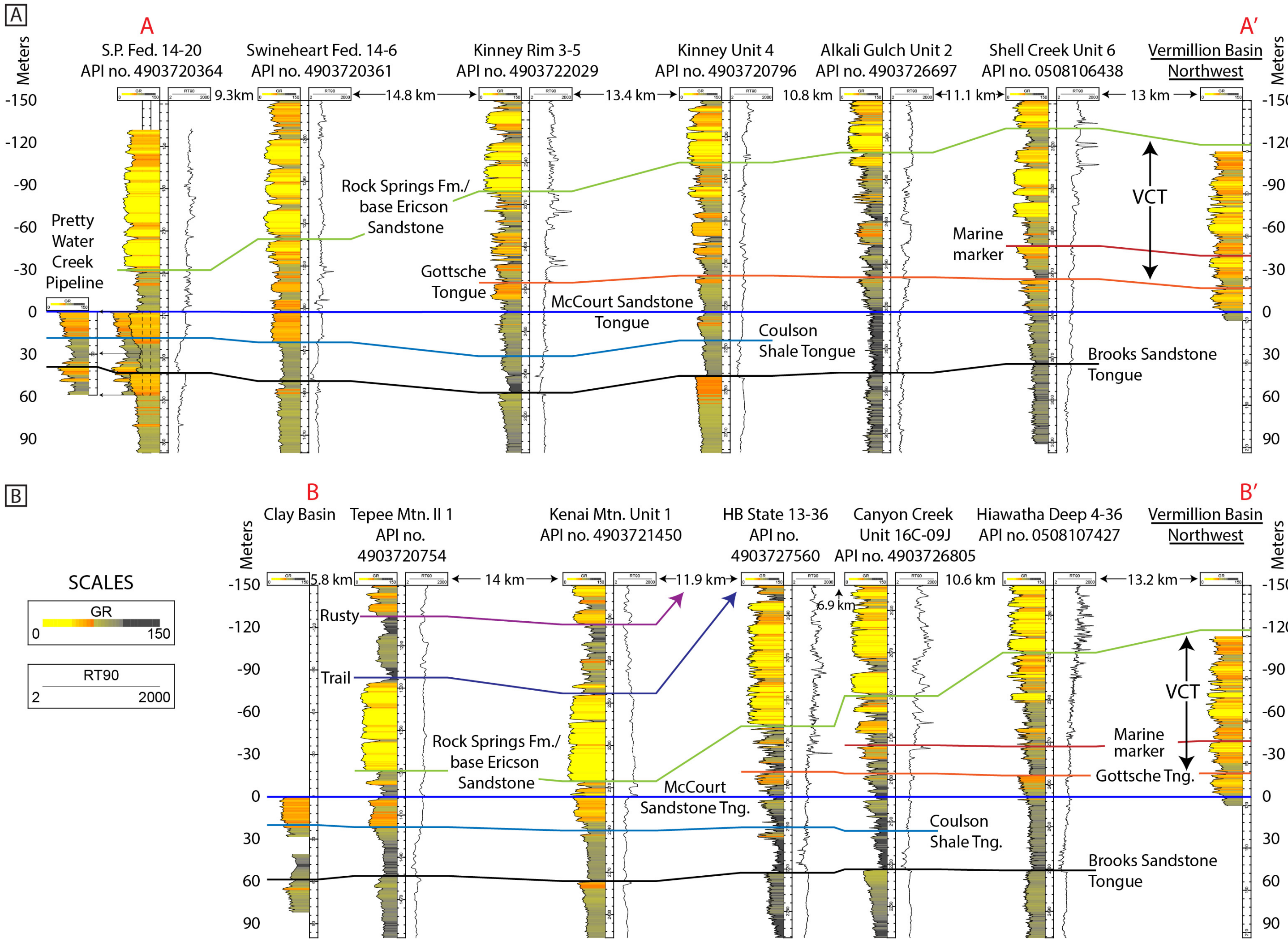

Figure 9. Surface to subsurface correlations. (A) Correlation from the east flank of the Rock Springs uplift (Pretty Water Creek Pipeline) to the Vermillion Creek type section. Prominent sandstones of the McCourt Sandstone Tongue pinch out in a southeastward direction. Upward-coarsening marine sandstones of the Vermillion Creek area are partly equivalent to the Gottsche Tongue of the Rock Springs uplift. Note the presence of a second coarsening-upward marine sandstone, labeled as "Marine Marker," which is the lower part of the Vermillion Creek Tongue. The basal Ericson Sandstone unconformity removes progressively more of the Rock Springs Formation to the west. Also note that the outcrop gamma ray for the Pretty Water Creek Pipeline location is shifted away from the neighboring well log (S.P. Fed. 14-20 well) for ease of viewing. The original position is still shown behind the S.P. Fed. 14-20 well. (B) Correlation from the Clay Basin area to the Vermillion Creek outcrop. Prominent sandstones of the McCourt Sandstone Tongue pinch out in a southeastward direction. Upward-coarsening marine sandstones of the Vermillion Creek area are partly equivalent to the Gottsche Tongue of the Clay Basin area. Again, note the presence of a second coarsening-upward marine sandstone, labeled as "Marine Marker," which is the lower part of the Vermillion Creek Tongue. The basal Ericson Sandstone unconformity removes progressively more of the Rock Springs Formation to the west. VCT = Vermillion Creek Tongue. See figure 1 for location of cross sections.

Our correlation panels indicate that almost the entire section preserved at the Vermillion Creek area is younger than the Rock Springs Formation at both the Rock Springs uplift and Clay Basin (figure 9). Another notable feature is the apparent thinning of the Gottsche Tongue between the Vermillion Creek area and Clay Basin (figure 9), indicating that the basal Ericson Sandstone erosional unconformity removed more of the Rock Springs Formation in the Clay Basin area, possibly due to increased uplift (e.g., Smith, 1961; Roehler, 1965; Miller, 1977; Uroza, 2008). The correlation panels also indicate that the Gottsche Tongue of the Rock Springs uplift and Clay Basin transitions into laterally continuous marine deposits approximately 16 km southeastward from the southernmost Rock Springs uplift outcrop (figure 9). Overlying this basal marine Gottsche Tongue is a progradational package of deltaic, delta plain, and distributary-channel complexes herein defined as the Vermillion Creek Tongue. A type section for this new tongue is presented in figure 4.

DISCUSSION

Comparison With Nearby Areas

Deposits of the sandy marine tongues of the Rock Springs Formation at the Rock Springs uplift and Clay Basin meet the established criteria for deltaic deposits, namely: (1) a direct link to feeding rivers can be identified, (2) significant progradation occurred indicating a fluvial sediment source, (3) deposits are upward-shallowing, (4) seaward-dipping clinoforms are present, and (5) the deposit is lobate or elongate as a shoreline protuberance (e.g., Kirschbaum, 1989; Roehler, 1990; Bhattacharya, 2006, 2010). Marine shoreline deposits exposed at the base of the Rock Springs Formation in the Vermillion Creek area are also interpreted as deltaic deposits. However, there are a few key differences. Outcrops in the Vermillion Creek area contain a significantly higher biodiversity (eight or more ichnogenera) than deltaic deposits of the other areas (an average of three different ichnogenera per location). Additionally, the total thickness of each of the FA1 sequences in the Vermillion Creek area is just over 20 m whereas similar deposits elsewhere are 40 m or more thick.

The delta-plain deposits of the Gottsche Tongue at the Rock Springs uplift and Clay Basin and the delta-plain interval in the Vermillion Creek Tongue are not time-equivalent (figure 9). However, both intervals record the final preserved marine influence of each area until flooding events associated with the Upper Campanian Almond Formation occurred. There are some similarities between locations. Thin, discontinuous coal beds are common in all areas, as well as thin sandy splay deposits. *Teredolites or Apectoichnus* bored logs in channel lag deposits were found in the Rock Springs uplift and in the Vermillion Creek area. Brackish-water burrows such as these, suggest close proximity to the sea in distributary channels (e.g., Bromley and others, 1984; Gingras and others, 2004, 2005; King and others, 2020).

The differences between the outcrops in the Vermillion Creek area and other areas are readily apparent. The Gottsche Tongue has a significantly lower net sandstone percentage (29% average near the Rock Springs uplift, n = 28) than the upper deposits of the Vermillion Creek Tongue (62% average near Vermillion Creek, n = 16). However, in spite of a low net sandstone percentage, multistory and multilateral deposits do exist in the Gottsche Tongue, though single story channel deposits are more common.

Stacking Patterns and Implications for Subsurface Exploration

The Vermillion Creek area exhibits an overall progression from fully marine deltaics to marine-influenced distributary-channels and delta-plain deposits. This progression is consistent with the progradation of a deltaic system having more proximal facies associations systematically overlying more distal facies associations (e.g., Coleman and Prior, 1982; Bhattacharya, 2006, 2010).

The stacked distributary-channel complexes are separated by laterally continuous delta-plain deposits suggesting periodic abandonment and reoccupation of the Vermillion Creek area by distributary channels. Periods of abandonment correlate with incidences of higher HI, suggesting marine or lacustrine influence. The fact that marine influence (marine trace fossils) is present in at least three of the six distributary-channel complexes, including the uppermost complexes, suggests aggradation of the shoreline. Contemporaneous shoreline deposits were likely near the Vermillion Creek area for the entirety of the deposition of the distributary-channel complexes. Wireline data is sparse and correlation is difficult east of the Vermillion Creek area. While difficult to prove time-equivalency, coarsening upward successions are present east of the Vermillion Creek area that may be time-equivalent to the delta-plain and distributary-channel deposits.

The interpretation that contemporaneous shoreline deposits are likely present to the east of the Vermillion Creek area has implications for oil and gas exploration activities in the nearby Sand Wash and Washakie Basins. Marine sandstone reservoirs may have greater prospectivity than channelized facies due to larger lateral extents. Oil and gas accumulation within reservoirs of this type, east of the Vermillion Basin, are sparsely tested, and may be significant (Finn and Johnson, 2005; Johnson and others, 2005). The type of delta has an influence on the geometry of subsurface reservoirs (e.g., Slatt, 2006). It is unknown what type of delta deposits are present east of Vermillion Creek. However, wave-dominated deltas typically have fewer distributary channels than their fluvial-dominated counterparts, and can become entrenched (e.g., Bhattacharya, 2006, 2010). The fact that the percentage of distributary-channel deposits in the Rock Springs Formation is significantly higher in the Vermillion Creek area than the Rock Springs Formation elsewhere may suggest a slight shift toward fluvial dominance, but also may be due to fluctuating accommodation. Distributary channels display high-sedimentation rates as indicated by significant soft-sediment deformation in channelized deposits and high sedimentation rates can be an indicator of fluvial dominance (e.g., Bhattacharya, 2006, 2010).

CONCLUSIONS

The Rock Springs Formation of the Vermillion Creek area in northwestern Colorado is composed of marine-deltaic, distributary-channel, and delta-plain sediments representing progradation to aggradation of the shoreline. The Rock Springs Formation outcrops in the Vermillion Creek area differs from Rock Springs Formation outcrops elsewhere in Utah and Wyoming by having thinner delta-front successions and having a higher net sandstone (distributary channels) within delta-plain deposits.

The Rock Springs Formation in the Vermillion Creek area is younger than Rock Springs Formation elsewhere in Utah and Wyoming. It also preserves the youngest available outcrop of the Rock Springs Formation described in literature and is an important data point between outcrops of the Rock Springs uplift or Clay Basin and contemporaneous deposits on the east and southeast edges of the Greater Green River Basin. Additionally, a new member of the Rock Springs Formation has been defined and has been named the Vermillion Creek Tongue.

Future subsurface exploration for hydrocarbons east of the Vermillion Basin is likely to encounter shoreline deposits that are time-equivalent to the distributary-channel complexes of the Vermillion Creek Tongue. This geographic area is not well tested, and may be significant.

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