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Characterizing the Low Net-to-Gross, Fluviodeltaic Dry Hollow Member of the Frontier Formation, Western Green River Basin, Wyoming

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A thesis submitted to the faculty of
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Master of Science

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ABSTRACT

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The Frontier Formation in the Green River Basin of southwestern Wyoming consists of Late Cretaceous (Cenomanian-Turonian) marine and non-marine sandstones, siltstones, mudstones and coals deposited on the western margin of the Cretaceous Interior Seaway. Tight gas reservoirs exist in subsurface fluviodeltaic sandstones in the upper Frontier Formation (Dry Hollow Member) on the north-south trending Moxa Arch within the basin. These strata crop out in hogback ridges of the Utah-Idaho-Wyoming Thrust Belt approximately 40 km west of the crest of the Moxa Arch. Detailed, quantitative outcrop descriptions were constructed using emerging photogrammetric techniques along with field observations and measured sections at five key outcrop localities along the thrust belt. Understanding the architectural style of this low net-to-gross fluvial system allows for improved reservoir prediction in this and other comparable basins.

The architectural style of the Dry Hollow Member fluvial deposits varies vertically as the result of a relative shoreline transgression during Dry Hollow deposition. Amalgamated conglomerates and associated fine to coarse sandstones near the base of the section and much thinner, isolated sandstones near the top of the Dry Hollow occur in laterally extensive units that can be identified over tens of kilometers. These units also provide means to relate outcrop and subsurface stratigraphic architecture. Combined with available subsurface data, fully-realized 3D static reservoir models for use as analogs in subsurface reservoir characterization may be constructed. Grain size, reservoir thickness and connectivity of fluvial sandstones is generally greatest near the base of this member and decreases upward overall. Despite relative isolation of some channel bodies, geocellular facies modeling indicates good lateral and vertical connectivity of most channel sandstones. The Kemmerer Coal Zone, with little sandstone, divides lower and upper well-connected sandy units.

Keywords: Cretaceous Interior Seaway, digital outcrop model, Dry Hollow, fluvial, fluviodeltaic, Frontier Formation, geocellular model, facies model, Green River Basin, low net-to-gross, photogrammetry, tight gas, Utah-Idaho-Wyoming Thrust Belt, Wyoming

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INTRODUCTION

The Frontier Formation in southwestern Wyoming has been intensively studied for over a century both academically and as a target for oil and gas exploration and production. Cobban and Reeside Jr. (1952) summarized Frontier stratigraphy throughout Wyoming, giving particular attention to biostratigraphy and discussed the history of the regional recognition and naming of the members of the Frontier Formation. De Chadenedes (1975) provided a compilation of various interpretations of the depositional environments of the Frontier in southwestern Wyoming. Merewether et al. (1984) synthesized stratigraphic data for the Frontier throughout the Green River Basin and listed a thorough history of research on the Frontier near the Moxa Arch. Myers (1977) compiled one of the most detailed descriptions of the Frontier outcrops in southwestern Wyoming and gave a history of the regional correlation of formation members in this area to other parts of the Frontier Formation. He also gave a brief history of petroleum exploration in the Frontier.

The study area (Figures 1 and 2) is located along US Highway 189 between Evanston and Kemmerer, Wyoming. Here, the Late Cretaceous Frontier Formation is exposed in a nearly 110 km long, north-south-striking series of hogback ridges and strike valleys. These strata were deposited on the western margin of the Cretaceous Interior Seaway (Figure 3). They were then thrusted and tilted into their current location during the Sevier Orogeny (De Chadenedes, 1975; DeCelles, 1994) as part of the Utah-Idaho-Wyoming Overthrust Belt. This area is of particular interest because 1) it contains some of the best exposures of the Frontier Formation in southwestern Wyoming, 2) outcrops on multiple thrust sheets allow for comparison of more proximal and distal portions of the Frontier depositional system, and 3) outcrops lie only a few kilometers west of the Moxa Arch, a structural trend that has been extensively drilled for

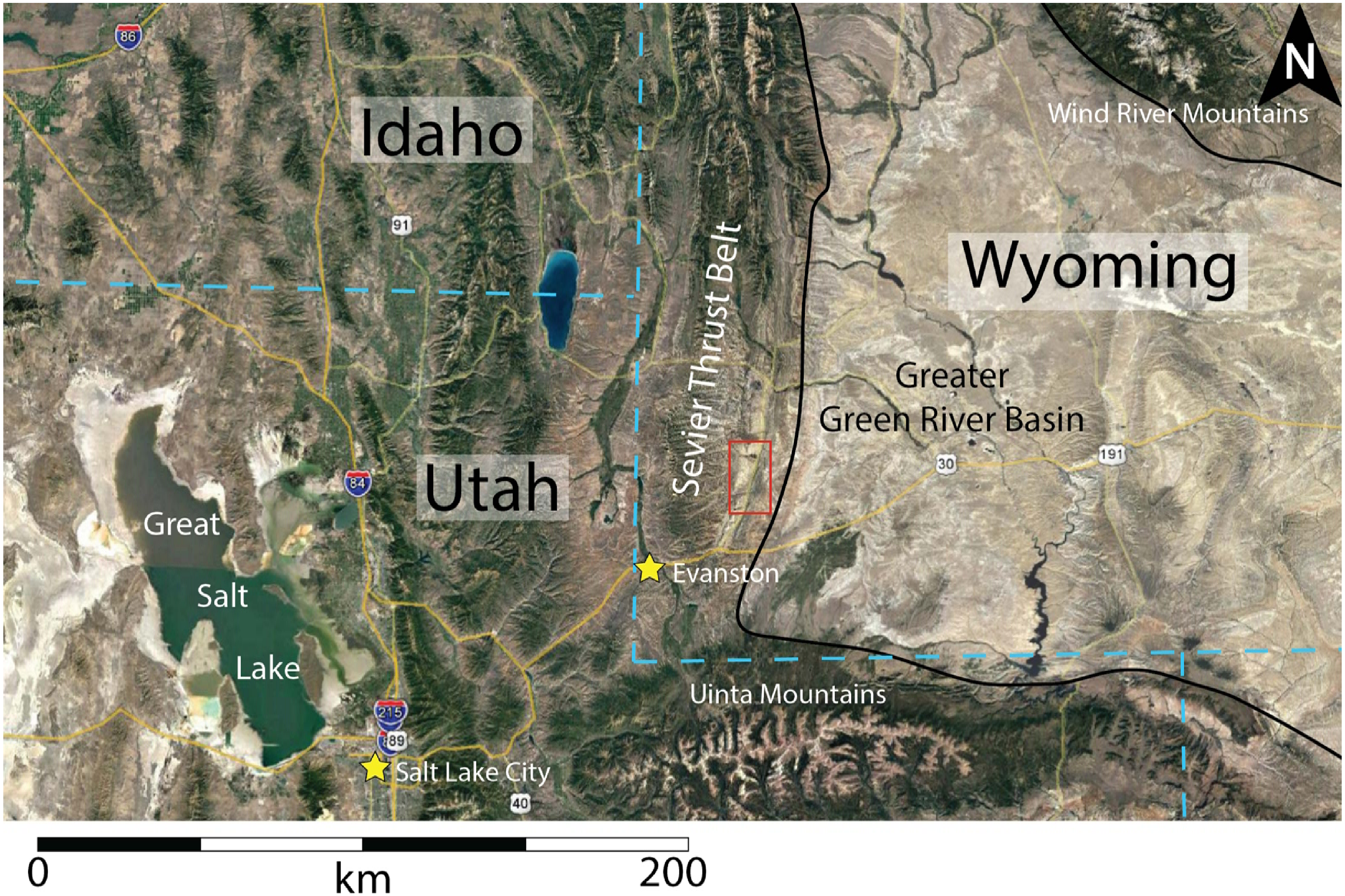

Figure 1. Frontier study area in southwestern Wyoming. Reference map shows study area (red box) in relation to the Sevier Thrust Belt (Utah-Idaho-Wyoming Overthrust Belt) and the greater Green River Basin.

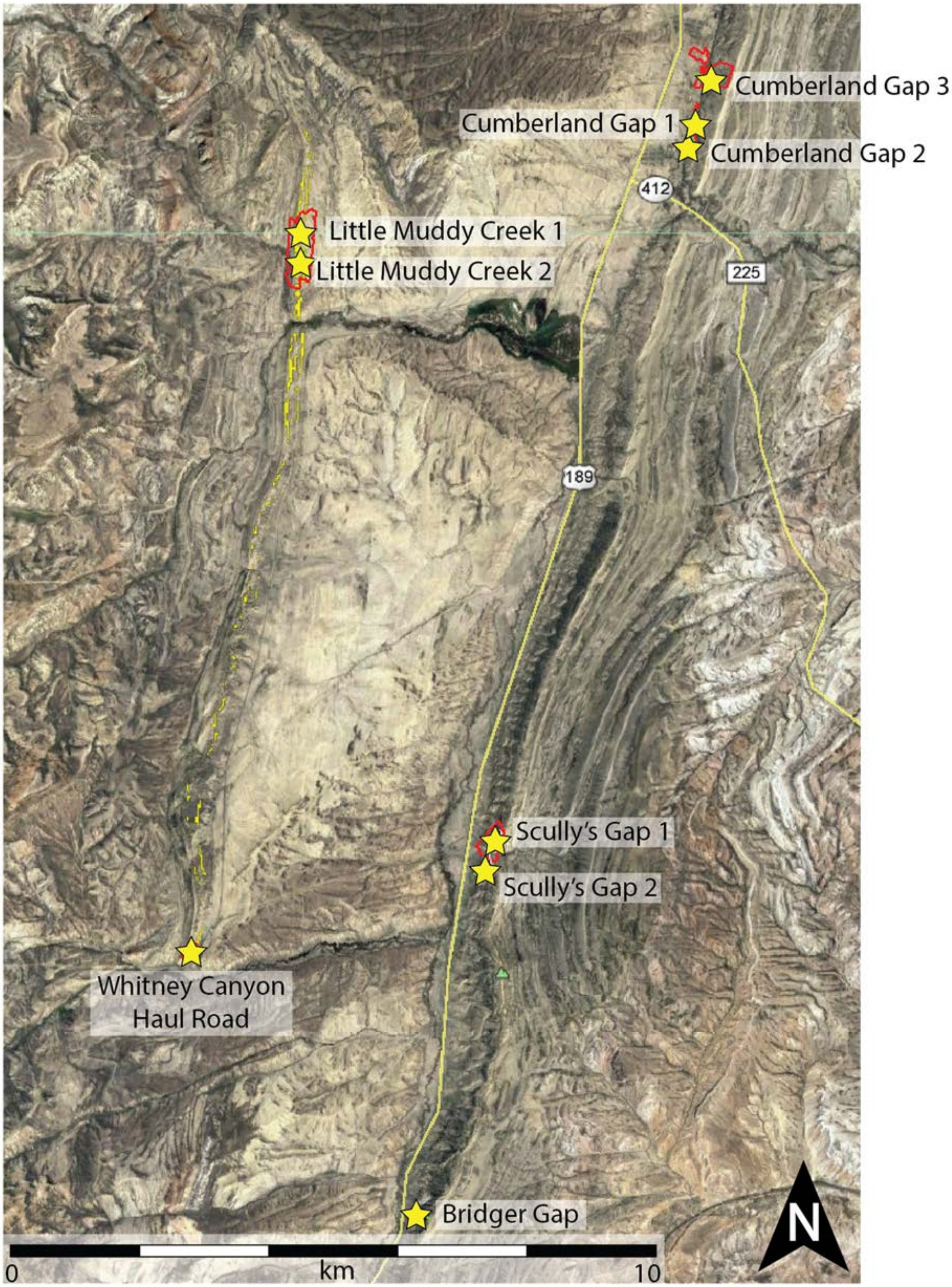

Figure 2. Frontier study area in southwestern Wyoming. Large scale map of study area in the Utah-Idaho-Wyoming Overthrust Belt along Highway 189 showing locations of measured sections (yellow stars) and photogrammetric models (red outlines).

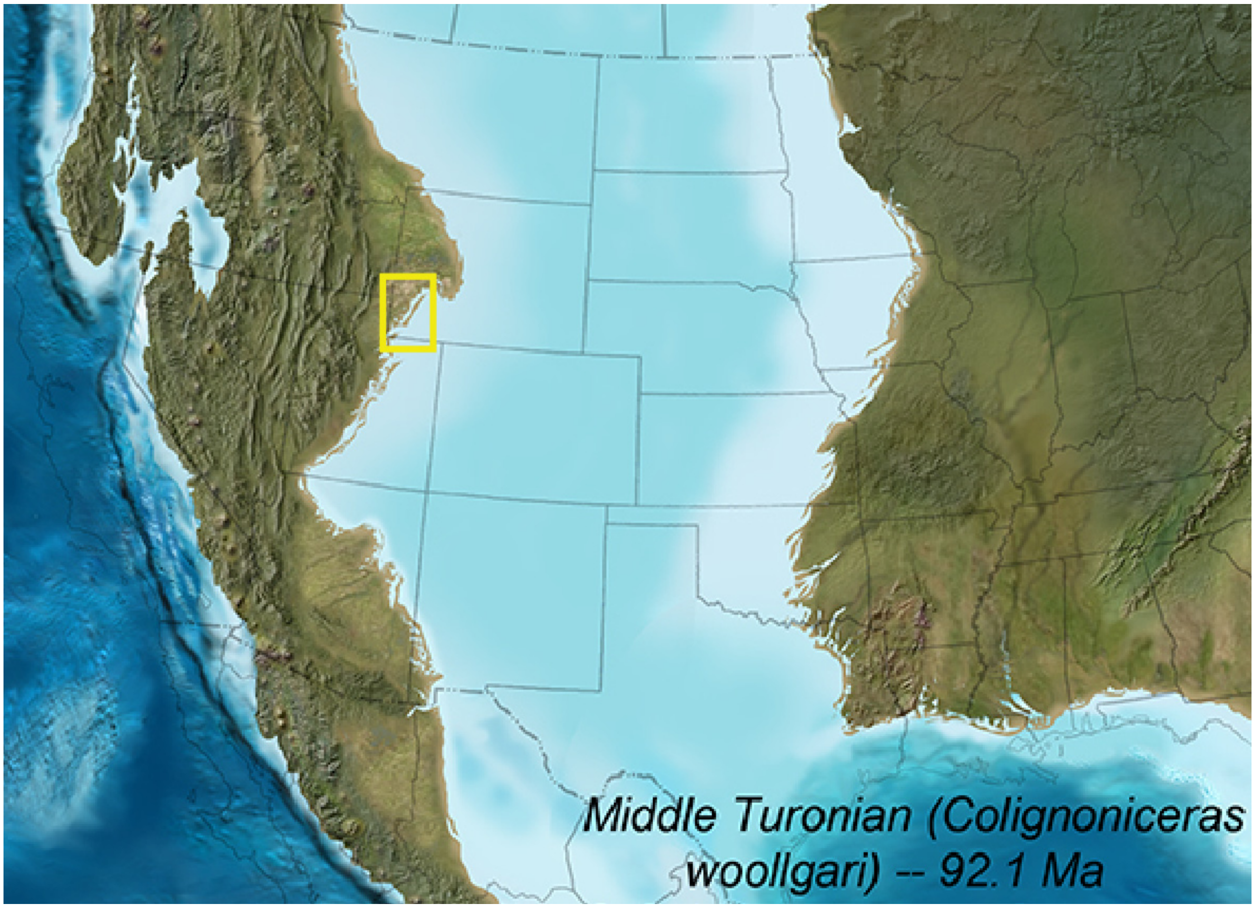

Figure 3. Paleogeographic reconstruction of the Cretaceous Interior Seaway during Frontier time in the Turonian age of the Late Cretaceous. Study area is highlighted in yellow. The Frontier Formation was deposited on the western margins of the Cretaceous Interior Seaway between approximately 99-88 Ma. Modified from Blakey (2014).

hydrocarbon production out of the Frontier and other formations. Well data along the Moxa Arch (provided by ConocoPhillips) allows for correlation of distal portions of the Frontier and a greater understanding of changes in the formation along depositional strike.

The Frontier Formation is made up of a varied succession of terrestrial to marine rocks. These include fluviodeltaic and shoreface sandstones, marine and terrestrial mudstones, and backshore coals (Cobban and Reeside Jr., 1952; De Chadenedes, 1975; Myers, 1977; Merewether et al., 1984). Predicting spatial and temporal variation of facies associations is a complex undertaking. This study seeks to better understand facies relationships, depositional environments, and regional paleogeography of the upper Frontier Formation in the western Green River Basin by utilizing subsurface well data and high-accuracy, geospatially referenced outcrop data to improve upon past models. This work is practically relevant in this area as hydrocarbons are being actively produced from a more distal part of the system (approximately 20-30 km east of outcrop locations) on the Moxa Arch (Myers, 1977; Wach, 1977; Harrison and Dutton, 1991; Kirschbaum and Roberts, 2005). It will also serve as a general model for understanding other low net-to-gross fluviodeltaic distributary systems.

BACKGROUND

Regional Geologic Setting

Tectonics

The greater Green River Basin is a sedimentary basin located predominantly in southwestern Wyoming with small portions in northeastern Utah and northwestern Colorado (Figure 4). The basin is divided by Laramide anticlinal structures into four subbasins; the Bridger or Green River Basin in the western half (Lamerson, 1982; Dickinson et al., 1988; Törö et al., 2015) and the Great Divide, Washakie, and Sand Wash Basins on the east. The Green River Basin is bounded by the Utah-Idaho-Wyoming Thrust Belt to the west (location of outcrop study area), the Rock Springs uplift to the east, the Wind River Mountains to the north and the Uinta Mountains to the south (Roehler, 1992). Another small sedimentary basin, the Fossil Basin, is located west of the thrust front (Lamerson, 1982).

While the interior of the Green River Basin was deformed by Laramide thick-skinned tectonics, its western margin was deformed predominantly by thin-skinned thrusting of the Sevier Orogeny. Sevier thrusting resulted in the formation of the Utah-Idaho-Wyoming Thrust

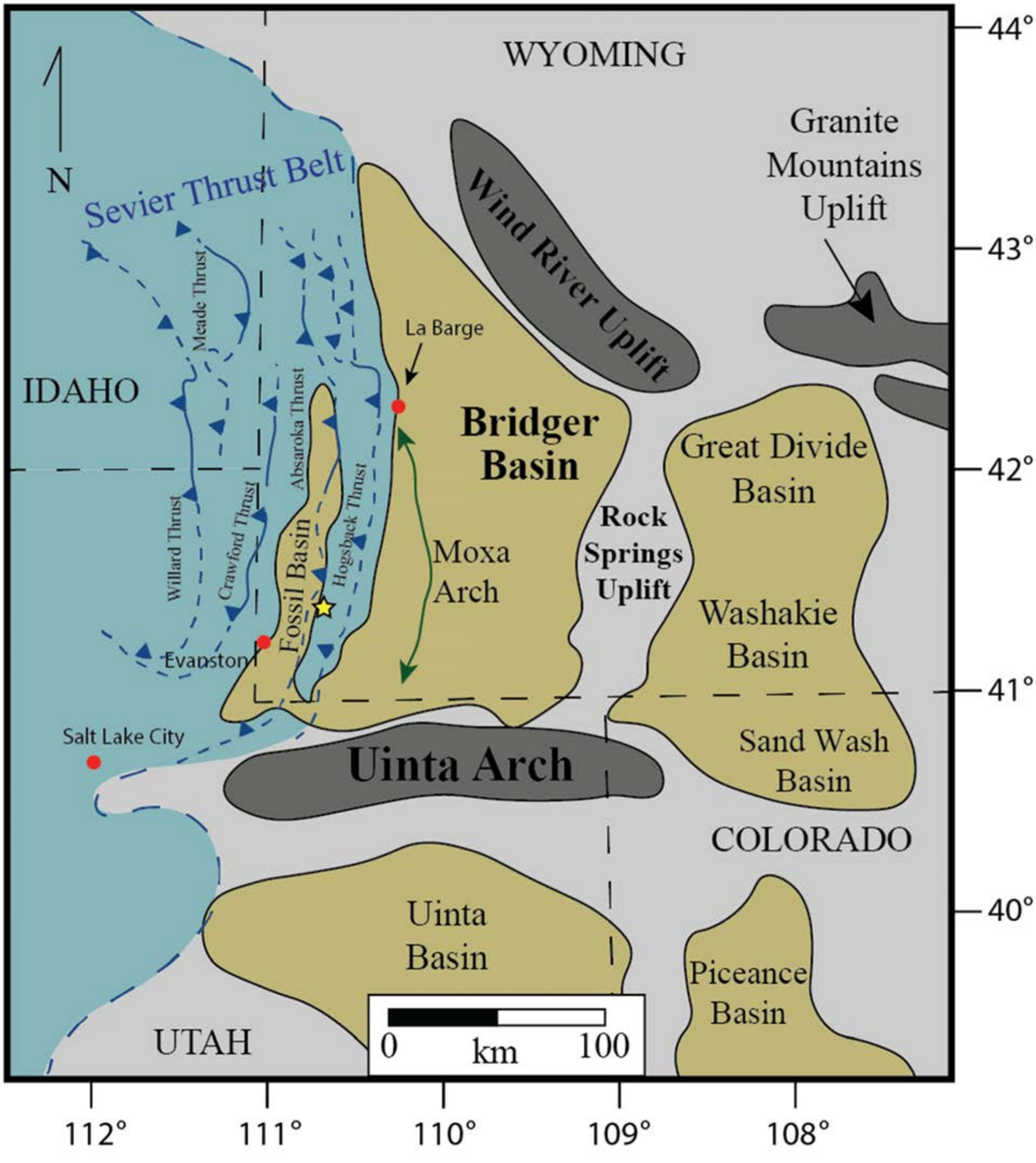

Figure 4. Map showing surface locations of major structural features in the greater Green River Basin region. Study area is marked by the yellow star. Important features include the Sevier thrusts of the Utah-Idaho-Wyoming Overthrust Belt, the Moxa Arch (Sevier forebulge), and Laramide uplifts bounding the western part of the basin. Note also subbasins within the Greater Green River Basin (Bridger or Green River, Great Divide, Washakie and Sand Wash). Modified from (Lamerson, 1982; Roehler, 1992; Smith et al., 2008; Törö et al., 2015).

Belt (Figure 4). Laramide tectonism also had some effect on the development of the thrust belt (reactivation) and sedimentation within the Green River Basin (Dixon, 1982; DeCelles, 1994), but this occurred after the time of Frontier deposition (Dickinson et al., 1988; Törö et al., 2015). Major faults in the thrust belt are (from west to east/oldest to youngest) the Willard, Meade, Crawford, Absaroka, and Hogsback thrusts (Lamerson, 1982; DeCelles, 1994). Proterozoic and Paleozoic rocks of the Willard Thrust provided the sediment source for the Frontier Formation. Conglomerates of the Frontier and other formations represent synorogenic sediments (Schmitt, 1985) and the Frontier underwent post-depositional deformation from movement on the Willard and later thrusts. Frontier outcrops in southwestern Wyoming occur within the Absaroka and Hogsback thrust sheets (Figure 5). The Absaroka thrust experienced eastward displacement of approximately 24-28 km (Peyton et al., 2011) and the Hogsback thrust approximately 15-20 km of eastward displacement (Dixon, 1982; Peyton et al., 2011).

Crustal loading from Sevier thrusting formed a foreland basin east of the orogenic belt where the thickest succession of Frontier sediments were deposited (Schmitt, 1985; Dickinson et al., 1988; Dutton, 1993; DeCelles, 1994; Hamlin, 1996; Kirschbaum and Roberts, 2005). Frontier strata thin to the east as they approach and overlie the Moxa Arch. The Moxa Arch has a complex and somewhat poorly understood history that involves several stages. The deep basement faults that core the structure likely predated Sevier thrusting (Dixon, 1982). The proto-Moxa Arch developed as a forebulge in the foreland basin system associated with the Sevier thrust front and was present as a topographic feature during the time of Frontier deposition (Harrison and Dutton, 1991; Hamlin, 1996; White et al., 2002). It experienced occasional subaerial exposure during lowstands (Harrison and Dutton, 1991; Hamlin, 1996) and may have been prominent enough at times to deflect fluvial systems within the Frontier or even serve as a

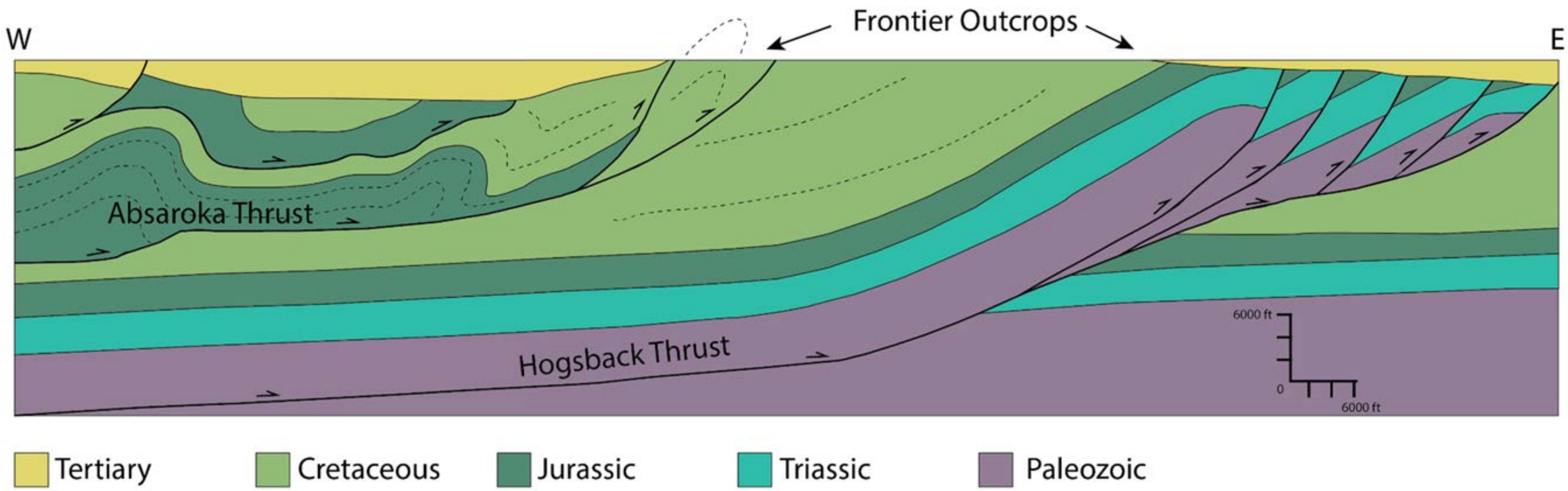

Figure 5. Simplified cross section through the study area. Locations of Frontier outcrops are noted. Outcrops occur on the Absaroka and Hogsback thrust sheets - the two outcrop localities would have been approximately 30-34 km apart at the time of deposition. Modified from Lamerson (1982).

sediment source. During Frontier time, the proto-Moxa Arch was most prominent to the south (directly east of the study area), resulting in a thicker Frontier section further north near LaBarge, Wyoming (Merewether et al., 1984; Hamlin, 1996). Laramide thrusting uplifted and tilted the proto-Moxa Arch, creating a southward plunging anticlinal feature (Hamlin, 1996). Most current oil and gas production from the Frontier is concentrated along the crest of this structure (Myers, 1977; Harrison and Dutton, 1991).

Stratigraphy

The Green River Basin contains a sedimentary fill of Paleozoic to Cenozoic rocks (Figure 6; Lamerson, 1982; Kirschbaum and Roberts, 2005). Cretaceous rocks, including the Frontier Formation, were deposited in or near the western margin of the Cretaceous Interior Seaway. Cretaceous rocks are composed of a succession of marine to terrestrial rocks ranging from black marine shales to conglomeratic alluvial deposits. The Frontier Formation itself is a relatively sandy formation that lies between two thick marine shales, the Hilliard (Baxter) Shale and the Mowry (locally known as Aspen) Shale (Myers, 1977). Sediments were deposited synorogenically by fluvial systems transporting sediments from the thrust belt in the west to the Cretaceous Interior Seaway in the east.

Lithologically, the Frontier Formation in the Green River Basin consists of a succession of nearshore shales, siltstones, sandstones, conglomerates, coals and bentonites (Myers, 1977). These were deposited along the western margin of the Cretaceous Interior Seaway (Figure 4) during the Cenomanian, Turonian, and early Coniacian ages of the early Late Cretaceous epoch, approximately 88-99 Ma (Merewether et al., 1984). Depositional environments consisted of varied terrestrial to marine settings which deposited deltaic, shoreface, estuarine, paludal/lagoonal, delta plain, tidal channel, fluvial, marine, and marine shale facies. The rocks of

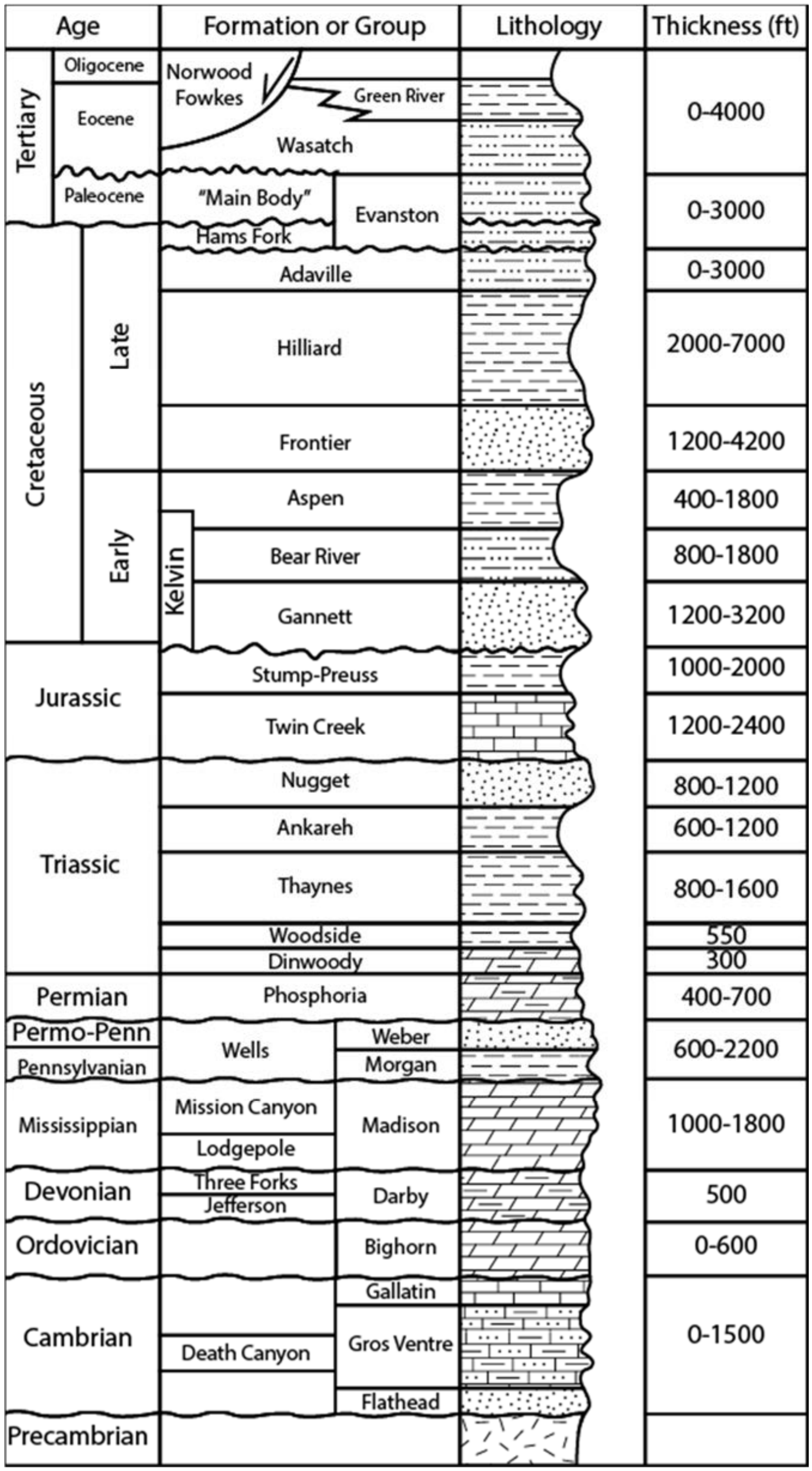

Figure 6. Generalized stratigraphic column from the western Green River Basin. Note the Frontier Formation in the early Upper Cretaceous. The Frontier is a sandy interval deposited on the margins of the Cretaceous Interior Seaway between two marine shales, the Hilliard and the Aspen. Modified from Lamerson (1982).

the Frontier represent two cycles of shoreline progradation into the Cretaceous Interior Seaway (Myers, 1977).

The Frontier Formation in the study area consists of five members (Figure 7) that are traceable throughout most of the study area. From oldest to youngest these are the Chalk Creek, Coalville, Allen Hollow, Oyster Ridge, and Dry Hollow Members (De Chadenedes, 1975; Myers, 1977). This study focuses on the uppermost part of the Oyster Ridge Member and the Dry Hollow Member.

It is worth noting that the sandstones of the Frontier Formation are commonly referred to as the First, Second, Third and Fourth Frontier Sandstones (Figure 7). These names are subsurface designations for sandstones encountered in the Frontier in the Green River Basin. The Dry Hollow Member of the Frontier Formation corresponds to the 'First Bench' of the Second Frontier and the shoreface sandstones of the Oyster Ridge Member correspond to the 'Second Bench' of the Second Frontier (Myers, 1977; Dutton and Hamlin, 1991; Hamlin, 1996; Feldman et al., 2014).

Chalk Creek Member

The Chalk Creek Member consists of prograding fluviodeltaic rocks (near-shore and delta-plain). It is characterized by thin laterally discontinuous sandstones interbedded with dominantly terrestrial fine-grained mudstones and coals. The member is approximately 950-1400 ft. thick.

Coalville Member

The Coalville Member contains the first two sandstones above the Chalk Creek (though these may combine or split into 1-3 sandstones). Sandstones are channelized fine-to-coarse sand

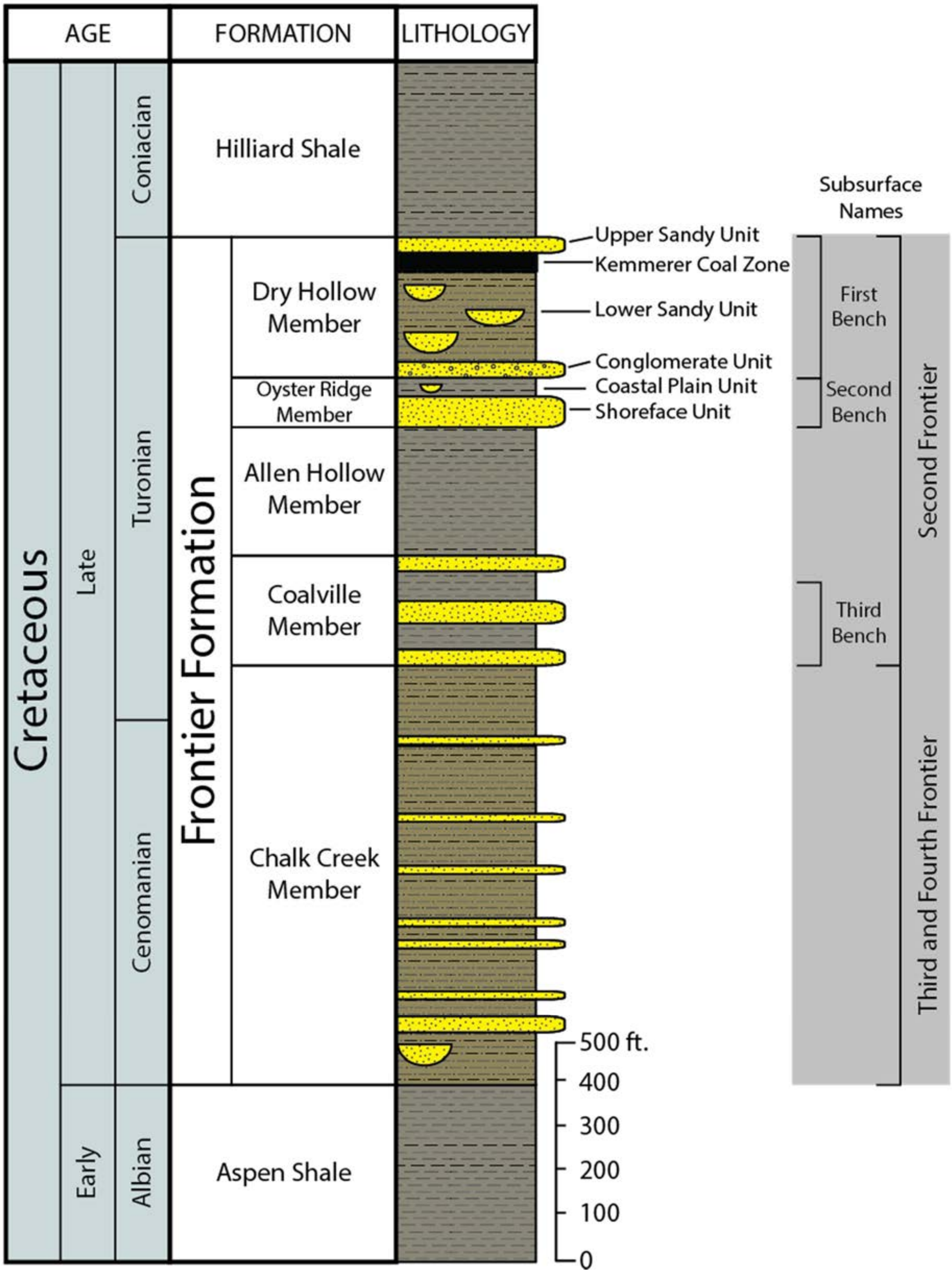

Figure 7. Generalized stratigraphic column of the Frontier Formation at Cumberland Gap, south of Kemmerer, WY. Note, the number of sandstones represented in this column may vary laterally within the individual members. The Dry Hollow, Oyster Ridge and Coalville members are referred to in the subsurface as the First, Second and Third Benches of the Second Frontier sandstones. The Chalk Creek Member makes up the Third and Fourth Frontier in the subsurface. The First Frontier is not present in the study area. Modified from Myers (1977) and Hamlin (1996).

(usually fine) and coarsen upward. Ripples, trough cross-stratification (TCS), *Ophiomorpha* burrows, and plant/mollusk fossils are common. There is considerable lateral variation in this member on both outcrop and regional scales. Myers (1977) interprets these as mixed estuarine deposits with some fluvial influence. The Coalville is approximately 100-150 ft. thick.

Allen Hollow Shale Member

The Allen Hollow Member is composed of gray, marine mudstones and contains rare, thin sandstones. The Allen Hollow commonly interfingers with the Oyster Ridge shoreface sandstones. This member is approximately 300 ft. thick.

Oyster Ridge Member

The Oyster Ridge Member consists of one or more thick, cliff-forming sandstones with interbedded marine shale. These sandstones are often planar bedded or massive and burrowed, but commonly contains beds exhibiting large scale TCS. It has been interpreted as a wave-dominated, tide-influenced shoreface where several prograding parasequences are present (Feldman et al., 2014). Tidal influence increases to the north (around LaBarge, WY), which Feldman (2014) interpreted as indicating that the Oyster Ridge was deposited in a protected bay that was open to the south (where wave influence dominates). Wave-dominated facies are most abundant in the study area. Beach sands, nearshore marine bars, delta front, tidal channel fills, ebb-tide deltas, flood-dominated tidal bars and estuarine facies are all represented within the member (De Chadenedes, 1975; Myers, 1977; Hamlin, 1996; Feldman et al., 2014). Abundant oyster fossils overlie the shoreface sandstones representing a transition into a lagoonal environment. Oyster deposits are sometimes channelized which may indicate deposition in tidal channels (Feldman et al., 2014). The Oyster Ridge is capped by coastal plain terrestrial deposits (fluvial sandstones, floodplain mudstones and siltstones, and rare, thin coals). This member is around 50-200 ft. (usually 60-100 ft.).

Dry Hollow Member

The Dry Hollow Member is composed predominantly of terrestrial fluviodeltaic and floodplain deposits and transitions into marine facies at the top where it is conformably overlain by the marine Hilliard Shale. A fluvial pebble conglomerate is typically present at the base of the member, which erodes into the upper Oyster Ridge on a lowstand surface of erosion (Myers, 1977; Hamlin, 1996). There is significant debate in the literature over the placement of the Oyster Ridge/Dry Hollow contact. We choose to use the pebble conglomerate of the Dry Hollow as the base of this member and group the underlying coastal plain mudstones and sandstones with the Oyster Ridge Member. Though it pinches and swells and is not fully continuous, the conglomeratic unit can be recognized in most parts of the study area. It therefore serves as a regionally recognizable marker and is consistent with a high-energy deposit that might be expected on top of the regional unconformity that is suggested to exist between the Dry Hollow and Oyster Ridge (Myers, 1977; Hamlin, 1996; Stonecipher, 2012). The Dry Hollow/Oyster Ridge contact is a lowstand surface of erosion that likely corresponds to a mid-Turonian (90 Ma) fall in eustatic sea level during which most of the are covered by the western Green River Basin was subaerially exposed and eroded (Hamlin, 1996).

Above the basal conglomerate, the Dry Hollow consists of fluvial deposits of fine-grained sandstone channels, floodplain/overbank mudstones and siltstones, and coals. A regionally extensive, thick accumulation of coal, the Kemmerer Coal Zone, is present near the top of the section. ‘Kemmerer Coal Zone’ is a local name for a coal-rich, sandstone-poor unit near the top of the Dry Hollow Member (Cobban and Reeside Jr., 1952). One or more fluvial sandstones commonly lie between this coal zone and the contact with the base of the Hilliard. The Dry Hollow can be up to 600 ft. thick.

METHODS

Measured Sections and Correlation Panels

Nine stratigraphic sections (Figure 2) were measured at five locales (Cumberland Gap Sections 1-3, Scully's Gap Sections 1-2, Bridger Gap Section, Little Muddy Creek Sections 1-2, and Whitney Canyon Haul Road Section) using a Jacob staff. Detailed measured sections can be found in Appendix A. Representative outcrop samples of identified lithofacies were collected for thin sections, measuring porosity and permeability, XRD analysis, and pyrolysis (Table 1). Effort was made to sample unweathered portions of the outcrop, although due to poor exposure, this was not always possible and weathering may have affected some of the samples (particularly of the conglomeratic facies and some fine-grained samples).

Pseudo gamma ray logs (Appendix B) for use in correlating outcrop data to subsurface well data were collected at the Little Muddy Creek 2 and Bridger Gap sections using an RS-230 BGO Super-SPEC Handheld Gamma-Ray Spectrometer (GRS). Readings were taken at one-meter intervals for most of the sections. Gamma-ray measurements were sparse (average of 10 m apart) in some mud-rich, slope-covered portions of the Little Muddy Creek 2 GRS log. This produced unrealistically blocky profiles for these segments of the logs. In order to create a more realistic profile for use in outcrop to well correlation, random noise (based on K, U, and Th values from similar units within the section) was added to these intervals using Microsoft Excel.

Measured sections were drafted in EasyCore 1.2.11 software, then imported into Schlumberger's Petrel E&P Software Platform 2016. Sections were placed in their correct spatial

Table 1. Sample Descriptions - Porosity/Permeability, XRD, Pyrolysis and Thin Sections

Section	Sample ID	Facies	Sample Description
Cumberland Gap 1	FDC1-6	2	fine fluvial sandstone
	FDC1-13	3	fine fluvial sandstone, lithic rich
Cumberland Gap 2	FDC2-8	3	fine fluvial sandstone
	FDC2-15a	5	coal from Kemmerer Coal Zone, just below a major channel
	FDC2-16b	2	fine fluvial sandstone; chute channel fill?
	FDC2-16d	2a	fine, thin-bedded fluvial sandstone
	FDC2-16e	2a	fine, thin-bedded fluvial sandstone
Cumberland Gap 3	FOC3-8	5	thin dark shale or shaley coal in upper Oyster Ridge
	FDC3-9b	1	coarse fluvial sandstone (associated with conglomerates)
	FDC3-9c	1	fine - medium fluvial sandstone, lithic rich (associated with conglomerates)
	FDC3-10	4	mottled mud/siltstone; coal fragments; directly underneath a thin fluvial sandstone
	FDC3-16	5	bituminous coal from Kemmerer Coal Zone - Cumberland Gap
	FDC3-17	3	fine fluvial sandstone
	FDC3-no#a	5	bituminous coal sample from Kemmerer Coal Zone tailings pile - Cumberland Gap
	FDC3-no#b	5	coalified wood fragment from Kemmerer Coal Zone tailings pile - Cumberland Gap
Scully's Gap 1	FDS1-4	3	fine fluvial sandstone
	FDS1-9a	1	coarse fluvial sandstone (associated with conglomerates)
	FDS1-9d	1	fine-medium sandstone (associated with conglomerates)
	FDS1-19	3	fine fluvial sandstone
Scully's Gap 2	FDS2-11	4	green siltstone or very fine sandstone
	FDS2-24	5	bituminous coal sample from Kemmerer Coal Zone - Scully's Gap
	FDS2-26	2	fine fluvial sandstone
Bridger Gap	FOB1-1	7	Oyster Ridge shoreface sandstone
	FDB1-9e	1	pebble conglomerate
Whitney Canyon Haul Road	FDH-10b	1	coarse sand and pebble conglomerate
	FDH-17a	5	bituminous coal near base of Kemmerer Coal Zone
	FDH-17b	4	soft, orange siltstone, Kemmerer Coal Zone
	FDH-17c	5	dark, mottled, coaly mudstone, Kemmerer Coal Zone
	FDH-17d	4	tan/gray siltstone, Kemmerer Coal Zone
	FDH-17e	4	dark, reddish, massive mudstone, Kemmerer Coal Zone
	FDH-17f	4	light, mottled mudstone or siltstone, Kemmerer Coal Zone
	FDH-18a	2	fine fluvial sandstone
	FDH-18b	2?	fine fluvial sandstone, dark, lensoidal body contained within a larger channel of Facies 2
Little Muddy Creek 1	FOM1-1	8	oyster bed; oyster shells with quartz sand matrix
	FDM1-5	2	fine fluvial sandstone
	FDM1-7	3	fine fluvial sandstone, lithic rich
	FDM1-11	3	fine fluvial sandstone
	FDM1-18	3	fine fluvial sandstone
Little Muddy Creek 2	FDM2-3	6	fine- medium fluvial sandstone, lithic rich
	FDM2-7	6	medium fluvial sandstone
	FDM2-9	2	fine fluvial sandstone; abundant fine-grained rip-up clasts
	FDM2-11	3?	fine- medium fluvial sandstone, lithic rich (unusually coarse for Facies 3)
	FOM2-23	4	mud/siltstone with abundant shell fossils
	FOM2-24	4	dark, reddish mudstone or siltstone with abundant shell and woody fossils
	FDM2-37	3	fine fluvial sandstone

positions as vertical pseudo wells. GR logs and subsurface well data were also imported into Petrel. Petrel was then used to create correlation panels for section and well data. To create a more depositionally accurate reconstruction, measured sections were restored to their unthrusted positions. Eastern outcrops on the Hogsback Thrust are restored 20 km to the west based on estimates of 12-14 miles (De Chadenedes, 1975) and 15-20 km (Dixon, 1982). Western outcrops on the Absaroka Thrust are shifted 48 km to the west - 28 km of movement on the Absaroka Thrust (Peyton et al., 2011) plus the 20 km from Hogsback displacement.

Well logs for 24 wells were provided by ConocoPhillips. Significant surfaces in the wells were correlated to significant surfaces in outcrop (the top of the Oyster Ridge shoreface, the Dry Hollow basal conglomerate, and the Dry Hollow/Hilliard contact) using well logs, measured sections, and GRS sections. This subsurface data allowed facies correlations to be extended into the Green River Basin as far as the western side of the Moxa Arch.

Thin Sections

Thin sections were made by cutting, mounting and grinding 1" plugs removed from outcrop samples using a drill press. Eight thin sections were made, one for each facies, with the exception of coals. Thin section were used to better understand the composition and compositional/textural maturity of the different sandstone facies. Although detailed analysis and point counts were not conducted on thin sections, they provided valuable insights into rock fabrics that were not readily obtained in the field.

Porosity/Permeability

Porosity and permeability measurements were performed on samples collected from outcrops at measured section localities. These measurements allow for better understanding of the potential of various sandstone facies as reservoir rocks in a petroleum system. Samples had 1" plugs removed using a drill press which were trimmed to an appropriate size for measurement using a tile saw. Porosity and permeability were measured on BYU campus using an Ultra-Pore 300 porosimeter and Ultra-Perm 500 permeameter. Confining pressure during permeability tests was 1000 psi. Porosity and permeability measurements were made on 25 plugs representing each of the various fluvial sandstone facies.

XRD

X-ray diffraction analysis was carried out on fourteen samples (five representative of sandstone facies, nine representative of various fine-grained facies) in order to better understand the mineralogical composition of Frontier facies. Samples were powdered using a tungsten ball mill and formed into pressed pellets. XRD was done in a Rigaku MiniFlex 500 Benchtop X-ray diffractometer. Rigaku's PDXL2 software was used to analyze data and complete analysis of mineral composition.

Pyrolysis

Thirteen samples of coal and fine-grained rocks of the Dry Hollow Member were analyzed for total organic carbon (TOC) and hydrocarbon generation potential. This was done to explore whether oil and gas could have been generated within the Frontier and potentially self-sourced parts of the formation. Samples were powdered using a tungsten ball mill and pyrolyzed in a HAWK Resource Workstation. The HAWK's PyroS3650_TOC850 analysis method was used to run samples. Results were analyzed using the HAWK-Eye software.

Photogrammetry

Photogrammetric modeling is a process by which photos of an object taken from multiple vantage points can be combined into a spatially accurate three dimensional model of that object. Though a relatively new technique, the use of digital outcrop models built using photogrammetric techniques has been well established as an effective tool for the geosciences (Fabuel-Perez et al., 2010; Bemis et al., 2014; García-Sellés et al., 2014). Key outcrops at all section localities (excluding Bridger Gap) were photographed using a GPS-enabled DJI Phantom

3 drone. Images were compiled and processed in Agisoft PhotoScan Professional 1.2.6 to produce 3D, georeferenced models of key outcrops (Appendix C). These models are based on point clouds which were manually classified by facies in Agisoft. Facies designations were based on ground observations and measured sections. The classified point clouds were then imported into Petrel software to provide control points for geocellular modeling of the upper Frontier Formation (Figures 8 and 9).

Petrel Facies Modeling

Facies modeling allows for facies distributions to be projected away from outcrop control in three dimensions. This was completed in Petrel for the Cumberland Gap locality. Six photogrammetric models were used as control for the model. The point clouds from the photogrammetric models were classified by facies using the Cumberland Gap sections 1-3 as control. These classified point clouds were then imported into Petrel and decimated to facilitate faster processing. The point clouds, measured sections, and correlation panels were used to identify significant units within the upper Frontier Formation. Where photogrammetric control was unavailable, points were selected on a DEM draped with satellite imagery to define these units (Figure 10). Surfaces were then built from the photogrammetric and DEM point clouds and used to define modeling zones for significant units in Petrel (Figure 11).

Six units were identified. From oldest to youngest these are: Oyster Ridge Shoreface Sandstone Unit, Oyster Ridge Coastal Plain Unit, Dry Hollow Conglomerate Unit, Dry Hollow Lower Sandy Unit, Kemmerer Coal Zone, and Dry Hollow Upper Sandy Unit. A geocellular model was then generated within this framework. A 5x5 m cell size was used. Cell height was determined using a proportional thickness setting. A certain number of layers was defined for

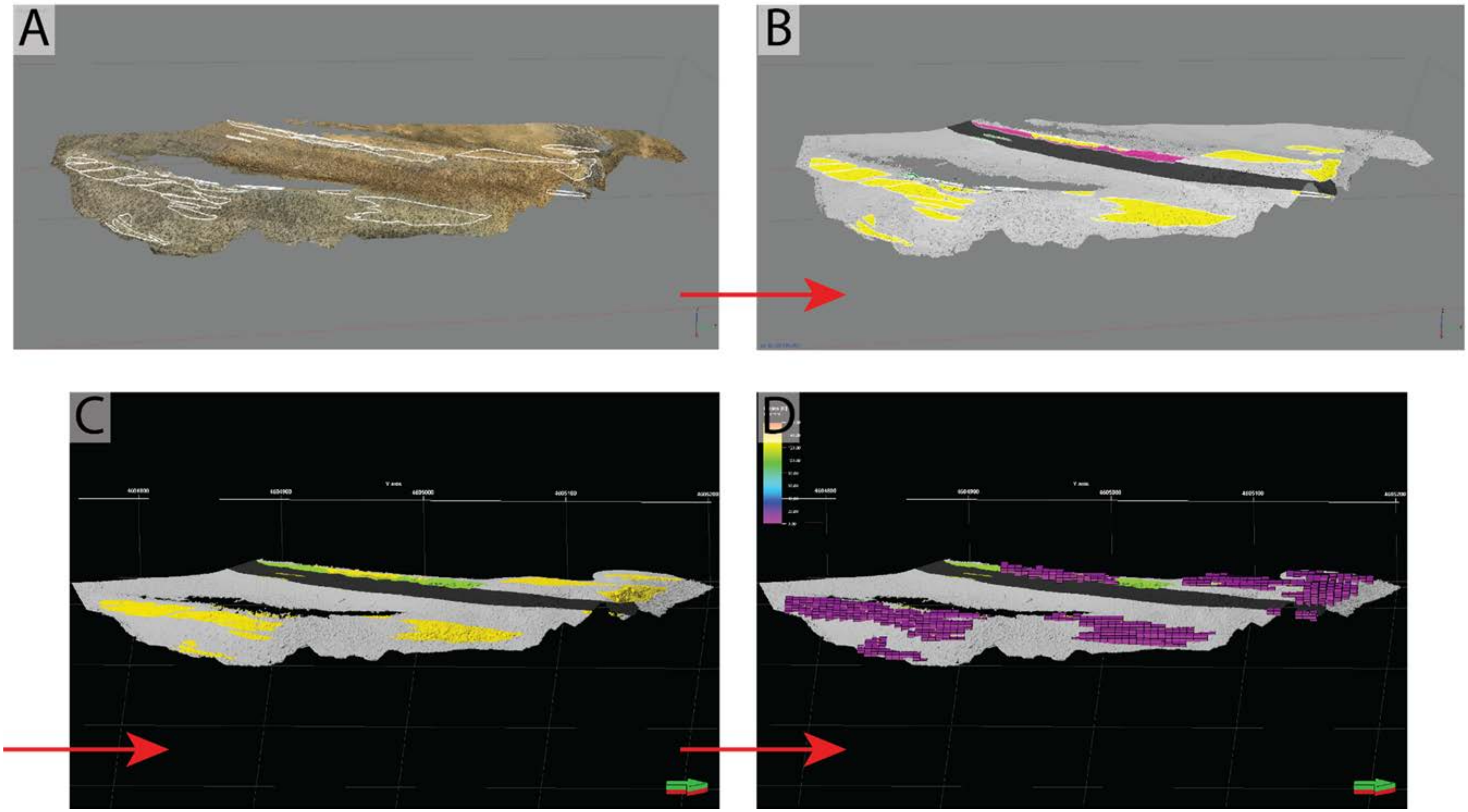

Figure 8. Example of use of photogrammetric model to create a 3D, spatially accurate geocellular model. A) Images of outcrop are taken using a drone and used to build a 3D photogrammetric model in Agisoft PhotoScan. B) Point cloud is used to manually classify facies. C) Facies classification point clouds are imported into Petrel. D) Point clouds are used to populate cells (purple) with facies information in a geocellular model in Petrel that can be linked to well and measured section data in order to model the depositional system.

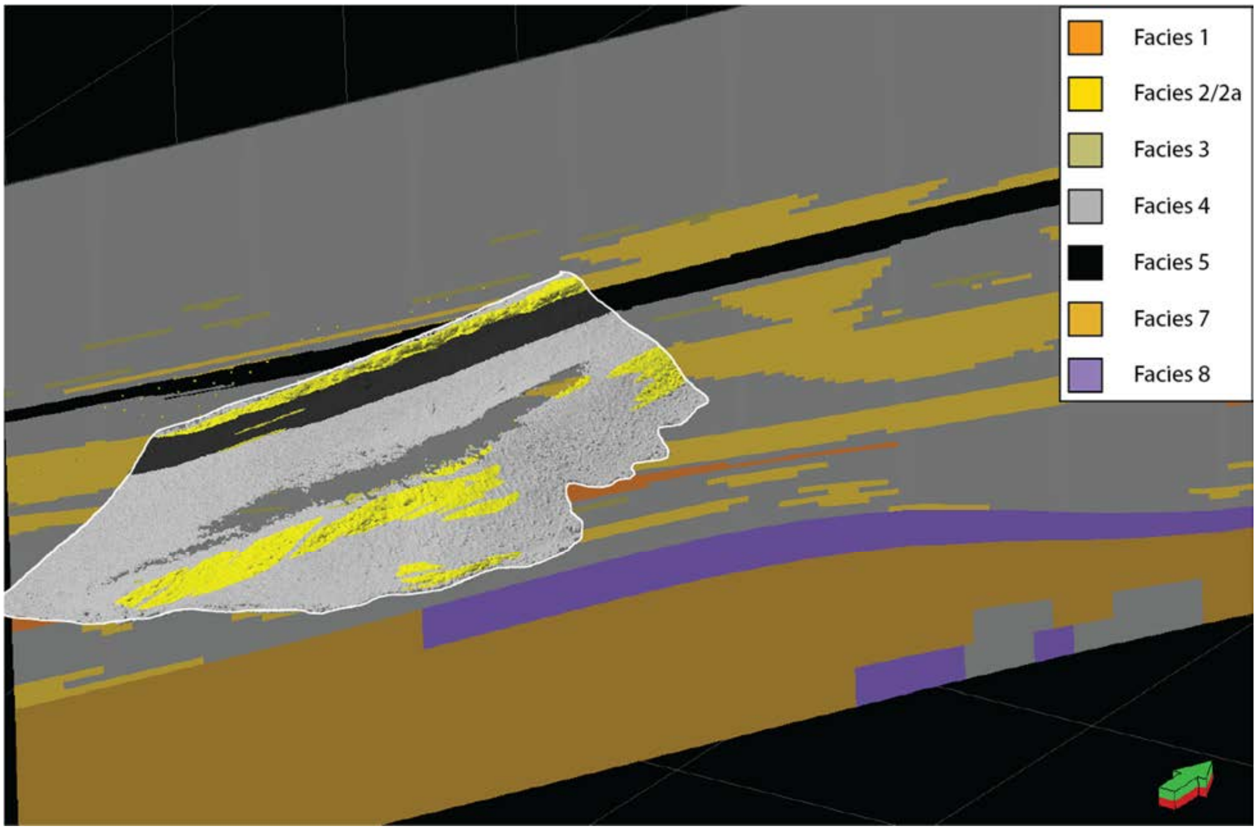

Figure 9. Representative cross section through finished facies model. The cross section intersects a point cloud (outlined in white) generated from a photogrammetric model. The model uses these imported points as control and extrapolates away from the outcrop. Figure 8 details the process of obtaining and importing these control points. Note the sandstone channels, mudstones, and coals in the facies model match up with corresponding control point in the point cloud.

each zone (5-25) based on the detail of control and size of significant features in each zone. The following cell heights resulted, from top to bottom:

- Dry Hollow Upper Sandy Unit: Range = 1.18-1.9 m, Average = 1.49 m, Standard Deviation = 0.12 m
- Kemmerer Coal Zone: Range = 0.01-2.89 m, Average = 1.22 m, Standard Deviation = 0.72 m
- Dry Hollow Lower Sandy Unit: Range = 0.04-1.63 m, Average = 1.17 m, Standard Deviation = 0.37 m

- Dry Hollow Conglomerate Unit: Range = 0.00-11.94 m, Average = 4.38 m, Standard Deviation = 2.38 m
- Oyster Ridge Coastal Plain Unit: Range = 0.01-5.50 m, Average = 2.09 m, Standard Deviation = 0.87 m
- Oysters Ridge Shoreface Sandstone Unit: Range = 6.02-14.70 m, Average = 10.71 m, Standard Deviation = 2.09 m

After defining modeling zones, facies models could be generated individually within each zone. In zones with photogrammetric point clouds, these points were used as control on the facies model. In zones without photogrammetry control, the distribution of facies was based on vertical facies distributions manually entered from measured sections. Two modeling methods were used - Sequential Indicator Simulation and Object Modeling (Figure 12). Both are stochastic methods. Facies distributions are determined stochastically while honoring control points and vertical facies profiles. Sequential Indicator Simulation works best when the shapes of facies bodies are irregular or unknown. Variograms are used to control the basic shape and trend of facies bodies. A trend of 103 degrees E-SE (perpendicular to strike and roughly equivalent to average sediment transport direction) was used for most facies. Object Modeling produces more realistic models of facies with a known geometry, such as fluvial channels. The distribution of facies is still determined stochastically in Object Modeling and variograms are still used to define trends. However, variables such as channel width, thickness, meander wavelength and amplitude can be decided deterministically by manually entering ranges for these parameters (Falivene et al., 2006). We entered values for channel width and thickness and meander amplitude based on outcrop measurements. Realistic ranges for meander wavelength (as well as amplitude) were also determined by looking at modern analogues for the Frontier (the Trinity

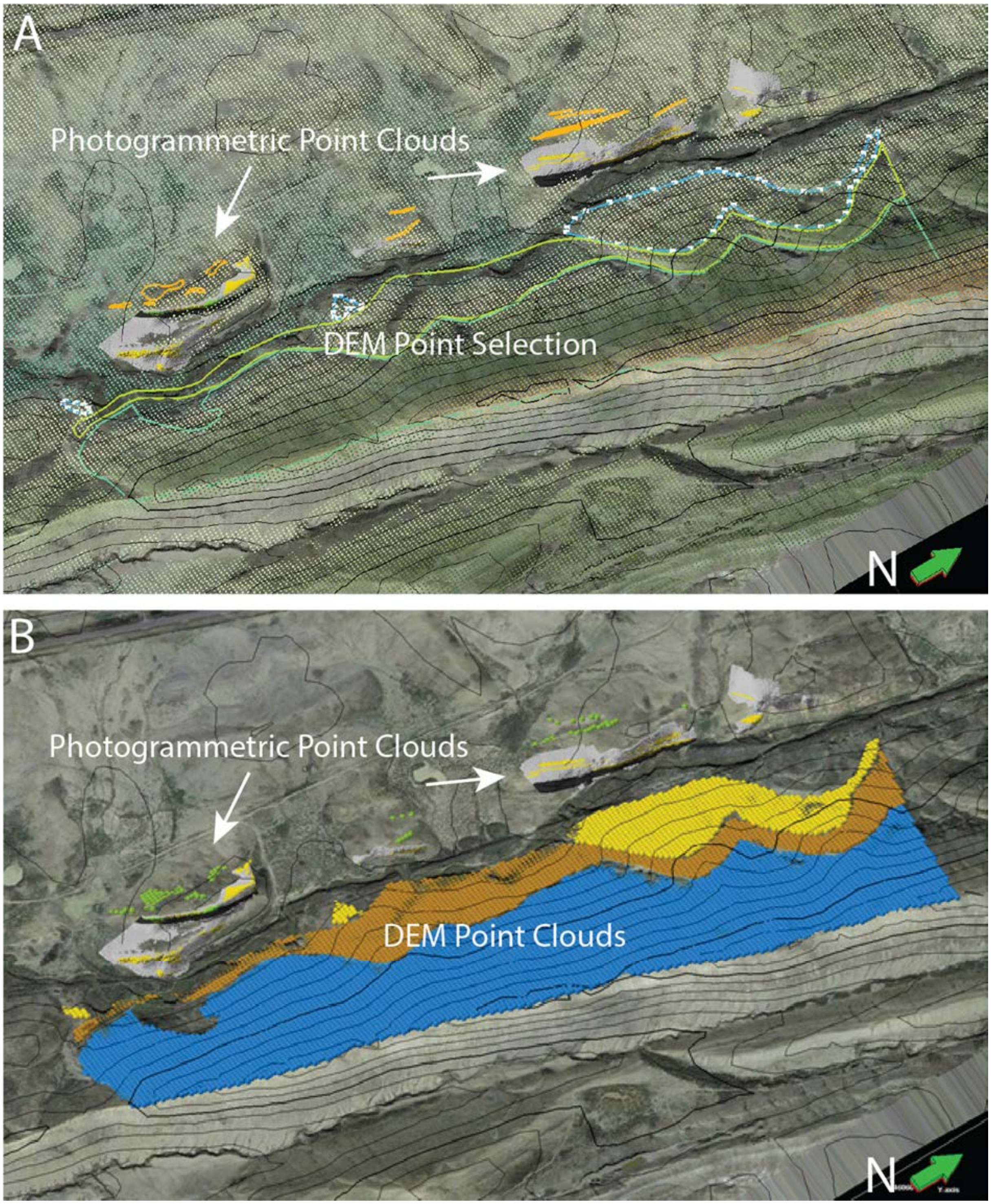

Figure 10. Selection of DEM points to supplement photogrammetric point clouds. Where photogrammetric control was unavailable for facies modeling, points were selected from a digital elevation model draped with satellite imagery to allow for definition of modeling zones outside the photogrammetric models. A) Selection of DEM points based on satellite imagery. B) Resulting DEM point clouds used to define Oyster Ridge Shoreface Sandstone (blue) and Coastal Plain (brown) Units and Dry Hollow Basal Conglomerate Unit (yellow).

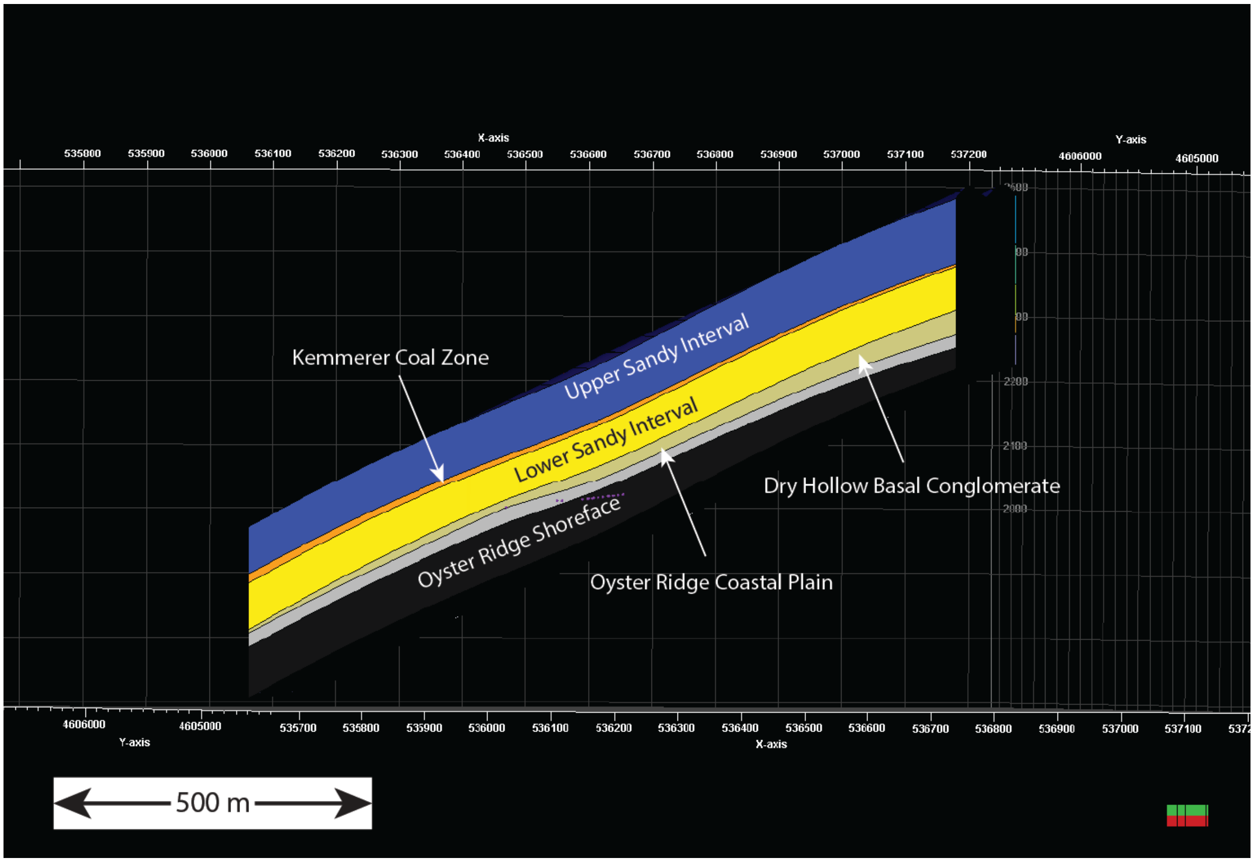

Figure 11. Zones for Petrel facies model. Six modeling zones were defined based off of the six laterally continuous correlation units identified in the upper Frontier. Spatially accurate points from photogrammetric models and from satellite and DEM data were used as guides to create surfaces that define the zones. Facies modeling can be done within individual zones to create a higher resolution model. Note that colors in this image are arbitrary.

River in Texas for fine sand fluvial channels and the Tagliamento River in Italy for conglomerates). We ran multiple (5-10) Sequential Indicator Simulation and Object Models for each zone, changing the starting seed points for the models and all variables. After observing each model, a simulation that looked most realistic was chosen to represent each zone.

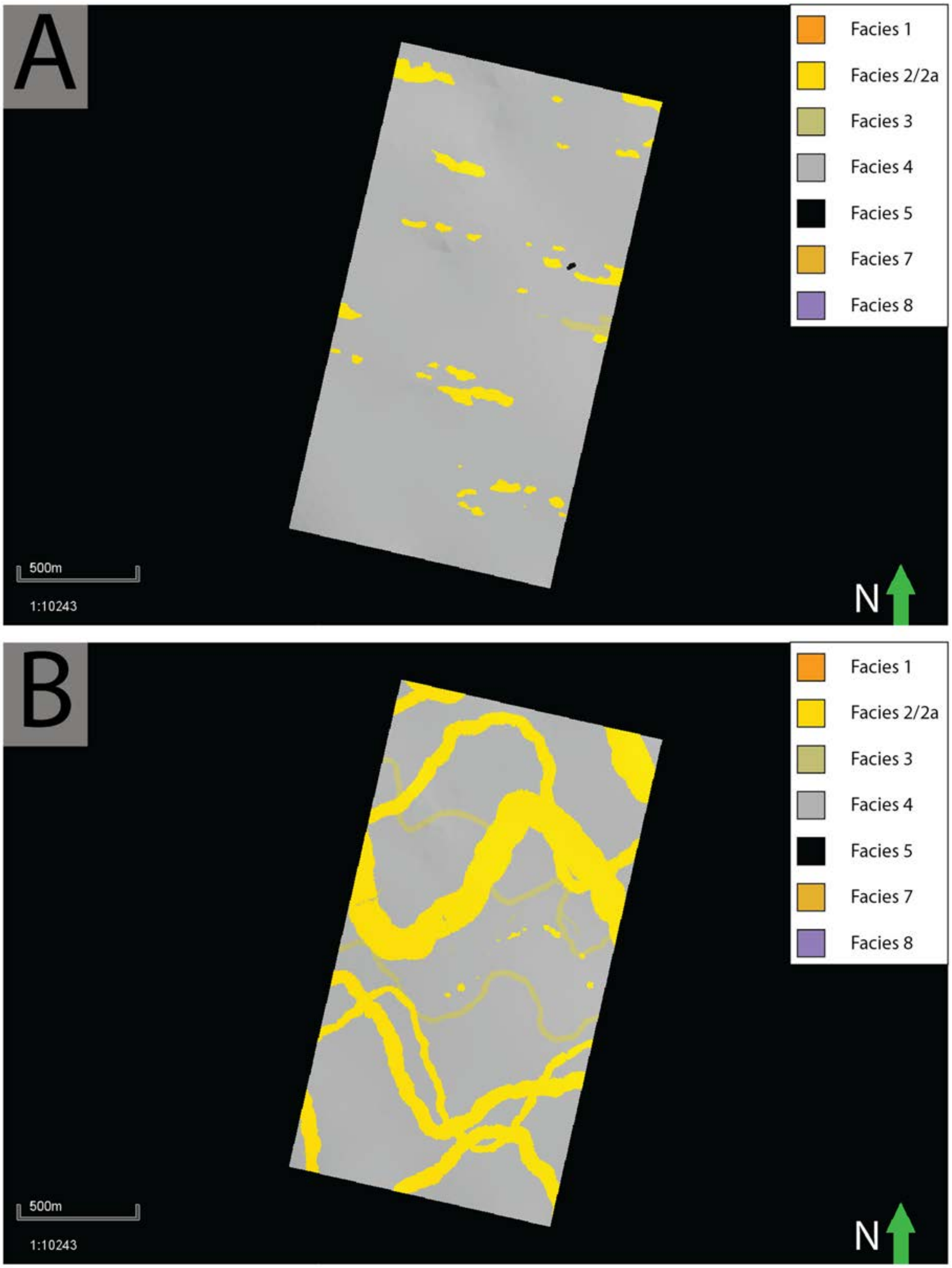

Figure 12. Sequential Indicator Simulation Modeling (A) vs. Stochastic Object Modeling (B) for the Lower Sandy Unit of the Dry Hollow Member. Both models were derived from the same control points. Object modeling produces a more realistic model for channelized deposits, whereas sequential indicator simulation modeling is more useful when specific facies geometries are unknown, such as in the Kemmerer Coal Zone or the Oyster Ridge oyster beds.

RESULTS

Lithofacies of the Dry Hollow and Oyster Ridge Members (Upper Frontier Formation)

Nine major lithofacies were identified in the upper part of the Frontier Formation (the Dry Hollow Member and the uppermost Oyster Ridge Member). These are described in detail in Table 2. Facies 1, 2, 2a, 3, 5 and 6 are terrestrial in origin (although Facies 2, 3 and 5 may show marine influence near the top of the Dry Hollow). Facies 4 encompasses both marine and non-marine mudstones. Facies 7 and 8 are exclusively marine.

Dominantly Terrestrial Facies

Facies 1: Conglomerates and coarse sandstone

Facies 1 is interpreted as a high-energy fluvial-lag deposit. Lenses of TCS chert-pebble conglomerate occur in close association with coarse, immature fluvial sandstones in channelized bodies. Fine TCS sandstones of Facies 2 commonly occur in these channels, especially toward their tops. The conglomeratic unit has a highly scoured basal contact and occurs sporadically at the base of the Dry Hollow Member (Figure 13).

Facies 2: Fine-grained, thick-bedded fluvial sandstone

Facies 2 accounts for the bulk of fluvial sandstones above the basal conglomerate in most sections. This facies is interpreted as major distributary channels in a deltaic settings (Figure 14). These are relatively clean, medium-grained fluvial sandstones exhibiting TCS, rare tabular cross-stratification, convolute bedding, fluid-escape structures and (in some beds) abundant rip-up clasts. Rarely, Facies 2 may be vertically or horizontally burrowed (extensive burrow networks exist in some horizons at the Whitney Canyon Haul Road section). It forms channelized sandstone bodies that are usually isolated, but may show some amalgamation and often appear to

Table 2. Lithofacies of the Dry Hollow and Oyster Ridge Members of the Frontier Formation

Facies	Lithology	Sedimentary Structures	Geometry	Fossils	Interpretation	Occurrence
1	Coarse to conglomeratic, lithic and chert-rich sandstone and conglomerate	coarse sand to pebble lenses, trough cross stratification (TCS), scoured base, usually closely associated with Facies 2, beds are medium to thick	lensoidal, conglomerates occur in a zone that is laterally persistent for 10's of miles but pinch and swell and are absent in some localities; channel bodies vary from 1-10 m thick and 10 - 100+ m wide	rare woody plant fragments	high-energy fluvial lag deposits	Dry Hollow Member
2	Fine-grained, thick bedded clean sandstone	TCS, rare tabular and ripple cross stratification, locally contains abundant convolute bedding, fluid escape structures and rip-up clasts (esp. in the lower Dry Hollow and upper Oyster Ridge), medium to thick-bedded	lensoidal; individual channel sands 0.5-2 m thick and 5-50 m wide; stacked channel bodies 5-10 m thick and 50-200 m wide	rare leafy and woody plant fragments, rare vertical and horizontal burrows (*Ophiomorpha* and *Thalassinoides)*	primary distributary channel fills	Common in both Dry Hollow and Oyster Ridge Mbrs.
2a	Facies 2 (thin-bedded variation)	TCS, 5-10 cm beds that are continuous over only a few meters, beds scour into each other frequently	lensoidal (surrounded a channel core of Facies 2 in the one location observed)	none observed	tidally-influenced, distal distributary channel fill	Dry Hollow Member
3	Fine-grained, thin bedded 'ratty' sandstone	TCS, both symmetric and assymetric ripple lamination, ripples sometimes show complex interference patterns	lensoidal or sheetlike; often occur in packages of 3-5 small channels 0.1-1 m thick and 10-30 m wide; stacked channel bodies 2-5 m thick and 100-200 m wide (occasionally a single sand with extend of 100's of m)	rare vertical and horizontal *Ophiomorpha*; bivalve shells are abundant in some beds near the top of the Dry Hollow	distal or secondary distributary channel fills, some with large width:thickness ratio may represent crevasse splays	Predominantly Dry Hollow Member, but may occur in the Oyster Ridge
4	Mudstones and siltstones	usually massive; sometimes poorly laminated	sheets? Exposures of this facies are very poor	root traces are common; woody plant fragments and bivalve fossils are locally abundant	interchannel, floodplain, interdistributary bay fill, and marine mudstones and siltstones	Common in both Dry Hollow and Oyster Ridge Mbrs.
5	Coals	none	coal beds tend to be thin and discontinuous except in the Kemmerer Coal Zone near the top of the Dry Hollow, where individual beds may be >1 m thick and occur with multiple other beds in a regionally extensive zone	common woody plant fragments (up to tree stump size)	alluvial plain or backshore (Kemmerer Coal Zone?) peat buildups in marshy environments	Predominantly Dry Hollow Member, but may occur in the Oyster Ridge
6	Medium-grained, lithic-rich, recessive sandstone	TCS, planar lamination, scoured basal contacts; usually associated with Facies 3 (sometimes 2)	lensoidal? Exposures of this facies are very poor	none observed	fluvial sandstones; possibly basal lags in fining-upward channel fills	Predominantly Dry Hollow Member, but may occur in the Oyster Ridge
7	Thin-bedded, fine-grained, bioturbated clean sandstone	planar lamination or large scale TCS	sheets; individual units laterally extensive over miles before pinching out; often multiple sandstones are stacked vertically with marine shale in between	common *Ophiomorpha* vertical burrows; shell fragments are common	Shoreface sandstones	Oyster Ridge Member
8	Oyster shell accumulations in fine sandstone/siltstone	usually massive, but sometimes found as small scoured and amalgamated channel bodies	two variations: most commonly laterally extensive and uniformly thick beds; also occurs in channelized sandstones at Cumberland Gap, Little Muddy Creek, and Whitney Canyon Haul Road outcrops	abundant oyster shells (*Ostrea soleniscus* Meek)	brackish water oyster reef buildups in backshore lagoonal/estuarine environments (or as lag deposits in tidal channels where chanelized)	Oyster Ridge Member (one minor occurrence observed in Dry Hollow)

Notes: Facies 1,2,2a, 3, 5, and 6 are fully terrestrial or have only slight marine influence. Facies 7 and 8 are fully marine. Facies 4 may be either terrestrial or marine in origin; fine-grained rocks were not split out into detailed facies because of poor exposure. Facies in gray occur in the Oyster Ridge only.

show compensational stacking (Straub et al., 2009; Hajek et al., 2010; Hofmann et al., 2011). Compensational stacking refers to the tendency of fluvial channels to shift laterally to fill topographic lows created by floodplain mudstones (that undergo more settling and compaction

Figure 13. Pebble conglomerates and coarse sandstones of Facies 1. Note trough cross bedding. Conglomerates generally form small lensoidal beds within larger fluvial sandstone bodies. Image shows Scully's Gap Section 2, Unit 10. Hammer for scale.

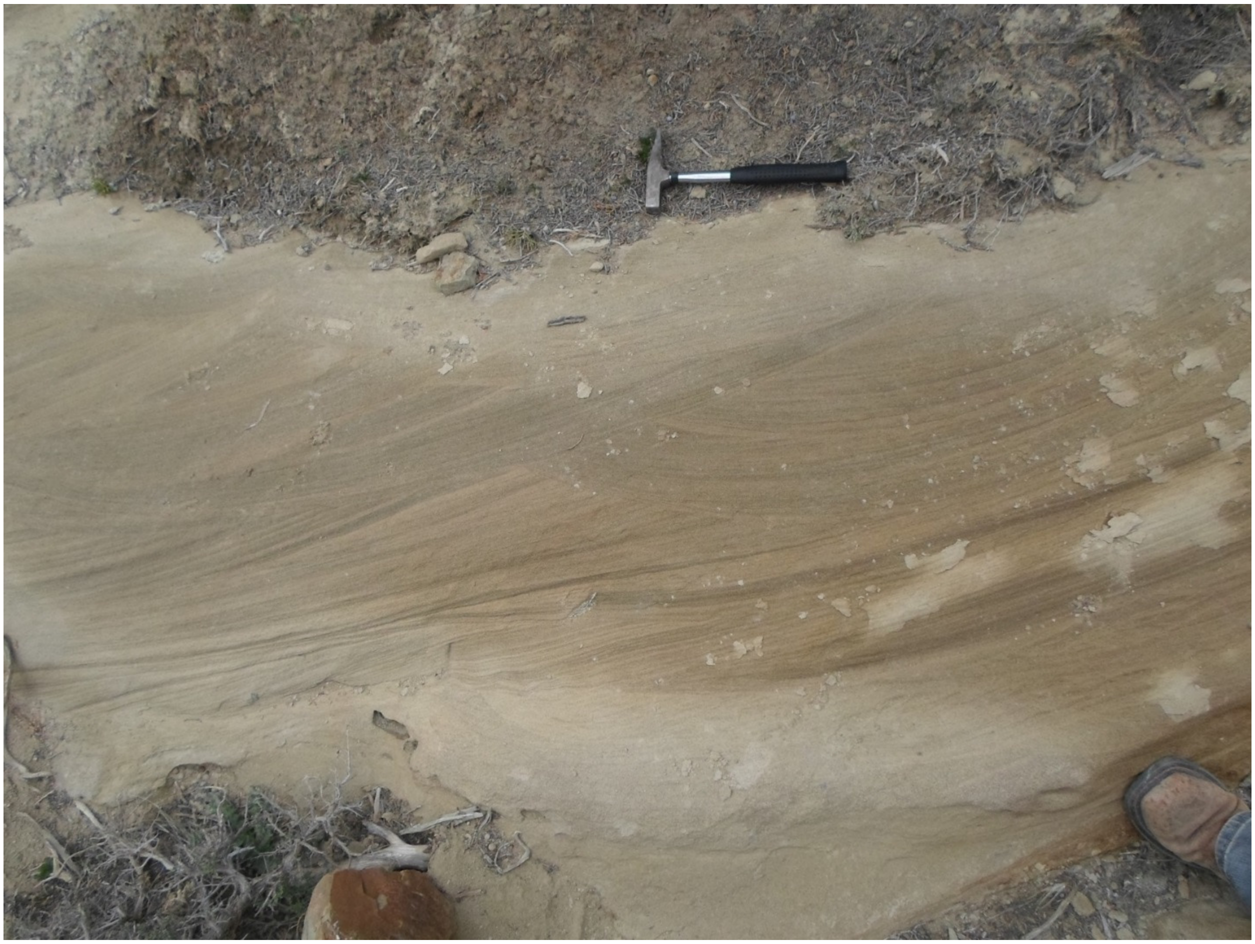

Figure 14. Fine, thick bedded fluvial sandstone of Facies 2. Note trough cross-stratification. Image shows Scully's Gap Section 2, Unit 12. Hammer for scale.

than channel sandstones). This results in channel belt stacking patterns where axes of younger channels are situated on or outside the margins of older sandstone channel fills.

Facies 2a: Fine-grained, thin-bedded fluvial sandstone

Facies 2a is a variation of Facies 2; the major difference is bed thickness. Facies 2a contains beds that are only 5-10 cm thick and continuous over <10 m laterally. This facies was only observed in one location at Cumberland Gap, just above the Kemmerer Coal Zone. It was observed in one wide, asymmetric channel. Most of this channel body is thin-bedded Facies 2a, with the exception of two lensoidal 'channel cores'. These two channel cores (approximately 70 m and 15 m wide) are located near the center of the channel body and are composed of normal, thick-bedded Facies 2. Both facies in this channel body exhibit southward migrating lateral accretion. Facies 2a may represent a tidally-influenced distal distributary channel fill. Thin bedding may be due to highly variable flow resulting from tidal influence. The channel cores may be subsequent channels that scoured into the main channel fill or, alternatively, could represent chute channels cutting across a point bar deposit (Grenfell et al., 2012) (Figure 15).

Figure 15. Thin bedded, fine fluvial sandstone of Facies 2a. Beds show internal ripple or trough cross-stratification. Beds are thin, discontinuous, and show evidence of lateral accretion (notice the strongly tilted beds on the right of the photograph. Thin bedding may be the result of tidal influence in a large distal distributary channel. Image shows Cumberland Gap Section 2, Unit 16. Hammer for scale.

Facies 3: Fine-grained, ratty fluvial sandstone

These sandstones are slightly finer grained than Facies 2. They exhibit TCS, ripple lamination, tend to be finely laminated, but are sometimes massive and are usually very well cemented. In some sections (especially near the contact with the Hilliard Shale) marine bivalve shells and trace fossils are common. Channel fills are generally less than 1 m thick and 50 m wide. Channel bodies often contain 3-5 compensationally stacked channels. Facies 3 is interpreted to represent small, secondary distributary channel fills (although in some rare cases it may also be the result of crevasse splays or thin marine sandstones; Figure 16).

Figure 16. Fine, ratty fluvial sandstones of Facies 3. Five thin sandstones cluster and stack in this location, typical of this facies. Note compensational stacking of channels (thickest part of top channel is above thin margin of bottom channel). Image shows Little Muddy Creek Section 2, Unit 37. Barbed wire fence for scale.

Facies 4: Marine and floodplain mudstones and siltstones

Mudstones and siltstones were not split into separate facies due to poor exposure. Varied red, brown, green and gray mudstones and siltstones are present throughout the upper Frontier Formation and the Hilliard Shale. Mudstones and siltstones are usually massive. Root traces, paleosols, and wood and bivalve fossils are common. Facies 4 can include overbank flood deposits, interchannel mudstones and siltstones, interdistributary bay fill, or marine shales. The majority of mudstones in the upper Frontier are terrestrial in origin. Mudstones are assumed to be marine in origin when in close association with the Oyster Ridge shoreface sandstones and at the top of the Frontier section at the transitional contact with the Hilliard Shale (Figure 17).

Facies 5: Coals

Facies 5 encompasses low grade – lignitic (Cobban and Reeside Jr., 1952) to bituminous (Schmitt, 1985) – coals and organic-rich mudrocks. Coals occur in thin (mm-several cm), noncontinuous beds throughout the section. These likely represent coals formed in oxbow lakes or other small, inter-channel lakes or interdistributary bays. The Kemmerer Coal Zone near the top of the Dry Hollow is laterally persistent across the study area with coals measuring up to several meters thick; woody plant fossils are common. Lateral continuity along with interfingering with oyster-rich beds further north (Myers, 1977), suggest deposition under brackish conditions influenced by the marine realm (Figure 17).

Facies 6: Medium-grained, lithic-rich, recessive fluvial sandstone

Facies 6 sandstones are fine- to medium-grained, well laminated sandstone with abundant lithics (and potentially some carbonaceous grains). These sandstones are less mature texturally and compositionally than Facies 2 and 3. They usually exhibit TCS and are often poorly

Figure 17. Mudstones and coals of Facies 4 and 5. This photo was taken in a well-exposed part of the Kemmerer Coal Zone. Note the varying reds, greens, grays and tans of mudstones with interbedded coal seams. Image shows Whitney Canyon Haul Road Section, Unit 17. Hammer for scale.

cemented and recessive. This facies is most common low in the Dry Hollow section and high in the Oyster Ridge section. Because it is almost always poorly exposed, it was not possible to accurately characterize typical geometries for this facies. In the Scully's Gap 1 Section, where it is most common it often occurs below Facies 3 sandstones and therefore may be a coarser-grained basal deposit in a coarsening upward channel fill. Facies 6 could serve as an important fluid flow pathway between major channel bodies as these sandstones can be several meters thick and are underrepresented in this and other studies due to poor exposure (Figure 18).

Figure 18. Medium, lithic-rich fluvial sandstone of Facies 6. This facies is usually poorly exposed, so typical geometries are unknown, but trough cross-stratification is evident, as seen above. Image shows Little Muddy Creek Section 2, Unit 3. Pencil for scale.

Marine Facies

Facies 7: Shoreface sandstones

Shoreface sandstones are found only at the top of the Oyster Ridge Member. Individual sandstone bodies may be tens of meters thick and have a sheet-like geometry; individual packages are continuous over tens of kilometers. Multiple sandstones may be present in the section, interfingering with marine shale of the underlying Allen Hollow Member. The sandstone is fine to very fine, well sorted and well rounded, and quartz-rich. Bedding is thin to medium and exhibits TCS and planar lamination. Vertical *Ophiomorpha* burrows and shell fragments are common. Although only the uppermost beds of this facies were measured for this study (to facilitate correlation of measured sections) the shoreface sandstones of the Oyster Ridge have been interpreted to represent distal lower shoreface to foreshore and tidal channel fill deposits (Feldman et al., 2014) and have the potential to serve as an important reservoir facies (Figure 19).

Facies 8: Oyster-rich deposits

0.1 - 5 m accumulations of oyster shells occur directly above the uppermost shoreface sandstone of the Oyster Ridge. Most commonly they form one or more thin, laterally continuous beds that divide the coastal plain deposits of the Oyster Ridge from the shoreface units. These thin beds are almost completely composed of compacted oyster shells with a fine quartz sand matrix. Rarely, oysters are preserved in growth position. Channelized oyster deposits also occur in several sections; the fraction of sand matrix is much higher in these instances. According to Myers (1977), accumulations of oysters indicate brackish water conditions such as those that occur in lagoonal settings on the modern Gulf Coast of the United States, where oyster reefs are

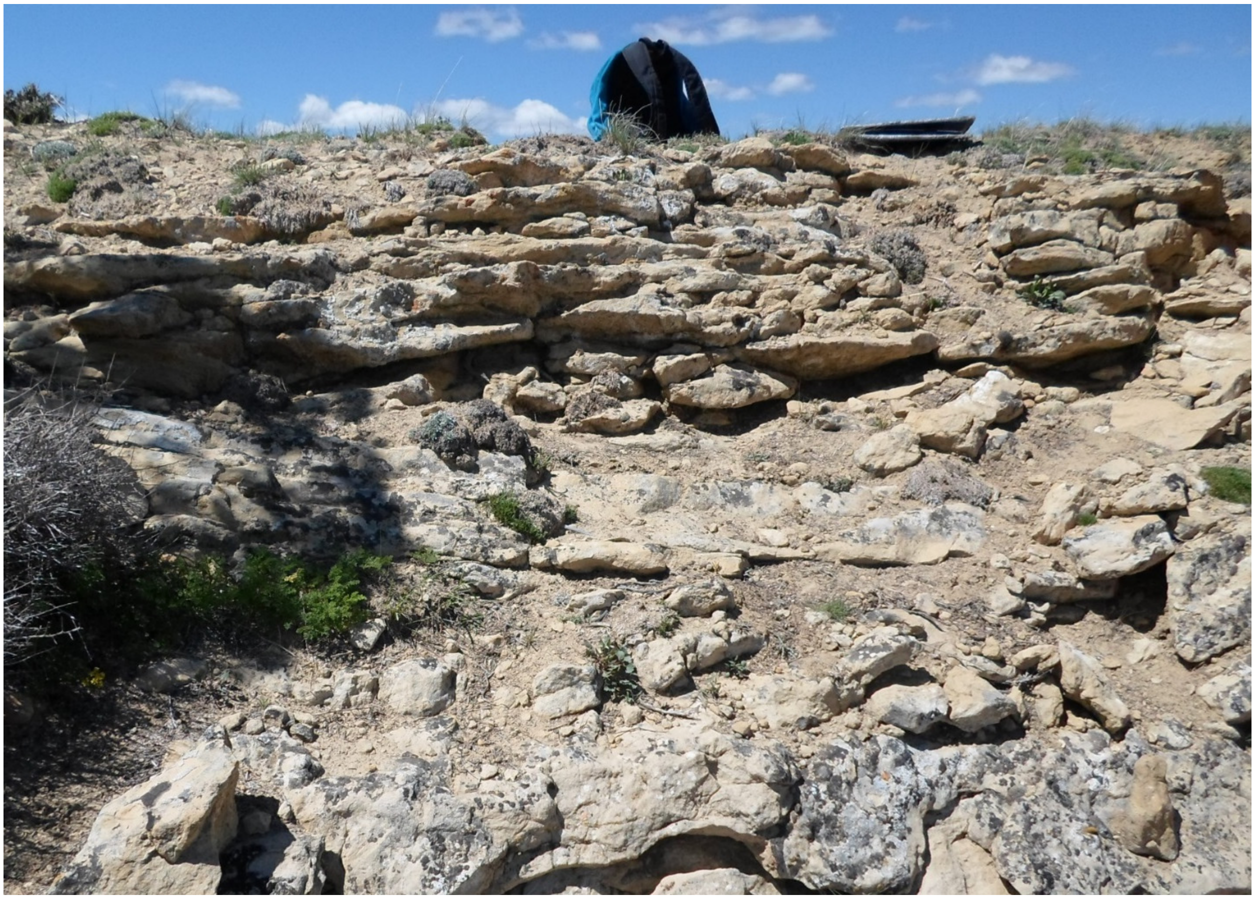

Figure 19. Shoreface sandstones of Facies 7 in the Oyster Ridge Member. In some localities the shoreface sandstones are much more massive and continuous. However, this shows a more typical expression of Facies 7 in the study area and particularly at the top of the shoreface unit. Sandstones have thin, irregular, discontinuous beds, contain mud partings, and are commonly burrowed by *Ophiomorpha*. Despite thin bedding the overall shoreface unit is generally several meters thick. Image shows Bridger Gap Section, Unit 1. Backpack for scale.

common. Thin, laterally continuous oyster beds with little sand were likely deposited in similar lagoonal settings. Channelized oyster beds may represent tidal channels deposits at the inlets to these lagoons (Figure 20).

Thin Sections

Thin sections were not point counted for detailed compositional data, but do provide insight into the textural and compositional maturity of samples (Figure 21). Compositional maturity especially can have a profound impact on diagenesis due to the presence of clays or other ductile grains that allow for mechanical compaction but prevent quartz overgrowths, or

Figure 20. Oyster shell deposits of Facies 8. Left photo (Hams Fork, north of Cumberland Gap) illustrates can be seen the more common, massively bedded oyster shell deposits that can be found over most of the Oyster Ridge shoreface sandstones. These are generally <2 m thick and are laterally extensive. Most of the rock is oyster shell material with a quartz sand matrix. Keys for scale. Right photo (Little Muddy Creek Section 1, Unit 1) illustrates channelized oyster deposits. These are much more sand rich and likely represent tidal channels. Jacob staff for scale.

quartz that may compact less but can also more fully cement through quartz overgrowths. Textural maturity also affects porosity, as poorly sorted sandstones have lower porosity than well sorted ones. In thin section, Facies 1 shows coarse, angular grains with abundant lithic fragments, probably largely chert. Facies 2 and 2a look quite similar. Both are well sorted and subangular with mostly quartz grains and a few dark lithics or organic fragments. Facies 3 is fine grained, well-sorted, and has angular grains that are more lithic rich than Facies 2. The Facies 4 mudstone section was poor quality but reveals that the quartz silt fraction was actually quite

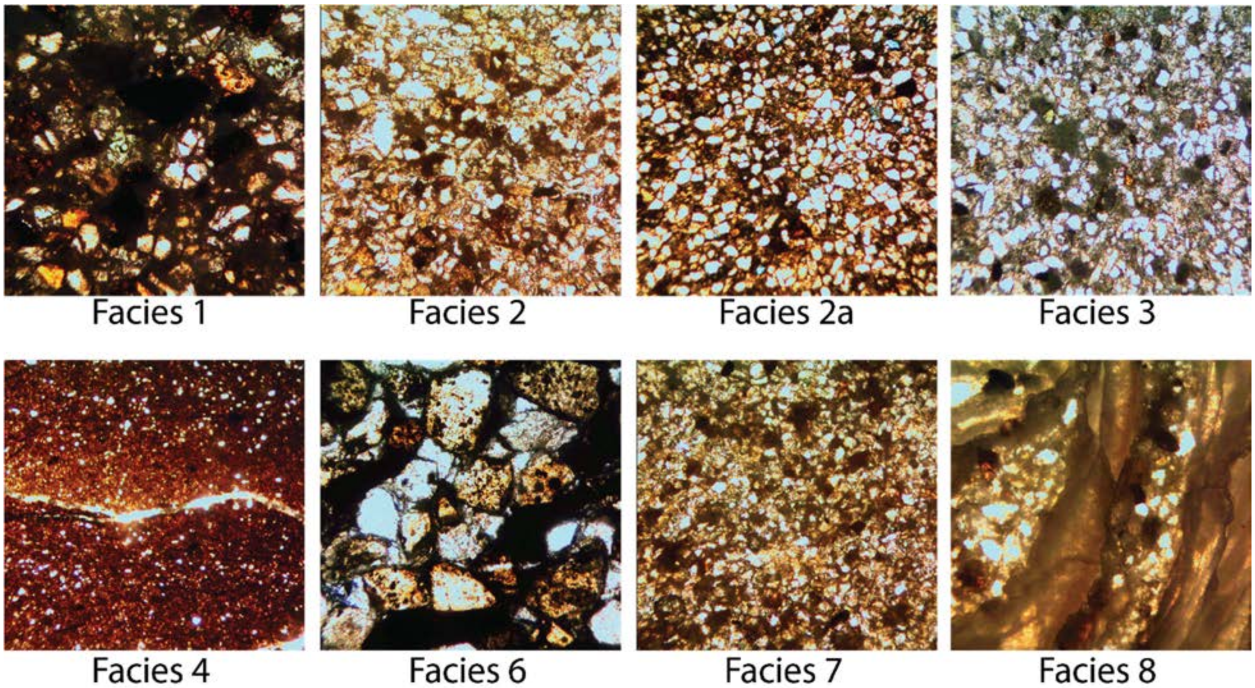

Figure 21. Photomicrographs (50x magnification) of thin sections of upper Frontier facies. All facies except for Facies 5 (coals) are represented. Note varying grain sizes and textural/compositional maturities. See Table 1 for sample descriptions (Facies 1 = FD1-9a; Facies 2 = FDC2-16b; Facies 2a = FDC2-16e; Facies 3 = FDS1-19; Facies 4 = FDM2-24; Facies 6 = FDM2-7; Facies 7 = FOB1-1; Facies 8 = FOM1-1). All thin sections are 1" wide.

high. Facies 6 shows medium, subangular, well-sorted grains with a high proportion of lithics and concave grain contacts, indicating mechanical compaction. Facies 7 is largely quartz with a few lithic or organic grains. Grains are subrounded and well-sorted. Facies 8 is composed almost entirely of deformed oyster shells in a matrix of well-sorted, fine quartz sand.

Porosity/Permeability

Frontier sandstones tend to have fair to good porosity and poor permeability. Porosity and permeability do have a strong positive correlation (Figure 22; Tables 3 and 4). There is some clustering by facies; Facies 1 conglomerates are generally the most porous and permeable, followed by Facies 2. Facies 3 is third most porous on average with Facies 6 having the lowest average porosity. Facies 6 does average a higher permeability than Facies 3, however.

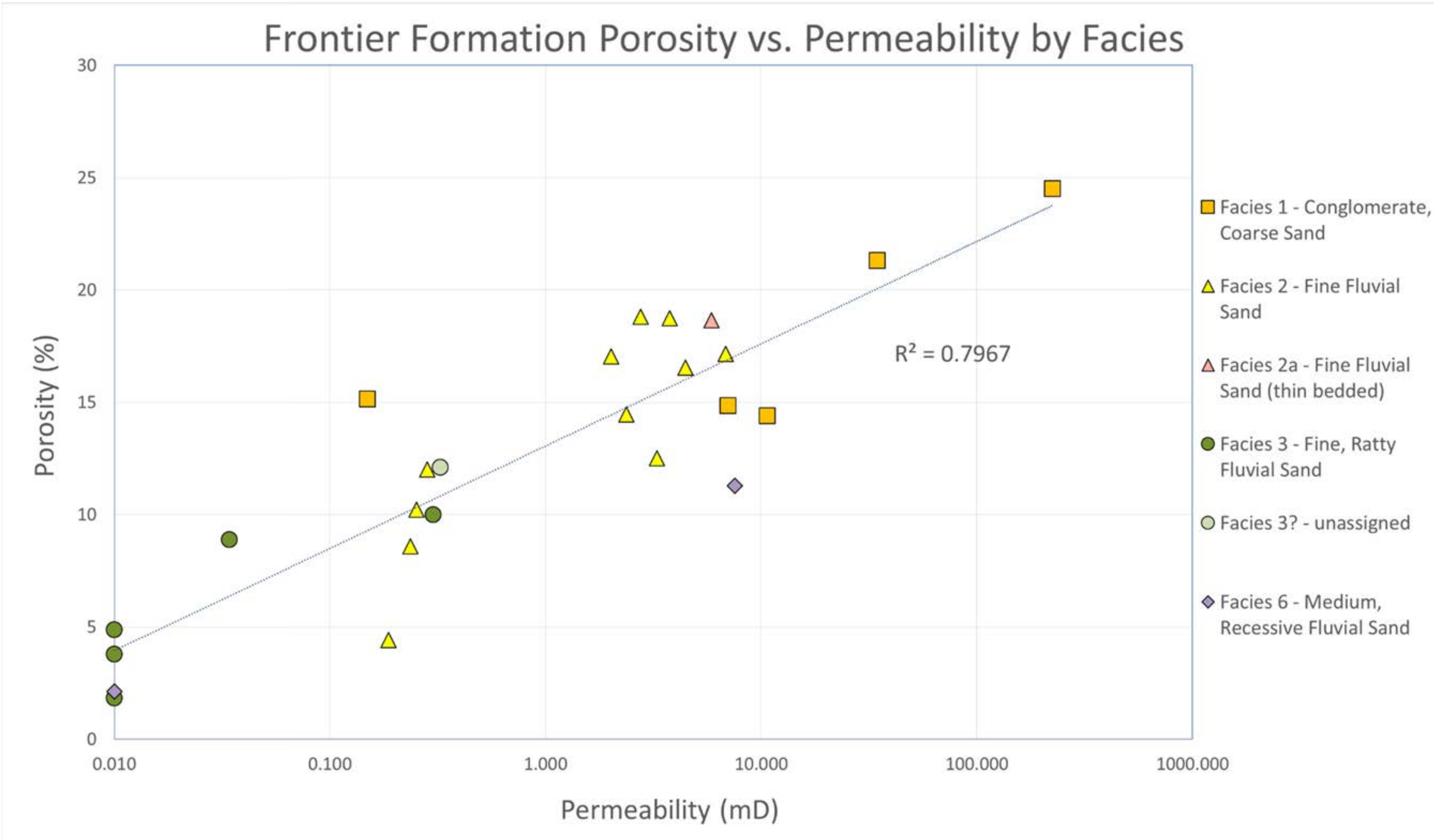

Figure 22. Porosity and permeability of Dry Hollow Member sandstones by facies. Samples from each section are represented. Porosity and permeability are usually low, but have a strong positive correlation. In general, Facies 1 is the most porous and permeable, followed by Facies 2/2a and lastly by Facies 3. Facies 6 does not show clear clustering, likely due to small sample size and possible error due to weathering of samples. Outlying Facies 1 results may also be affected

Table 3. Porosity and Permeability Statistical Analysis

Porosity Statistics (% porosity)

Facies	Min	Max	Average	Standard Deviation	# of Samples
1	14.399	24.492	18.040	4.587	5
2/2a	4.414	18.808	14.097	4.620	12
3	1.838	12.112	6.913	4.001	6
6	2.130	11.280	6.705	6.470	2

Permeability Statistics (mD)

Facies	Min	Max	Average	Standard Deviation	# of Samples
1	0.150	225.333	55.591	95.778	5
2/2a	0.187	6.863	2.695	2.272	12
3	0.010	0.325	0.115	0.154	6
6	0.010	7.573	3.792	5.348	2

Note: For statistical calculations, facies 2 and 2a have been combined; the unassigned (likely facies 3) sample has also been included in the facies 3 sample set.

Table 4. Porosity and Permeability Results

Sample	Facies	Average Permeability (mD)	Porosity (%)
FDH-10b	1	10.700	14.399
FDB1-9e	1	34.733	21.314
FDC3-9b	1	0.150	15.139
FDS1-9d	1	7.040	14.855
FDC3-9c	1	225.333	24.492
FDM1-5	2	0.252	10.216
FDC1-13	2	3.763	18.748
FDM1-7	2	0.236	8.595
FDC3-17	2	2.760	18.808
FDS1-4	2	3.290	12.51
FDC2-8	2	0.187	4.414
FDS2-26	2	6.863	17.152
FDH-18a	2	0.283	12.015
FDM2-9	2	2.367	14.452
FDC1-6	2	2.010	17.056
FDC2-16b	2	4.453	16.543
FDC2-16d	2a	5.877	18.659
FDM2-37	3	0.302	9.99
FDM1-18	3	0.010	4.881
FDS1-19	3	0.010	1.838
FDH-18b	3	0.034	8.877
FDM1-11	3	0.010	3.78
FDM2-11	none (3?)	0.325	12.112
FDM2-3	6	7.573	11.28
FDS2-11	6	0.010	2.13

Notes: Samples with permeabililty below the limit of detection (BLD) are plotted as having 0.01 mD of permeabilty in Figure 22 in order to plot on the graph. Outlying permeability of sample FDC3-9c may be due to weathering of the sample.

XRD

Frontier sandstones have a variety of mineral compositions (Table 5). One representative sample of each sandstone facies was analyzed. Oyster Ridge shoreface sandstones are the ‘cleanest’ at around 80% quartz. The Facies 2 sample was about 66% quartz and 20% clay minerals. The Facies 6 sample had a similar amount of quartz and clays and also had a high carbonate content (20%). Both the Facies 1 and Facies 3 samples had <40% quartz and high levels of carbonate. Mineralogy has had an important influence on the diagenesis of Frontier sandstones. Ductile grains such as feldspar reduce porosity by mechanical compaction. Clays can help preserve porosity by preventing quartz overgrowths. Calcite is precipitated as cement. In the study area, feldspar and ductile rock fragments are less common than they are in the Frontier on the northern end of the Moxa Arch. In the south (study area) comparatively less mechanical compaction took place, however, quartz cement is more common, reducing intergranular porosity (Dutton, 1993).

Fine-grained rocks of Facies 4 also had a wide range of compositions (Table 6). Quartz volumes ranged from 2-71%, feldspars from 4-35%, carbonate minerals were 0-78%, and clays composed from 2-72% of these rocks. This attests to the heterogeneity of Facies 4; it likely represents a wide variety of depositional processes. Good exposures and careful study of these mudstones and siltstones could provide further valuable context for better understanding the depositional and diagenetic history of the fluvial system.

Table 5. XRD Results - Composition of Frontier Sandstones

Mineral Components	Samples				
	FDC2-16b	FDM2-7	FDS1-9a	FDS1-19	FOB1-1
Quartz	66%	64%	38%	26%	78%
Feldspar	6%	1%	2%	12%	5%
Carbonate	6%	20%	47%	55%	8%
Clay and Micas	20%	15%	6%	7%	8%
other	2%	0%	7%	1%	1%

Note: See Table 1 for sample descriptions. Results have been grouped by mineral types for simplification.

Table 6. XRD Results - Composition of Fine-grained Frontier Rocks

Mineral Components	Samples								
	FDC3-10	FDH-17b	FDH-17c	FDH-17d	FDH-17e	FDH-17f	FDM2-23	FDM2-24	FOM1-1
Quartz	39%	33%	8%	68%	71%	51%	2%	5%	11%
Feldspar	21%	16%	9%	5%	5%	11%	20%	35%	4%
Carbonate	8%	1%	3%	2%	0%	3%	52%	38%	78%
Clays and Micas	28%	36%	72%	22%	22%	29%	8%	17%	2%
other	4%	14%	9%	3%	2%	6%	17%	5%	6%

Note: See Table 1 for sample descriptions. Results have been grouped by mineral types for simplification.

Pyrolysis

The coals and mudstones of the Frontier show significant variation in the amount of total organic carbon present (Table 7). TOC ranges from <1% in siltstones to nearly 74% in some coals (coaly rocks were always >30% TOC). According to trends observed by Sykes and Snowdon (2002) and source rock potential classification from Peters (1986), none of the mudstones tested from the Frontier have good source-rock potential. They are organic poor and the kerogen yield (mgHC/g rock) is too small. All of the coals, however, have high enough TOC and kerogen yield and have been heated to a maximum temperature that is high enough to allow for the generation of hydrocarbons (likely gas). The Frontier Formation on the Moxa Arch entered the oil and gas windows during the Paleogene (Kirschbaum and Roberts, 2005). The Frontier may, therefore, be partially self-sourcing, particularly in the sands that overly the Kemmerer Coal Zone. Self-sourcing is likely a very minor contributor to overall hydrocarbon charging, however, given the abundance of other potential source-rocks such as the underlying Aspen/Mowry Shale and is unnecessary for a functioning petroleum system to exist.

Table 7. Pyrolysis Results for Frontier Coals and Fine-grained Rocks

Measurement	Sample ID												
	FDH-17e	FDH-17c	FDH-17f	FDM2-24	FDH-17b	FDC3-10	FDC2-15a	FDC3-16	FOC3-8	FDS2-24	FDH-17a	FDC3-no#a	FDC3-no#b
S1-Free Oil (mgHC/g rock)	0.1	0.16	0.06	0.07	0.07	0.1	0.7	1.01	0.44	1.12	0.55	1.76	0.55
S2-Kerogen Yield (mgHC/g rock)	0.75	2.63	0.26	1.07	0.3	0.68	12.62	22.57	20.99	30.81	20.91	79.27	18.63
S3 (mgCO2/g rock)	1.96	3.84	0.7	2.86	1.09	1.25	25.21	29.2	16.29	25.41	25.18	13.38	3.76
Tmax-Maturity (°C)	443	443	443	484	439	448	434	432	445	430	434	432	431
TOC-Total Organic Carbon (Weight %)	1.78	4.43	0.57	1.94	0.49	0.91	47.4	61.32	30.86	65.18	46.96	73.77	14.6
CC-Carbonate Carbon (Weight %)	0.29	0.31	0.24	5.49	0.12	1.33	1.24	1.38	1.65	1.59	1.36	1.29	0.56
GOC-Generative OC (Weight %)	0.14	0.36	0.05	0.21	0.07	0.11	1.99	2.98	2.34	3.57	2.61	7.36	1.77
NGOC-Non-generative OC (Weight %)	1.64	4.07	0.52	1.73	0.42	0.8	45.41	58.35	28.52	61.61	44.35	66.41	12.84
AI-Adsorption Index (Weight %)	1.46	3.63	0.47	1.59	0.4	0.75	38.87	50.28	25.31	53.45	38.51	60.49	11.98
OSI-Oil Sat.Index (mgHC/gTOC)	5	3	10	3	14	10	1	1	1	1	1	2	3
PI-Production Index	0.12	0.06	0.19	0.06	0.19	0.12	0.05	0.04	0.02	0.04	0.03	0.02	0.03
HI-Hydrogen Index (mgHC/gTOC)	42	59	45	55	60	74	26	36	68	47	44	107	127
OI-Oxygen Index (mgCO2/gTOC)	110	86	122	147	221	136	53	47	52	38	53	18	25

Notes: See Table 1 for sample descriptions. Samples are predominantly coals and dark mudstones, but also include organic poor mudstones and siltstones for comparison.

Net-to-gross Ratios

Calculations of net-to-gross ratios and net sandstone volumes were based on measured sections. Measured thicknesses of all sandy facies (1, 2, 2a, 3, and 6) within a given section were added together to get net sandstone thickness and divided by the bulk thickness of the section to calculate net-to-gross ratios (Tables 8-11).

Net sandstone thicknesses and net-to-gross ratios reflect the lateral variability of the upper Frontier. Within individual units, net-to-gross ratios had standard deviations ranging from 13-41%. Net sandstone thicknesses showed even higher variability, though this was partially due to the varying thicknesses of the sections themselves. Some general trends in the sandstone content of vertical units do exist however. On average, the unit with the highest net-to-gross ratios was the Upper Sandy Unit, just above the Kemmerer Coal Zone, with an average of 51% sandstone. This was followed by the Lower Sandy and Oyster Ridge Coastal Plain Units, averaging 33% and 28% sandstone, respectively. The Kemmerer Coal Zone averaged only 5% net-to-gross. Net-to-gross for all sections and units combined averaged 31%. These ratios are important as a higher net-to-gross will increase both vertical and lateral connectivity of sandstones.

With regards to individual sections, Scully's Gap, Whitney Canyon Haul Road, and Cumberland Gap sections had to the highest net-to-gross, ranging from 20-50% sandstone. The sections at Little Muddy Creek and Bridger Gap had net-to-gross ratios of only 8-12%. Similar trends exist for net sandstone thickness in other locations, with the Scully's Gap 1 and Haul Road sections containing about 40 m of sandstone each and Scully's Gap 2 and Cumberland Gap sections 1 and 2 about 20 m of sandstone each. The Little Muddy Creek and Cumberland Gap 3 sections contained 13-16 m of sandstone and the Bridger Gap section showed only 5.8 m.

Table 8: Net to Gross Ratios and Net Sand Thicknesses for Frontier Measured Sections

Section	Unit	Gross Thickness (m)	Net Sand (m)	Net:Gross
Bridger	DH Upper Sandy	9.5	0.3	3%
	Coal Zone	7	0	0%
	DH Lower Sandy	34	4.6	14%
	OR Coastal Plain	21	0.9	4%
Scully 2	DH Upper Sandy	6	6	100%
	Coal Zone	10.2	4.1	40%
	DH Lower Sandy	40.5	13	32%
	OR Coastal Plain	4	1.5	38%
Scully 1	DH Upper Sandy	8.2	1.7	21%
	Coal Zone	11.1	0	0%
	DH Lower Sandy	49.5	33.1	67%
	OR Coastal Plain	20.4	9.3	46%
Cumberland 2	DH Upper Sandy	7.5	5.3	71%
	Coal Zone	14.5	0	0%
	DH Lower Sandy	33.5	15.3	46%
	OR Coastal Plain			
Cumberland 1	DH Upper Sandy	8.3	8.3	100%
	Coal Zone	14	0	0%
	DH Lower Sandy	18	11.9	66%
	OR Coastal Plain			
Cumberland 3	DH Upper Sandy	13.7	6.9	50%
	Coal Zone	8.5	0	0%
	DH Lower Sandy	33.5	3.9	12%
	OR Coastal Plain	9	2.1	23%
Muddy 1	DH Upper Sandy	12.5	1.5	12%
	Coal Zone	13.5	0	0%
	DH Lower Sandy	94	9.6	10%
	OR Coastal Plain	19	3.9	21%
Muddy 2	DH Upper Sandy	12.3	1.9	15%
	Coal Zone	15	1	7%
	DH Lower Sandy	86.5	11.7	14%
	OR Coastal Plain	17	1.5	9%
Haul Road	DH Upper Sandy	10.5	10.5	100%
	Coal Zone	11.5	0	0%
	DH Lower Sandy	34.5	14.1	41%
	OR Coastal Plain	24.6	13.6	55%

Notes: Gross thickness is the full thickness of the section. Net sand is the combined thickness of all sandy units of any facies within the section. Net:Gross is the ratio of thickness of sandy facies to non-sandy facies. Tables 9-11 break out these three measurements and give statistical analyses of the results. Blacked out zones were not measured for those sections.

Table 9: Gross Thicknesses (m) for Frontier Measured Sections

Section	Unit				
	Bulk Section	DH Upper Sandy	Coal Zone	DH Lower Sandy	OR Coastal Plain
Bridger	71.5	9.5	7.0	34.0	21.0
Scully 2	56.7	6.0	10.2	40.5	4.0
Scully 1	89.2	8.2	11.1	49.5	20.4
Cumberland 2	55.5	7.5	14.5	33.5	
Cumberland 1	40.3	8.3	14.0	18.0	
Cumberland 3	64.7	13.7	8.5	33.5	9.0
Muddy 1	139.0	12.5	13.5	94.0	19.0
Muddy 2	130.8	12.3	15.0	86.5	17.0
Haul Road	81.1	10.5	11.5	34.5	24.6
Average	81.0	9.8	11.7	47.1	16.4
Median	71.5	9.5	11.5	34.5	19.0
St. Dev.	33.8	2.6	2.8	25.9	7.3
Max	139.0	13.7	15.0	94.0	24.6
Min	40.3	6.0	7.0	18.0	4.0

Notes: Blacked out zones were not measured for those sections.

Table 10. Net Sand Thicknesses (m) for Frontier Measured Sections

Section	Unit				
	Bulk Section	DH Upper Sandy	Coal Zone	DH Lower Sandy	OR Coastal Plain
Bridger	5.8	0.3	0.0	4.6	0.9
Scully 2	23.1	6.0	4.1	4.1	1.5
Scully 1	44.1	1.7	0.0	33.1	9.3
Cumberland 2	20.6	5.3	0.0	0.0	
Cumberland 1	20.2	8.3	0.0	11.9	
Cumberland 3	12.9	6.9	0.0	3.9	2.1
Muddy 1	15.0	1.5	0.0	9.6	3.9
Muddy 2	16.1	1.9	1.0	11.7	1.5
Haul Road	38.2	10.5	0.0	14.1	13.6
Average	21.8	4.7	0.6	10.3	4.7
Median	20.2	5.3	0.0	9.6	2.1
St. Dev.	12.2	3.5	1.4	9.7	4.9
Max	44.1	10.5	4.1	33.1	13.6
Min	5.8	0.3	0.0	0.0	0.9

Notes: Net sand thicknesses are the sum of thicknesses of all sandy units, regardless of

Table 11. Net:Gross Ratios for Fontier Measured Sections

Section	Unit				
	Bulk Section	DH Upper Sandy	Coal Zone	DH Lower Sandy	OR Coastal Plain
Bridger	8%	3%	0%	14%	4%
Scully 2	41%	100%	40%	32%	38%
Scully 1	49%	21%	0%	67%	46%
Cumberland 2	37%	71%	0%	46%	
Cumberland 1	50%	100%	0%	66%	
Cumberland 3	20%	50%	0%	12%	23%
Muddy 1	11%	12%	0%	10%	21%
Muddy 2	12%	15%	7%	14%	9%
Haul Road	47%	100%	0%	41%	55%
Average	31%	52%	5%	33%	28%
Median	37%	50%	0%	32%	23%
St. Dev.	18%	41%	13%	23%	19%
Max	50%	100%	40%	67%	55%
Min	8%	3%	0%	10%	4%

Notes: Net:Gross ratios are a ratio of net sand thickness to gross thickness.

It should be noted that these calculations may overestimate the proportion of sandstone in the upper Frontier Formation. Locations for measured sections were based largely on good outcrop quality, which generally corresponded to sections with higher volumes of resistant sandstone. Therefore, these sections are likely somewhat more sand rich than the upper Frontier as a whole.

Channel Dimensions

Measurements of channel dimensions were made at the Little Muddy Creek locality using a combination of outcrop observations and satellite imagery (Figures 23 and 24; Table 12). Average measured channel width was 74 m with an average channel height (thickness) of 2 m. The average channel width/height ratio was 54 (slightly different than the ratio that would be obtained solely from average width and height). Fluvial channels in the Frontier were deposited by meandering rivers, so it is unlikely that all of the measured channels intersect the outcrop

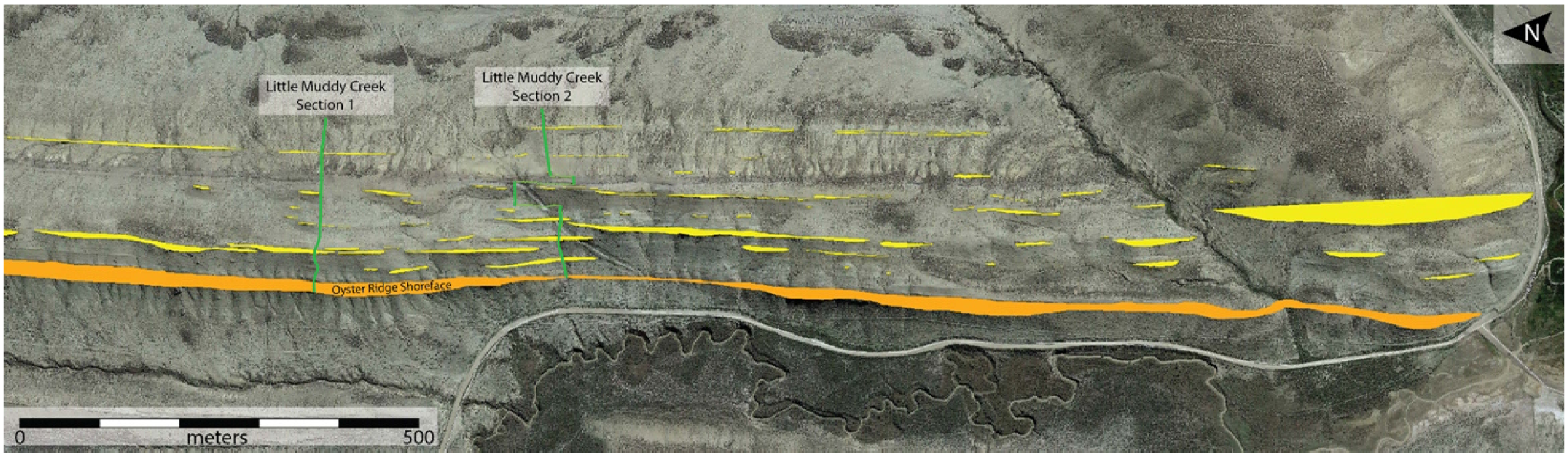

Figure 23. Little Muddy Creek locality with highlighted channels used to measure channel dimensions. Fluvial channels in the Dry Hollow Member are shown in yellow, the shoreface sandstones of the Oyster Ridge are shown in orange and measured sections are highlighted in green. Note that channel width/height ratios are generally quite large. See also Figure 22 and Table 12. Modified from Google Earth, 2017.

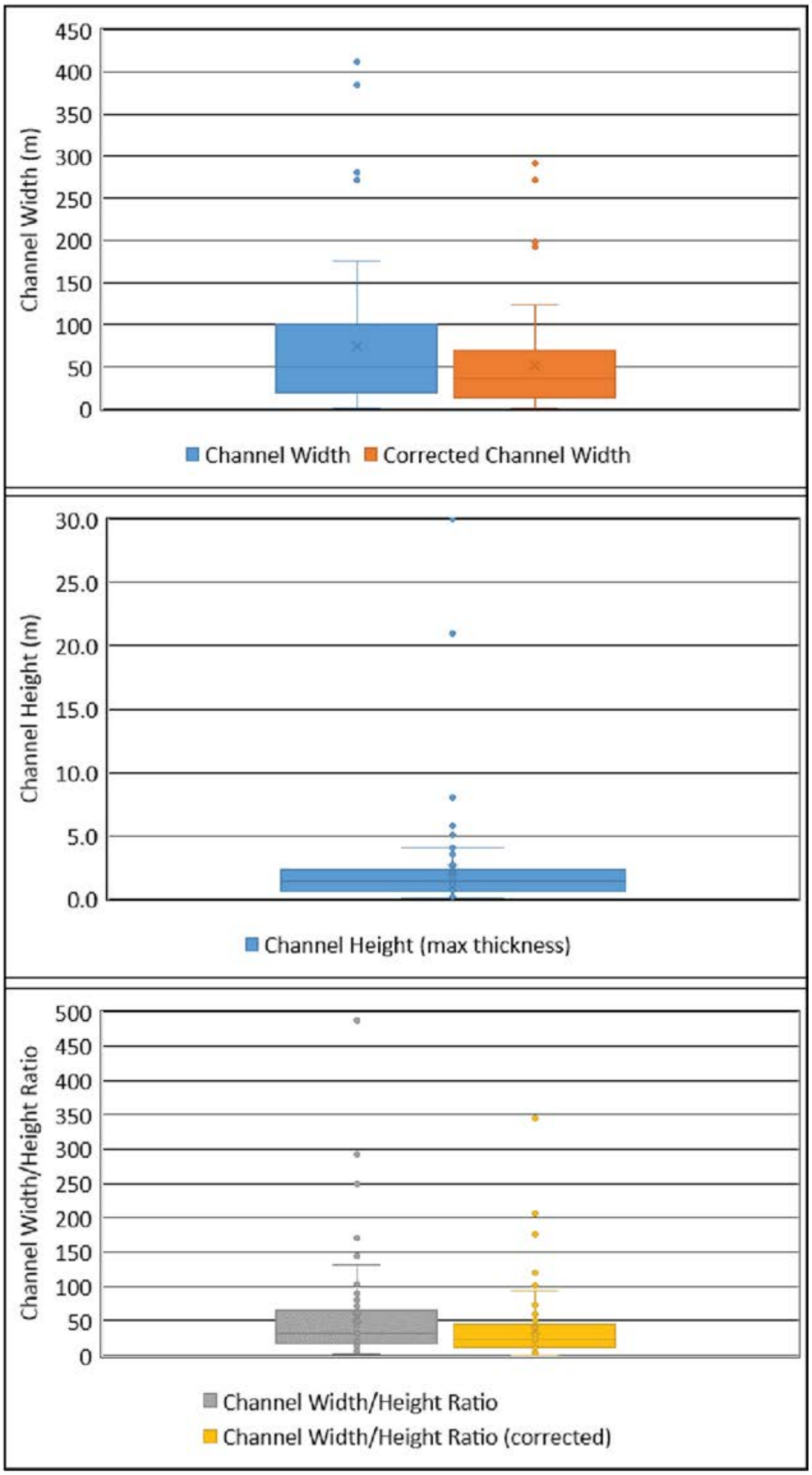

Figure 24. Range of channel widths, thicknesses and width/height ratios for the Little Muddy Creek locality. Note that some outlying points show unusually high width/height ratios up to nearly 500. These likely represent either thin sandstones reworked by marine influence or channels that are exposed in outcrop at highly oblique angles to the direction of flow. More typical width/height ratios are around 30-60. Corrected channel widths assume an outcrop exposure that cuts 45 degrees to the angle of flow, though there is a high degree of uncertainty associated with this assumption. See also Figure 21 and Table 12.

perpendicular to the direction of flow. It is possible that some sandstones with unusually large width/height ratios were even channels flowing nearly parallel to modern strike. To attempt to account for this variability, measured channel widths were adjusted as if all channels intersected the outcrop at 45 degrees to the direction of flow. This correction resulted in an average channel width of 52 m and an average width/height ratio of 39 (changes of 30% and 28% respectively). In reality, this assumption is a great oversimplification and the actual degree of variation from the measured channel widths may be much greater. However, it may have some usefulness as a rough average, under the assumption that paleoflow was roughly east-southeast (Schmitt, 1985). It is possible in some cases to estimate sinuosity of fluvial channels from their net-to-gross ratios. The low net-to-gross at Little Muddy Creek does indicate predominantly suspended load channels that should be highly sinuous (Morris and Richmond, 1992; Morris et al., 2003).

Table 12. Dry Hollow Channel Dimensions at Little Muddy Creek

Dimensions	Mean	Median	Max	Min
Measured Channel Width	74	51	412	2.0
Corrected Channel Width	52	36	291	1.4
Channel Thickness	2.4	1.4	30	0.1
Measured Width/Height Ratio	54	32	487	1.3
Corrected Width/Height Ratio	39	23	344	0.9

Notes: Channel dimensions at the Little Muddy Creek locality were measured using Google Earth satellite imagery (quality checked against photogrammetric models and measured sections). Corrected widths are calculated under the assumption that channels are exposed in outcrop at 45 degrees to the direction of flow.

Temporal and Spatial Facies Trends

Correlation panels were drafted between measured sections and/or wells along five cross sectional lines (Figures 25): north to south along strike through the eastern (Hogsback) sections, western (Absaroka) sections, and along the Moxa Arch and from west to east along depositional dip on the northern and southern ends of the study area.

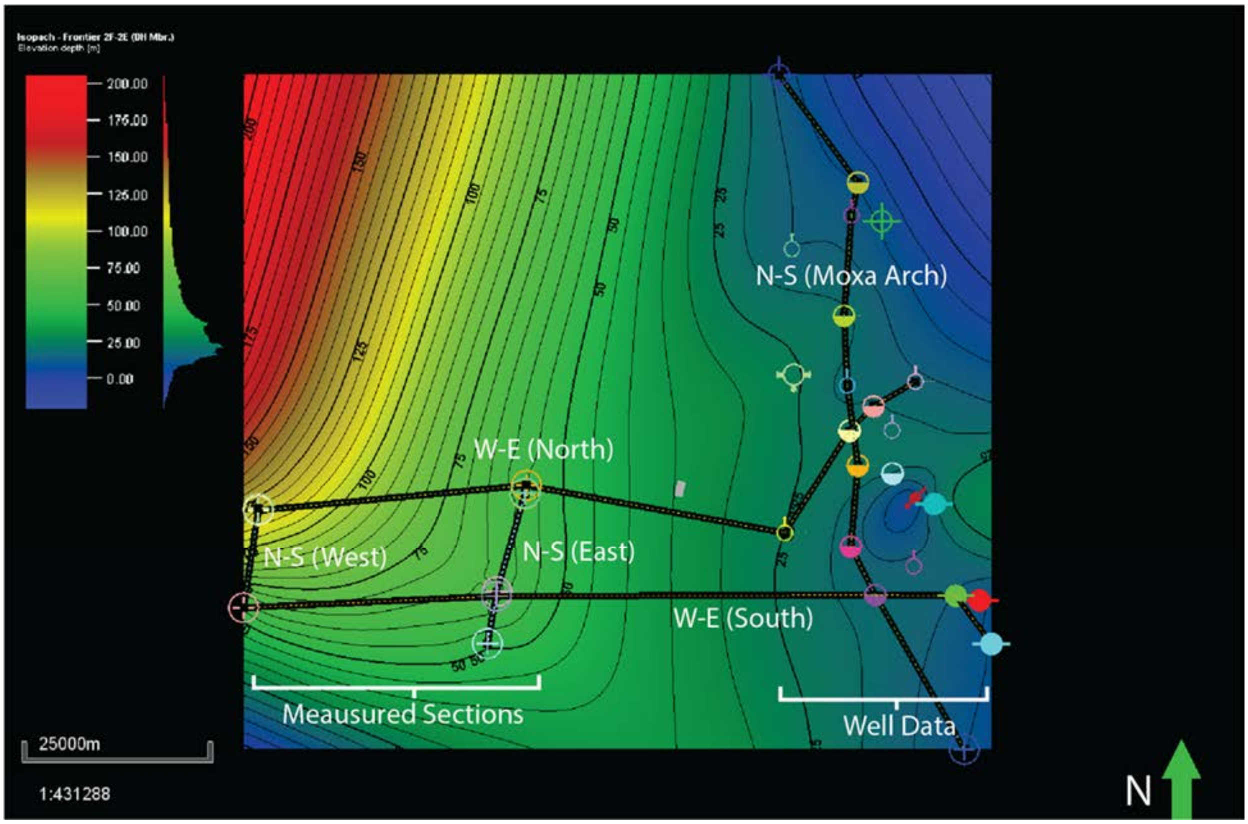

Figure 25. Locations of correlation panels. Five correlation panels were created using measured sections and subsurface well data. Measured sections have been restored to their pre-thrusted positions. The correlation locations are shown on an isopach map of the Dry Hollow Member.

In the correlation panels, a relative regression is evident between the Oyster Ridge shoreface sandstones and the contact with the Dry Hollow. Moving up through the Oyster Ridge, facies change from shoreface sands to lagoonal oyster beds, to coastal plain fluviodeltaics. This created a shift from sheet-like sand geometries to more isolated channels in the Coastal Plain Unit. The Dry Hollow Member shows an overall transgressive trend. The basal conglomerates that overly the coastal plain are often amalgamated into broad, single-story channel bodies, although these are not always present. Above the conglomerate, channels generally become smaller and less amalgamated until there is almost no sandstone in the Kemmerer Coal Zone. On top of the coal zone, single-story channels again appear but the transition to marine shales of the Hilliard is rapid.

Though these temporal trends are generally true for the upper Frontier, a great deal of lateral variability also exists in outcrop. The two strike-view (N-S) correlation panels show very different trends. The most proximal outcrops (western/Absaroka; Figure 26) show a dramatic thickening from the Whitney Canyon Haul Road section (85 m) and the Little Muddy Creek sections (180 m). This thickening appears to take place within the Lower Sandy Unit between the coal zone and the base of the conglomerate. Despite this thickening of the section, the net amount of sandstone actually decreases, though there is a fairly large (but dispersed) channel complex at Little Muddy Creek. In contrast, on the eastern (Hogsback) outcrops (Figure 27), the section is thickest in the middle of the study area at Scully's Gap at around 100 m. It thins to the north and south to around 70-75 m at Cumberland Gap and Bridger Gap. Net sandstone also decreases to the north and south. The N-S well correlation across the Moxa Arch (Figure 28) shows a similar thickness distribution to the Hogsback outcrops, though it is thinner overall (about 30 m in the middle of the study area and 10-15 m on the northern and southern ends of the study area). The distribution of sandstone is different here as well however, with larger net thicknesses of sandstone more common in the thinner parts of the section.

Trends along depositional dip (W-E) were somewhat more expected. The deposition of Frontier sediments into a foreland basin indicates that they should be thickest nearest the orogenic front (west) and thinner in a basinward direction (east). This is especially true because of the presence of the Moxa Arch. The northern W-E section (from Muddy Creek to Cumberland Gap to the Moxa Arch; Figure 29) showed a dramatic thinning of the Dry Hollow Member from around 100 m at Little Muddy Creek to 60 m at Cumberland Gap, to only 10-15 m thick on the Moxa Arch. The coastal plain facies of the Oyster Ridge thins from around 20 m at Little Muddy Creek to almost nothing on the Moxa Arch. The southern W-E section (Haul Road to Scully's

Gap to the Moxa; Figure 30) shows a similar trend. Here, however, there is very little change in thickness between the Absaroka and Hogsback outcrops; in fact, the Oyster Ridge Coastal Plain Unit thickens slightly. The section thins moving eastward from Scully's Gap, however, from approximately 90 m (55 m Dry Hollow, 35 m Oyster Ridge) to <20 m on the Moxa Arch (10 m Dry Hollow and 10 m Oyster Ridge).

Both W-E sections show a similar trend in net-to-gross ratios, with relative sandstone content generally increasing onto the Moxa Arch. It appears to be fine-grained rocks that are lost from the sections as it thins. This is probably due to increased winnowing of fine-grained sediment with decreased accommodation. The major difference between the two cross sections is in the thickness change between Absaroka and Hogsback outcrops. It is difficult to know whether the Little Muddy Creek sections are anomalously thin or whether the Haul Road section is unusually thin, due to lack of other outcrops from this point in the system. This would be an important variable to quantify if possible.

The contrasting thickness and facies distributions observed in these five cross sections highlights the complexity of the interplay between allo- (structure, eustatic sea level, and climate/sediment supply) and autocyclic (avulsion, sediment compaction) controls on the depositional system. It also highlights the need to characterize these systems at a fine scale in order to gain a useful understanding of them.

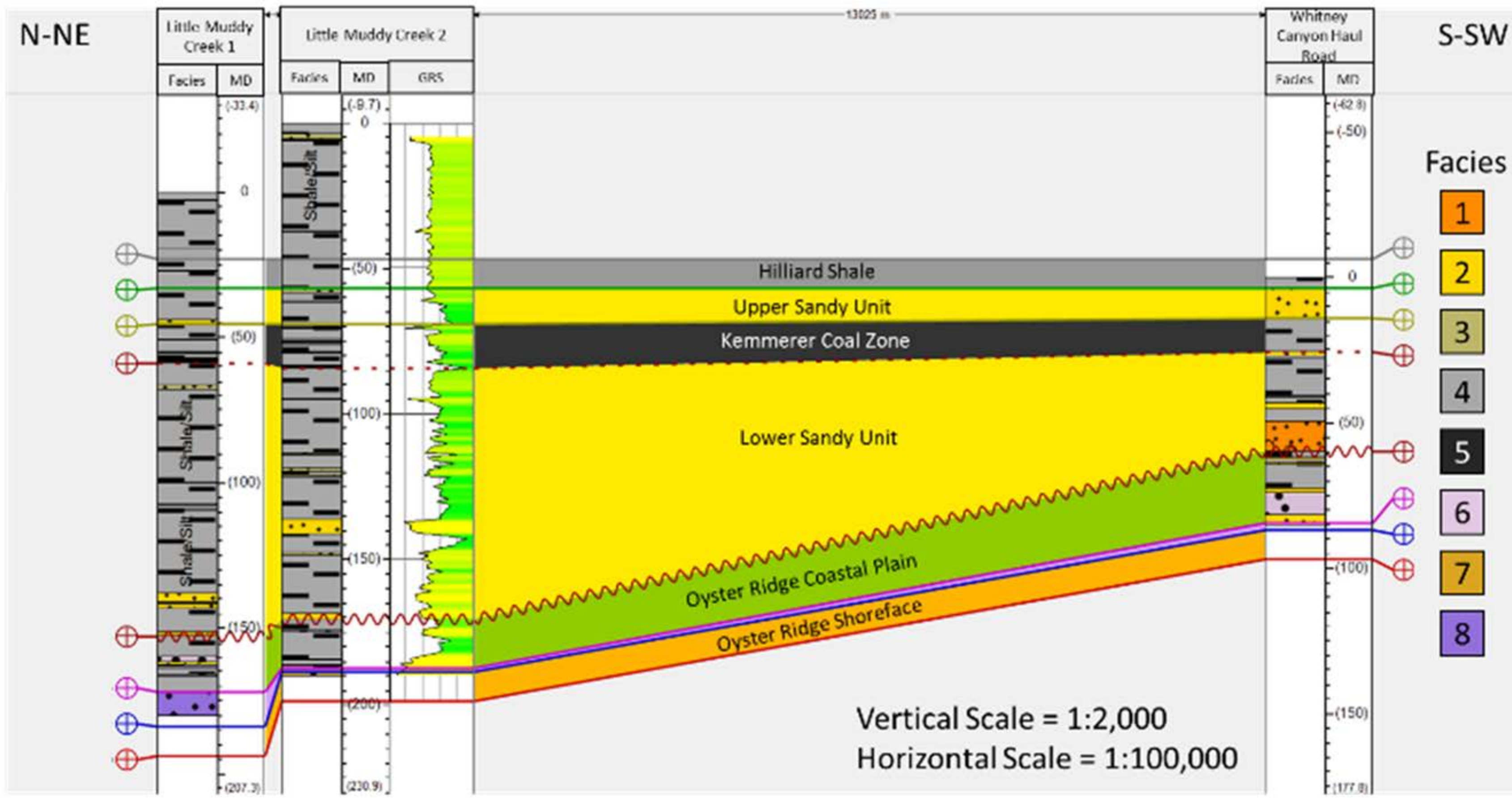

Figure 26. N-S correlation panel of western sections (Absaroka Thrust). Notice the dramatic thickening and relative drop in net-to-gross ratio that takes places between the Haul Road and Muddy Creek sections. GRS indicates a gamma ray scintillometer log. MD is depth in meters.

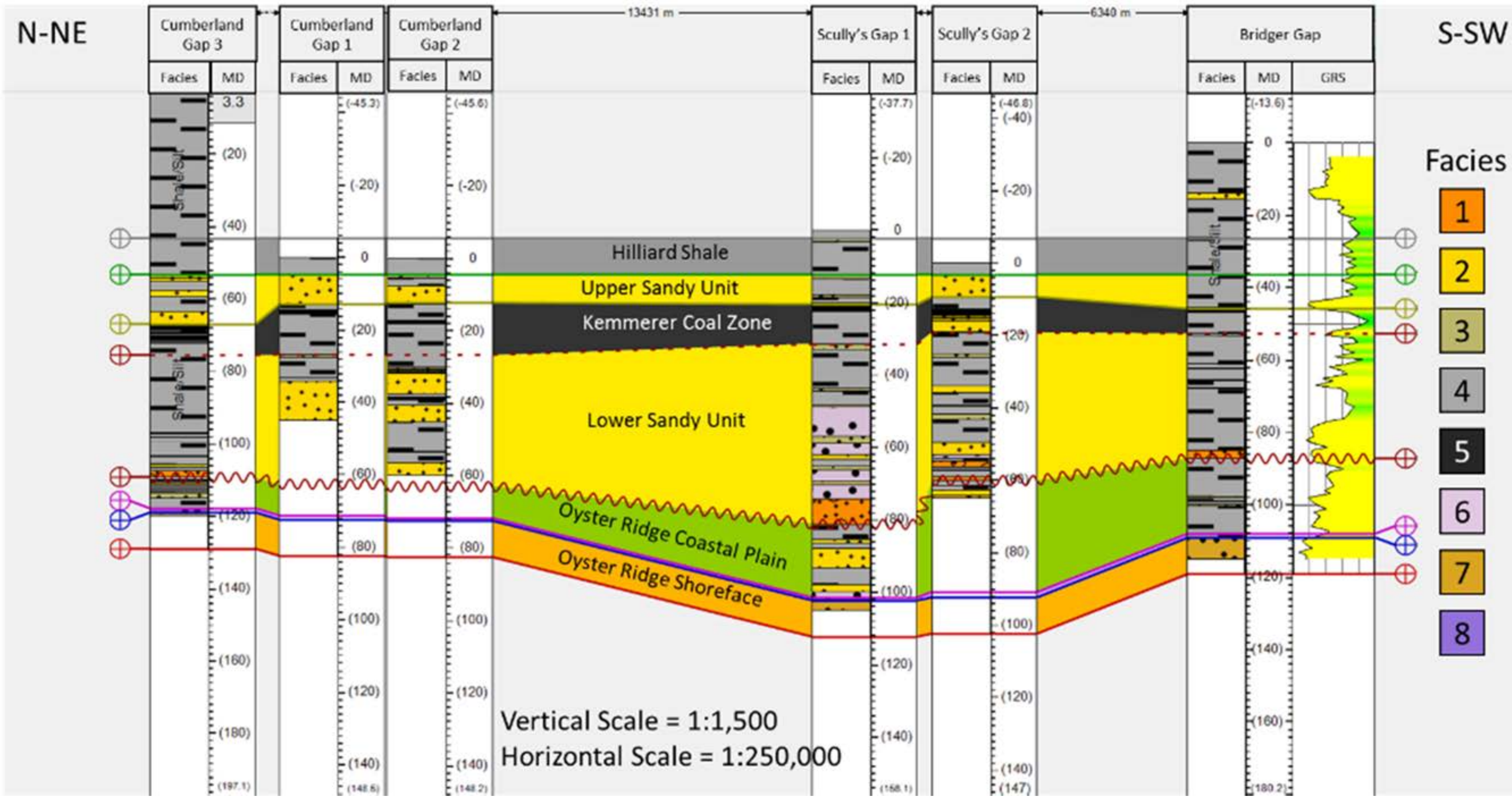

Figure 27. N-S correlation panel of the eastern sections (Hogsback Thrust). Net-to-gross ratios and section thicknesses are greatest near the central part of the study area (Scully's Gap) and decrease toward the north and south. GRS indicates a gamma ray scintillometer log. MD is depth in meters.

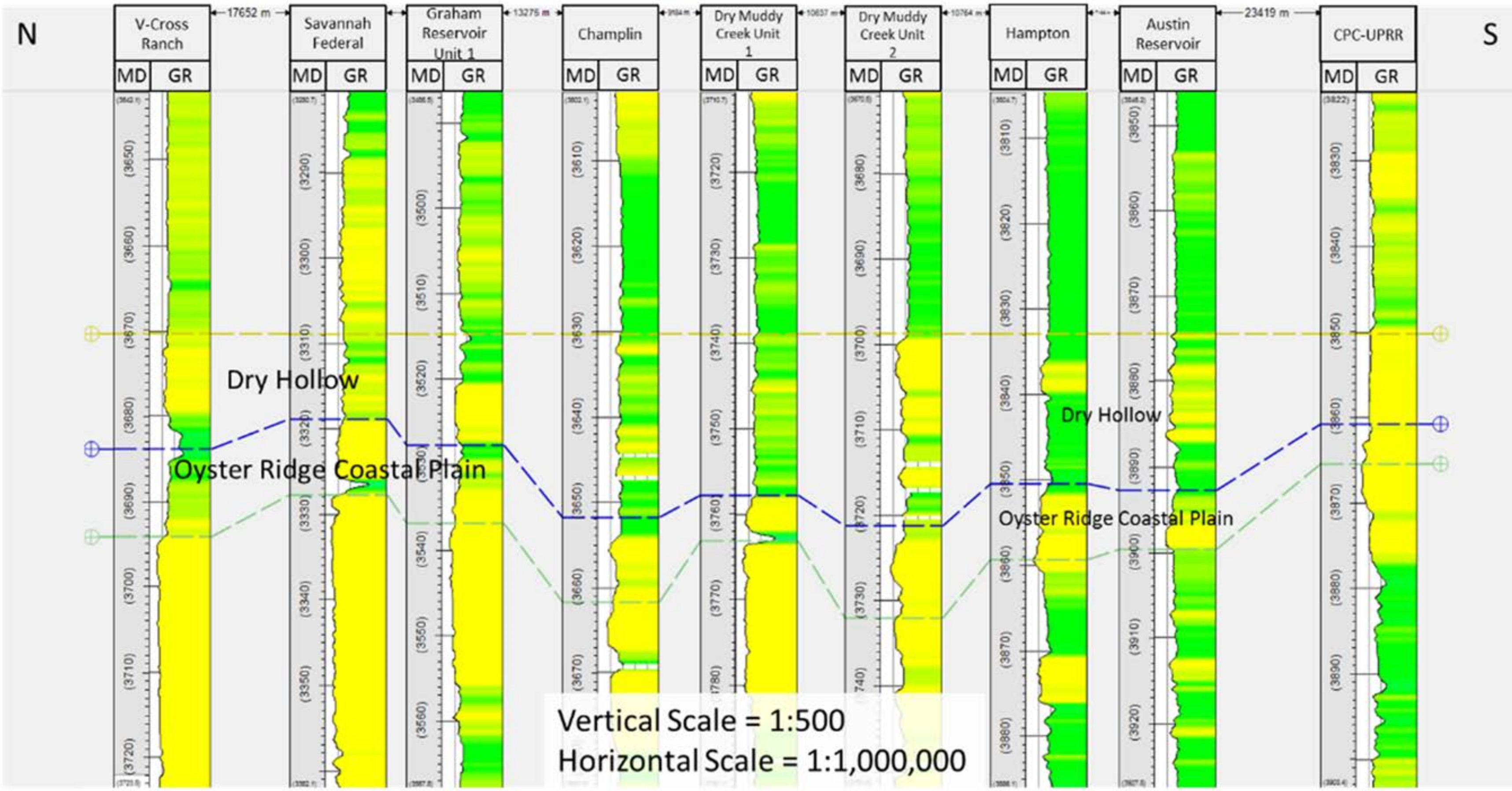

Figure 28. N-S correlation panel of wells on the western flank of the Moxa Arch. Net-to-gross ratios increase to the north and south while overall thickness of the section decreases. This may be due to low accommodation, which increases winnowing of fine-grained sediments. MD is depth in meters. GR is a gamma-ray well log.

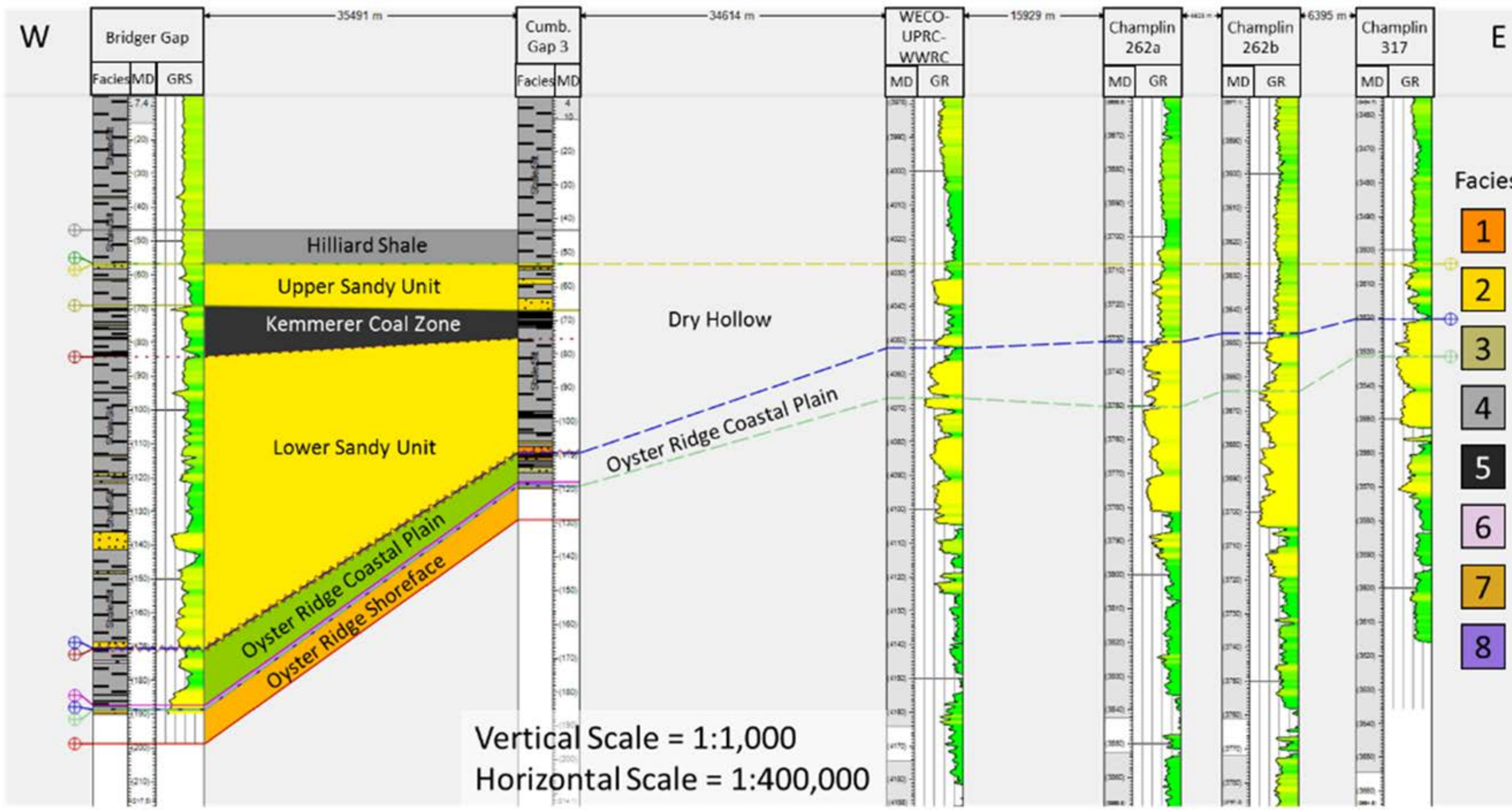

Figure 29. W-E correlation panel of the northern part of the study area. Note the substantial thinning that takes place moving from west to east both between outcrop locations and between outcrops and the Moxa Arch. This is due to an decrease in subsidence and accommodation as the system migrated away from the orogenic front and deep foreland basin and over the top of the Moxa Arch forebulge. GRS indicates a gamma ray scintillometer log. MD is depth in meters. GR is a gamma-ray well log.

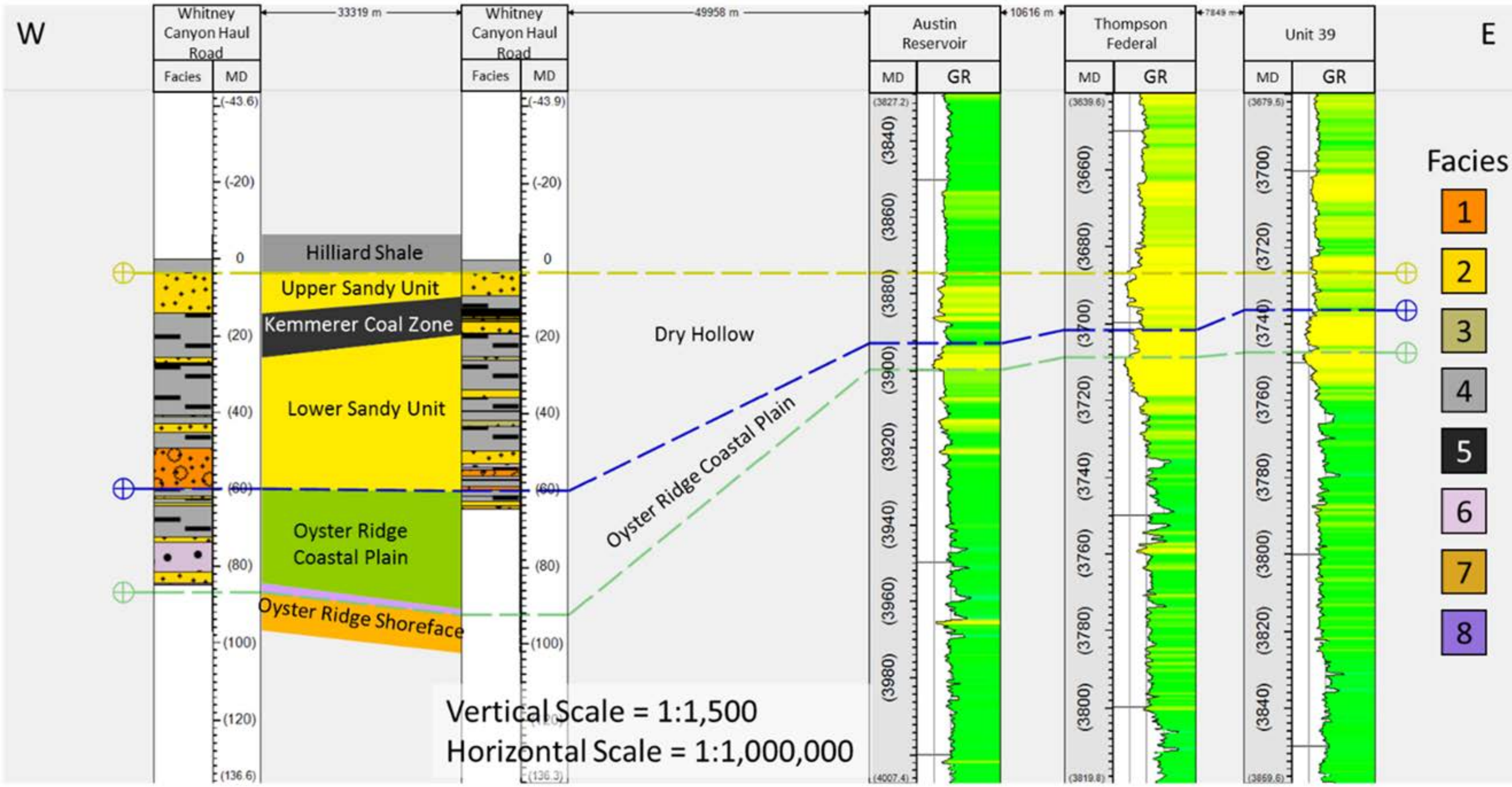

Figure 30. W-E correlation panel of the southern part of the study area. As it does further north, the section thins dramatically onto the Moxa Arch; however, there is little thickness change between measured sections. This may indicate a lack of subsidence/accommodation relative to the northern part of the study area, or may simply show that a lack of deposition due to allocyclic controls on the locations of fluvial channels. MD is depth in meters. GR is a gamma-ray well log.

Modeling and Photogrammetry

Facies modeling and generation of isopachs maps in Petrel revealed trends and aspects of the Frontier that were not readily evident through correlation panels alone. Correlation lines for the top and bottom of the Frontier and the top and bottom of the Oyster Ridge Coastal Plain Unit (all fluvial intervals) could be traced throughout the study area. Isopachs were generated for both the Dry Hollow Member and the Oyster Ridge Coastal Plain Unit individually (Figures 31 and 32). A combined isopach was also generated (Figure 33). While thickness of the section does not necessarily correlate with net sandstone thickness, this is a useful tool for determining the overall transport path for sediment through the system. The Oyster Ridge Coastal Plain isopach shows the thickest accumulation of sediment in the southwest corner of the study area with the overall trend toward the northeast. The Dry Hollow isopach shows an opposite trend, with the thickest accumulations of sediment in the northwest of the study area and thinning toward the southeast, with some thinner accumulations trending toward the east and slightly northeast. It is possible that the southeast trend in the Dry Hollow is largely a result of sparse outcrop data skewing the trend in this direction. While it certainly seems to exist to some extent, there may have been a stronger trend to the northeast as indicated by the denser well data. Either way it would appear that the direction of transport turned to the east after the most distal part of the system represented in outcrop.

On a smaller scale, trends become evident in the facies models that are not obvious when looking at outcrop and well data alone. Facies models were generated for each of the six correlation units within the upper Frontier (Figure 34). These reveal possible distributions of facies based on the outcrop control and variables in the facies body geometries (Figure 35). The most realistic results were obtained by Sequential Indictor Simulation modeling for the

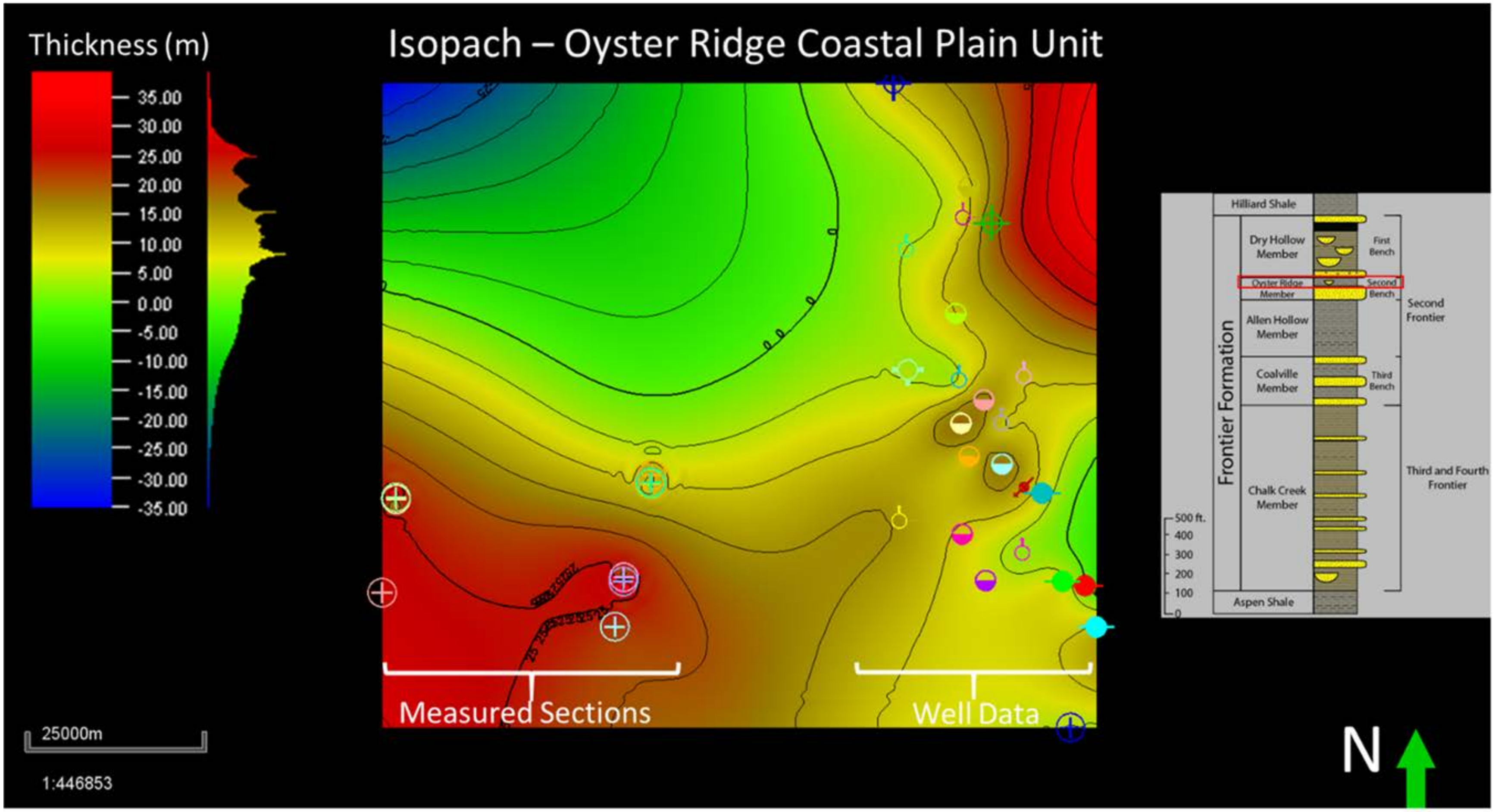

Figure 31. Isopach map of the Oyster Ridge Coastal Plain Unit, generated from measured section and well data. General thickness trends are toward the northeast; these may correspond to the general direction of sediment transport or have underlying structural controls. Negative thicknesses in the northwest corner are due to continuation of trends into an area with no control points.

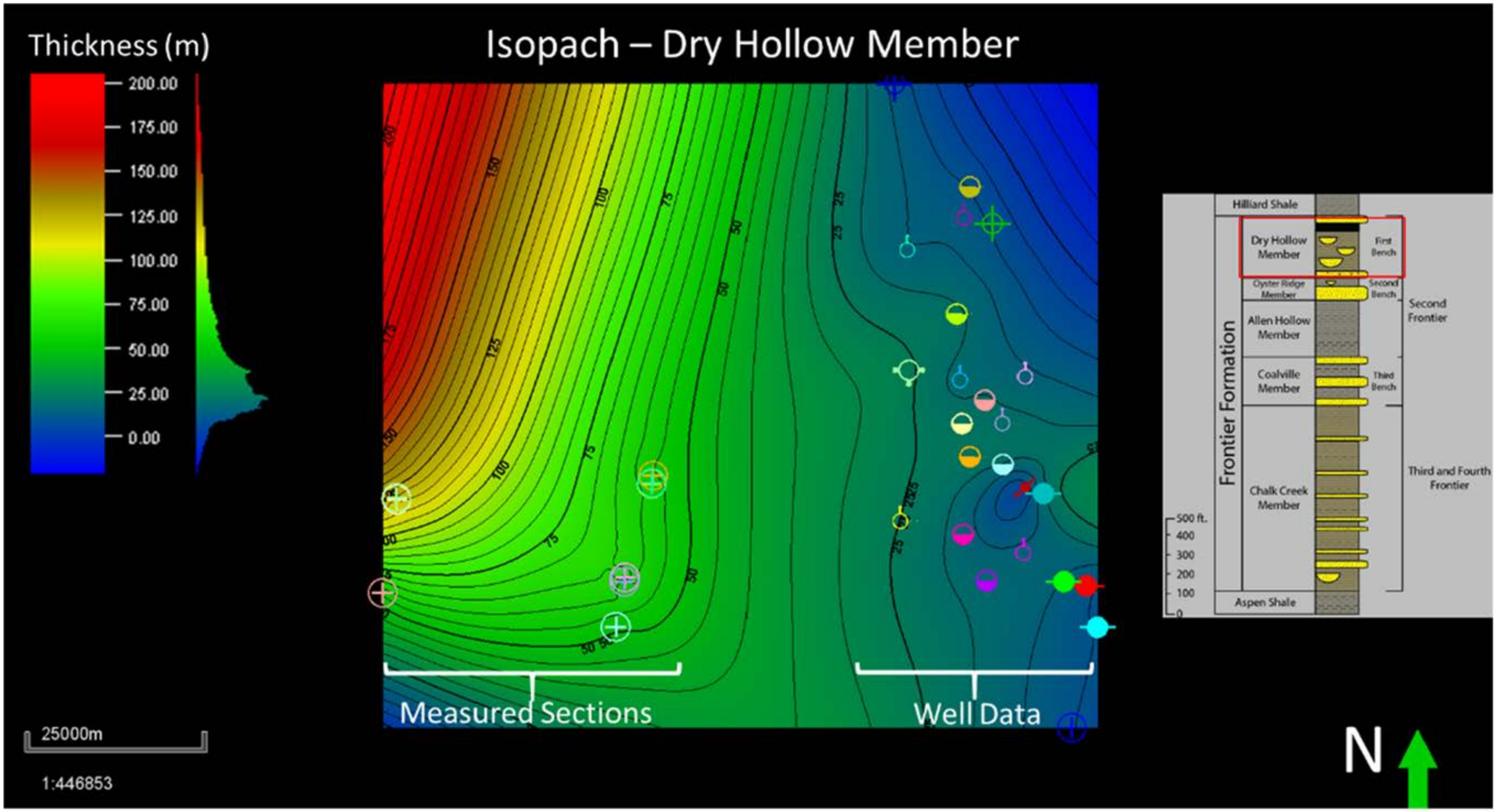

Figure 32. Isopach map of the Dry Hollow Member of the Frontier, generated from measured section and well data. General thickness trends are toward the southeast; these may correspond to the general direction of sediment transport or have underlying structural controls. Some thicker packages on the Moxa Arch also trend to the northeast and may represent deposition by distributary channel systems.

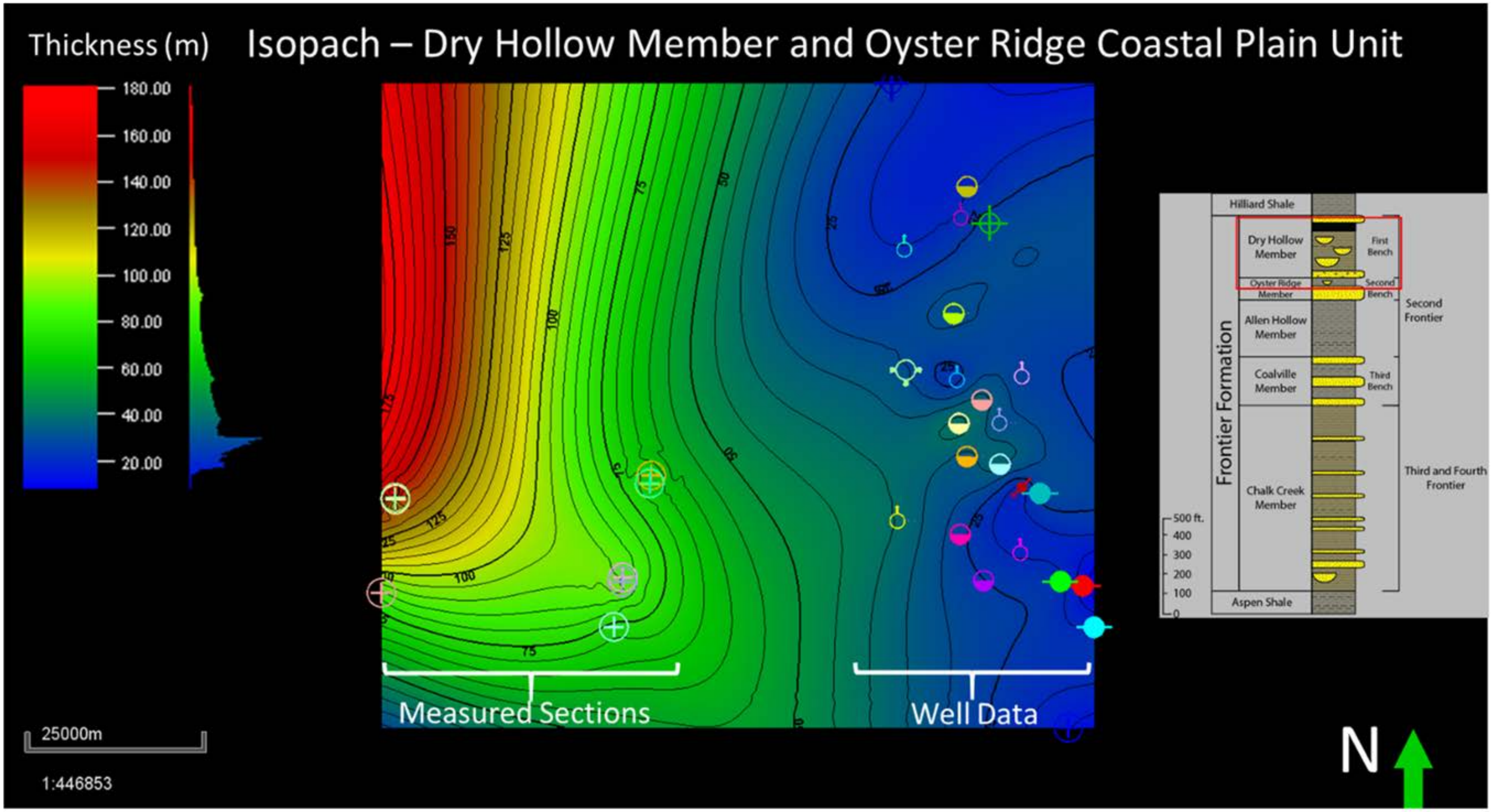

Figure 33. Isopach map of the combined Oyster Ridge Coastal Plain Unit and Dry Hollow Member, generated from measured section and well data. Thickness trends from both packages are visible and trend toward the southeast nearer measured sections and to the northeast when approaching the Moxa Arch. These trends may represent a deflection of eastward flowing fluvial systems by the Moxa Arch.

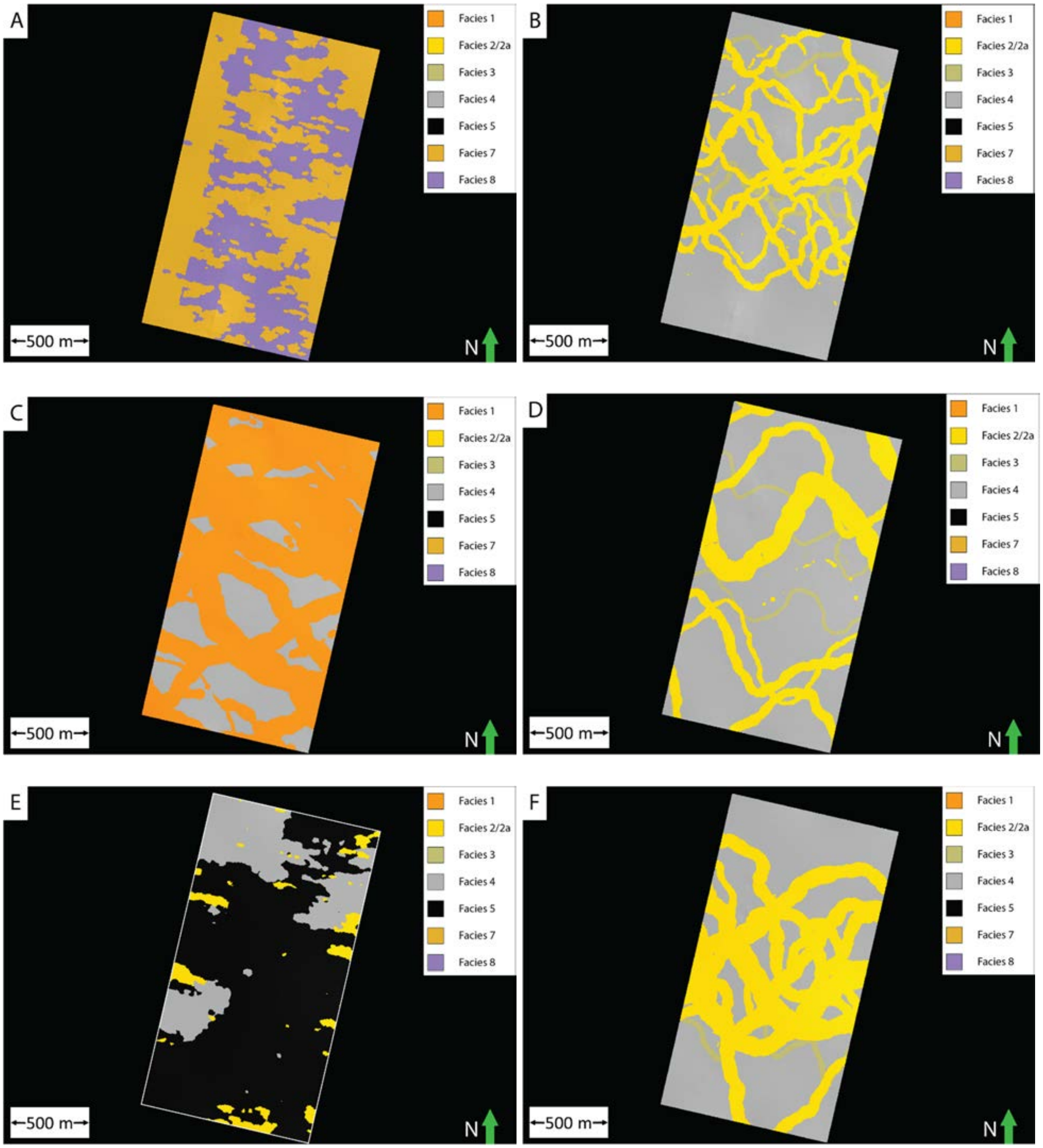

Figure 34. Representative map-view cross sections of each unit within the upper Frontier facies model at Cumberland Gap. A) Oyster Ridge Shoreface Unit. B) Oyster Ridge Coastal Plain Unit. C) Dry Hollow Conglomerate Unit. D) Dry Hollow Lower Sandy Unit. E) Kemmerer Coal Zone. F) Dry Hollow Upper Sandy Unit. The facies model allows for improved understanding of possible facies relationships within the upper Frontier. Low net-to-gross ratios indicate a meandering fluvial system, so channelized sandstones were given high sinuosity (the conglomerate had a lower sinuosity than other channel sandstones). Note that lateral connectivity of channels is high in all units except for the Kemmerer Coal Zone. Although the model may overestimate the abundance of sandstone between outcrop control point, this high connectivity likely exists within channel belts observed in outcrop as it was present in all realizations of the facies model.

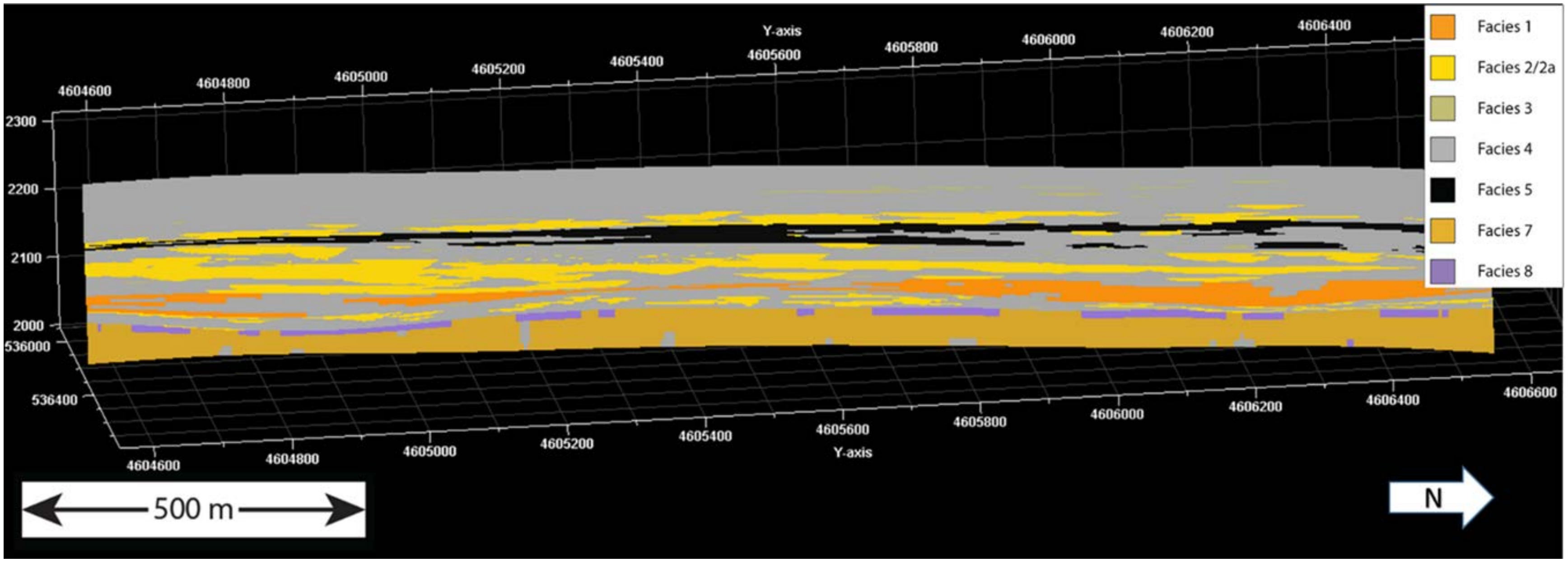

Figure 35. Cross section through facies model along depositional strike. Significant lateral units can be easily identified. From bottom to top these are the Oyster Ridge Shoreface Unit (tan and purple), the Oyster Ridge Coastal Plain Unit (yellow channels above the shoreface), the Dry Hollow Conglomerate Unit (orange), the Dry Hollow Lower Sandy Unit (yellow channels above conglomerate), the Kemmerer Coal Zone (black coal seams), and the Dry Hollow Upper Sandy Interval (yellow channels above coal and olive channels at top of model). The facies model allows for improved understanding of possible facies relationships within the upper Frontier. There is fair to excellent lateral and vertical connectivity of sandstone facies within all units except the Kemmerer Coal Zone, despite relatively low net-to-gross ratios. Although the model may overestimate the abundance of sandstone between outcrop control point, this high connectivity likely exists within channel belts observed in outcrop as it was present in all realizations of the facies model.

Kemmerer Coal Zone and the Oyster Ridge shoreface sandstones and oyster beds, where facies geometries were irregular or sheet-like. Object Modeling returned more realistic results for the channelized intervals however. This realistic channel geometry is important to be able to accurately understand how channels interact with one another. In outcrop, most channels appear to be fairly isolated. However, the facies model revealed that there is actually a high degree of connectivity between fluvial sandstones within certain units (Figure 36). According to the model, nearly 100% of fluvial sandstones within the Oyster Ridge Coastal Plain and the Dry Hollow

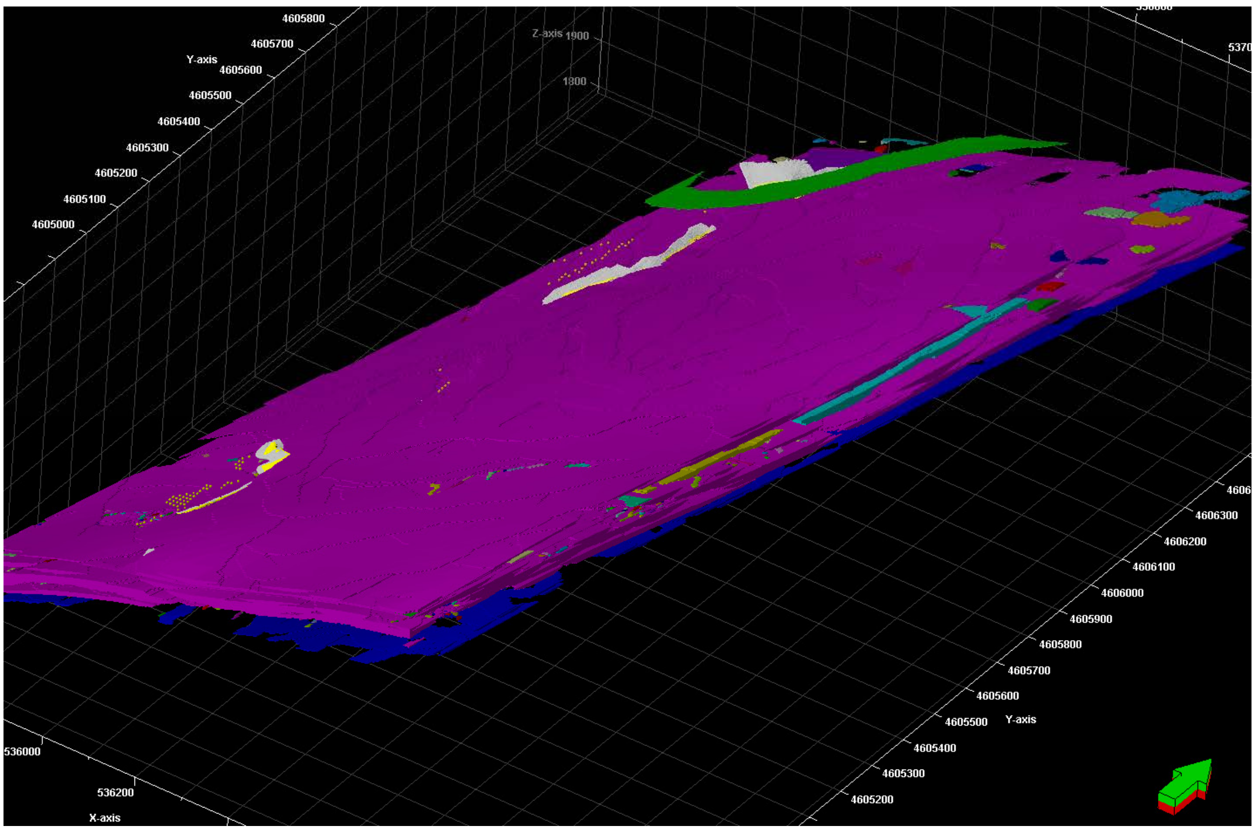

Figure 36. Connectivity of Facies 2 sandstones in facies model. Channels of the same color are connected to each other either vertically or laterally. Blue channels at the bottom are in the Oyster Ridge Coastal Plain Unit, while purple channels are in the Upper and Lower Sandy Units of the Dry Hollow. Multicolored channels in the middle of the middle and top of the model are isolated sandstones within the coal zone and uppermost Dry Hollow. High connectivity exists vertically and laterally within all sandy facies of all units except for the Kemmerer Coal Zone. The coal zone is a barrier to vertical connectivity. Lateral connectivity is probably overestimated between outcrops due to sampling bias (i.e., outcrop occurs where sandstone is the most abundant). However, high connectivity likely exists within the channel belts observed in outcrop.

Conglomerate and Lower and Upper Sandy Units were laterally and vertically connected to other channel sandstones within those intervals. Even with relatively low net-to-gross ratios, there seems to be enough sandstone present vertically and laterally to connect most channels. It is important to note that vertical connectivity was interrupted by the Kemmerer Coal Zone, where sandstones are rare and isolated. This was the largest barrier to vertical connectivity in the model.

There are limits to the accuracy of the facies model. Variables describing channel dimensions and meanders may be inaccurate. Another serious limitation in this scenario is the possibility that the lateral continuity of fluvial sandstones was overestimated. Photogrammetric models were made in locations with high-quality outcrops, meaning they are likely skewed toward areas with great amounts of resistant (i.e. sandstone) facies. This means that when the model extrapolates between the outcrops (using the facies proportions in the control points) it is probably overestimating the amount of sandstone present there. In reality, channel belts are probably more isolated than they appear in the model. This would decrease the overall lateral connectivity within each unit. However, the channel belts in the outcrop should still be modeled accurately, meaning that within channel belts, connectivity should be almost 100%.

DISCUSSION

Depositional History

The shoreface sandstones of the Oyster Ridge Member (Figure 37a) are the first nearshore, high energy deposits that exist after the highstand that deposited the shales of the Allen Hollow Member. These are capped by oyster-rich beds in both laterally extensive, thin, brackish water lagoonal deposits and localized, tidal channel deposits. Coastal plain fluviodeltaic sandstones, siltstones, mudstones, and rare,thin coals were deposited over the oyster

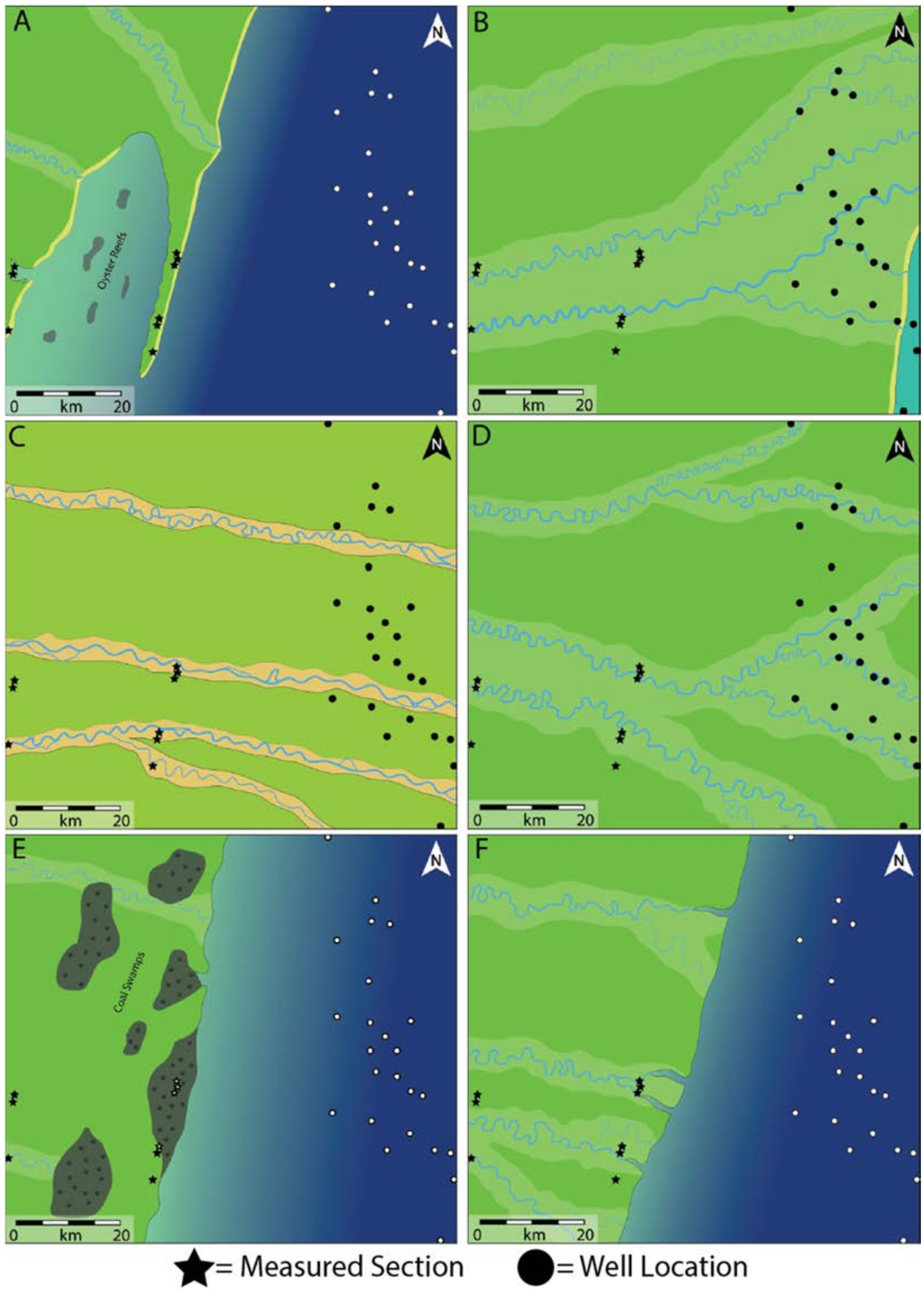

Figure 37. Paleogeographic reconstructions of significant upper Frontier units. A) Oyster Ridge Shoreface Unit. B) Oyster Ridge Coastal Plain Unit. C) Dry Hollow Conglomerate Unit. D) Dry Hollow Lower Sandy Unit. E) Kemmerer Coal Zone. F) Dry Hollow Upper Sandy Unit. Specific locations of channel belts and other features are based on actual data and observations where they are available, however, many features shown on the maps are only hypothetical (though they are based on trends observed in wells and outcrop). Scale of some features (i.e. meanders) are exaggerated for clarity. Note the relative regression of sea level during the time of Oyster Ridge deposition and the relative transgression that takes place during Dry Hollow deposition.

accumulations (Figure 37b). The progression from deep marine, to shoreface, to backshore/lagoonal, to coastal plain environments is a Waltherian succession consistent with a regression of relative sea level during Allen Hollow-Oyster Ridge time. This relative regression is likely due to progradation of the shoreline (Hamlin, 1996).

This regression evidently continued to the point that subaerial exposure existed on the Moxa Arch (Hamlin, 1996; Stonecipher, 2012) and resulted in a lowstand surface of erosion that truncates the top of the Oyster Ridge coastal plain deposits. The pebble conglomerates present at the base of the Dry Hollow are the first sediments to be deposited on top of the unconformity (Figure 37c). Relatively high energy conditions existed at this point, indicating an increase in gradient or in proximity to the hinterlands. The conglomeratic basal unit is regionally traceable and relatively continuous in comparison to other Frontier fluvial deposits. This laterally extensive but vertically restricted occurrence may indicate high rates of channel avulsion and mobility (Gibling, 2006), low rates of subsidence/low accommodation, or both.

Energy conditions decreased after the deposition of the basal conglomeratic unit, which is overlain by more distal facies. Conglomerates are overlain by floodplain mudstones and siltstones and channelized, fine, fluvial sandstones of Facies 2 and 3 of the Dry Hollow Lower Sandy Unit (Figure 37d). Individual channel bodies are more isolated than in the conglomerates and often multistoried. These channels represent distal parts of the main fluvial system or distributary channels in a delta setting. Soft sediment deformation and rip-up clasts are common, especially low in the section, indicating rapid deposition. Depositional conditions during this time appear to have been similar to those during deposition of the coastal plain facies of the Oyster Ridge. Possible causes for the change in depositional conditions include erosion of the hinterlands or the beginning of a transgression. The change in architectural style could show an increase in subsidence rate/accommodation, increase in sediment supply (evidenced by rapid sedimentation), and/or decrease in avulsion frequency (Heller and Paola, 1996).

Near the base of the Kemmerer Coal Zone, sandstones become rarer. Channels that do exist are dominated by Facies 3, are isolated, and represent distal, secondary distributary channels. Bivalve fossils, including oysters, occur at Little Muddy Creek, indicating at least local marine influence. The Kemmerer Coal Zone (Figure 37e) contains almost no sand and is composed of mudstones and coal seams up to several meters thick. The coal was deposited in backshore and interdistributary/alluvial plain marshes. Some marine influence is evidenced by interfingering with oyster bearing shales north of the study area (Myers, 1977). The progression from large to smaller, more distal distributary channels and then to backshore marshes is further evidence of a transgression occurring during this time period. The Kemmerer Coal Zone likely represents transgressive flooding and the beginning of retrogradational stacking of parasequences (Bohacs and Suter, 1997).

The final occurrence of Facies 2 is just above the coal zone, where large, single story channels scour into the surface of the uppermost coal seams (Figure 37f). Large channels occur at this stratigraphic level at Cumberland Gap, Scully's Gap, and the Whitney Canyon Haul Road section. Usually only one channel sandstone is present, though at the Cumberland Gap 3 Section up to three or four channels are compensationally stacked. These channels all show a strongly asymmetrical form and some have indications of marine influence; *Ophiomorpha* and *Thalassinoides* occur here in the Haul Road section. Myers (1977) suggests that these are transgressive sandstones based on fossils of brackish and marine water fauna. Perhaps the marine influence and restricted occurrence may be explained by interpreting these as channels deposited in bayhead deltas of flooded incised valleys. This would be consistent with the transgressive trend seen throughout deposition of the Dry Hollow. An alternate interpretation could involve upstream avulsion of an isolated fluvial system.

Where sandstones do exist above this level, they are almost exclusively ratty, Facies 3 channels. Marine influence is widely evident in the form of bivalve fossils and *Ophiomorpha* burrows. Channel bodies are isolated, though individual channels do tend to cluster into bodies of 3-5 compensationally stacked sandstone lenses. A continued transgression is interpreted to have resulted in the conformable, fining upward succession observed as these distal distributary sandstones are gradually replaced by the marine shales and occasional thin sandstones and siltstones of the Hilliard Shale.

Temporal and Spatial Trends of the Upper Frontier Formation

Temporal Trends

The lateral persistence of the Oyster Ridge shoreface sandstones and oyster beds, the Dry Hollow basal conglomerate, and the Kemmerer Coal Zone allowed for reliable correlation of measured sections and designations of significant units within the Dry Hollow and upper Oyster Ridge. Some of these units can be (relatively) high net-to-gross, while the Kemmerer Coal Zone is nearly always devoid of sandstone. Despite great lateral variability, these correlations make it possible to recognize both regressive (Oyster Ridge) and transgressive (Dry Hollow) trends within the upper Frontier Formation. This understanding provides great predictive power in estimating where in the section channelized sandstones could be found - overall trends indicate that younger strata will tend to gradually become more mud rich as the system migrates landward, with the one exception to this rule being the Upper Sandy Unit, just above the Kemmerer Coal Zone. From a reservoir standpoint, this is important to understand because of its impact on vertical connectivity. Channel sandstones are well-connected within channel belts until the Kemmerer Coal Zone is reached. This partitions the vertical connectivity of a potential reservoir, but may also provide a seal/stratigraphic trap.

Spatial Trends

While there are some distinct temporal trends, the upper Frontier is also highly variable laterally and these changes can occur on a relatively small scale. The most significant lateral changes are the presence of channel clusters. Channel clusters occur in the Dry Hollow at Scully's Gap, Little Muddy Creek, and Cumberland Gap. At Scully's Gap the section can be up to 50% sandstone. However, this can rapidly change. In the Lower Sandy Unit at Cumberland Gap, net-to-gross is 46-6% at the Cumberland Gap 1 and 2 sections. Less than a kilometer north at the Cumberland 3 section this percentage falls to 12%. Changes in net-to-gross do not necessarily reflect other variables in the formation, either. Scully's Gap is one of the thickest sections and also one of the sandiest. Little Muddy Creek, though, is the thickest section and has one of the lowest net-to-gross ratios. A similar trend occurs from north to south along the Moxa Arch; thinner packages of sediment tended to be more sandstone rich in this cross section. This trend could be explained in several ways. One possible explanation is that net-to-gross ratios are tied to subsidence rates and resulting availability of accommodation. A lower rate of subsidence (less accommodation) can lead to greater winnowing of fine-grained sediment and a relative enrichment of sand sized sediment deposited in a fluvial system (Heller and Paola, 1996). Because sandstones of the Dry Hollow are still channelized on the Moxa Arch, this explanation seems more likely than an increase in energy/flow velocity or a change in depositional environment.

Trends in spatial variability do exist within the Dry Hollow. For example, there does not seem to be much change in the depositional setting between the Absaroka and Hogsback outcrops, despite nearly 30 km of separation between the two at the time of deposition. Facies do not change dramatically. This suggests that this was a fairly uniform part of the fluvial system. Moving toward the Moxa Arch there are rapid changes in architecture. Lithofacies do not necessarily change dramatically, but their distribution and abundance do. This limits the usefulness of directly applying observations of fluvial architecture in outcrop to their equivalent units in the subsurface, but it does provide valuable insight into the control exerted on the fluvial system by the underlying structural geology. Autocyclic processes can probably explain much of the lateral variability as well. The specific locations of channel belts may have some ties to allocyclic processes, but likely are due mostly to processes such as upstream channel avulsion.

These large scale trends are important to understand. Other large scale trends include the high vertical and lateral connectivity within fluvial channels of the Oyster Ridge Coastal Plain and the Dry Hollow Conglomerate and the Upper and Lower Sandy Units. The poor connectivity of the rare sandstones in the Kemmerer Coal Zone is equally important to understand. Smaller scale trends are equally important for a full understanding of the system, and these heterogeneities are particularly prevalent in a low net-to-gross setting like the Frontier. One example involves the Dry Hollow conglomerate. This is present and seemingly laterally well connected everywhere except at Little Muddy Creek. Close examination of this section shows that where the conglomerate is missing, the Oyster Ridge shoreface thickens and oyster shell deposits become channelized. It is possible that an underlying structural or depositional trend focused tidal channels here in an area where shoreface sandstones had also accumulated (perhaps and incised valley). A large cluster of channel fill sandstones occurs in the Dry Hollow higher in the section here. Perhaps conglomerate was present at one time but was removed by these fluvial channels, which may have been focused by the same underlying driver as the tidal channels. This trend would not be evident from studying outcrops just a few kilometers away, but may lead to the discovery of a driving mechanism behind the location of a fluvial fairway. Another example is the rapid change in the Lower Sandy Unit at Cumberland Gap from a relatively high net-to-gross section in the south, to an almost sand free section just a kilometer north. For most of the Dry Hollow Member, sub-kilometer lateral resolution of these fluviodeltaics rocks would likely be needed to fully characterize the nature of the deposits.

Reservoir Potential

Porosity and permeability measurements (Tables 3, 4) suggest that, while very tight by conventional standards, rocks similar to the sandstones of the Dry Hollow in the outcrops in the study area could be feasibly producible through unconventional production techniques such as horizontal drilling and hydraulic fracturing. Facies 1 and 2 would serve as the best reservoirs in the Dry Hollow. The conglomerates are the most laterally continuous of the fluvial facies and the most porous and permeable on average. However, they are limited in their vertical extent. Facies 2 sandstones have slightly poorer reservoir properties, but with multistoried channel bodies they would provide more feet of pay in a given vertical section. If fluvial fairways, such as those at Muddy Creek, Scully's Gap, or Cumberland Gap could be identified and their trends accurately determined, then horizontal drilling along depositional dip could produce good results in hydrocarbon exploration.

A boost to reservoir potential in a Frontier type fluvial system is the high vertical and lateral connectivity within the higher net-to-gross units. Lateral connectivity in the facies model is likely overestimated between outcrops, but within channel belts it should be equivalent to the model. Even excellent connectivity does not guarantee that every sandstone would be charged with hydrocarbons. Channel to channel connections and sandstone geometries are complex and there could easily be parts of the system that have been bypassed, depending on migration pathways. The Frontier is in a good position to fully charge however, as it lies between thick packages of potential source rocks and even has the potential for some self-sourcing of coalbed methane. Other elements of the petroleum system are in place, with abundant seals from the marine shale and floodplain mudstones of the upper Frontier and Hilliard Shale.

While Facies 1 and 2 are the best candidates for reservoir rocks, Facies 6 would potentially provide a significant increase to vertical and lateral connectivity. This is somewhat uncertain because poor exposure has limited our understanding of this facies, but it seems to be a major component in at least some section (e.g., Scully's Gap 1). Ratty, Facies 3 sandstones may also help increase connectivity, however, this facies is generally fairly isolated and is often nearly impermeable. It is possible that these channels may occasionally provide small breaches through the mud-rich units where they generally occur to allow charging of larger channel bodies.

CONCLUSION

This study characterizers the low net-to-gross fluviodeltaic deposits of the Dry Hollow and Oyster Ridge members of the Frontier Formation in southwestern Wyoming. Through a combination of traditional geologic field techniques and newer, quantitative techniques (photogrammetry and geocellular facies modeling) we identify six significant, traceable units within the upper Frontier: the Oyster Ridge Shoreface Unit, Oyster Ridge Coastal Plain Unit, the Dry Hollow Conglomerate Unit, the Dry Hollow Lower Sandy Unit, the Kemmerer Coal Zone, and the Dry Hollow Upper Sandy Unit. Considerable variation exists within these units, highlighting the difficulties faced in understanding the complexities of fluviodeltaic depositional settings.

Correlation between measured sections and subsurface well data basinward of outcrop exposures helps to reveal temporal and spatial trends within the upper Frontier. The Dry Hollow is an overall transgressive unit as evidenced by the decrease in fluvial sandstones and increase in marine influence in the upper part of the member. It unconformably overlies the regressive Oyster Ridge member. Net-to-gross ratios change dramatically, sometimes over <1 km laterally. Clustered channel belts do exist and recognizing and predicting their existence is a critical part of understanding a low net-to-gross system. Significant changes in architecture also occur along depositional dip. Strata thin dramatically basinward onto the Moxa Arch. This places some limits on the ability to apply outcrop observation to more distal parts of the system, but provides valuable insight into the importance of structural control on the Frontier. Simplified paleogeographic maps of key times during Frontier deposition were created using these trends. The creation of these maps allows for visualization of the depositional environments that deposited the units within the upper Frontier. This increases understanding of the Frontier on a large scale and provides greater predictive power in characterizing facies distributions.

Fluvial sandstones of the Dry Hollow would have the potential to serve as petroleum reservoirs in the subsurface and do produce oil and gas on the Moxa Arch. The best reservoir facies are Facies 1 (conglomerates) and Facies 2 (fine fluvial sandstones), though other facies may play important roles in increasing connectivity. Net-to-gross calculations and geocellular facies modeling indicate that the best units for potential hydrocarbon exploration in a similar system in the subsurface would be the basal Conglomerate and Lower Sandy Units of the Dry Hollow Member. Facies models show that fluvial sandstones are abundant enough to connect with each other and have the potential to migrate and trap hydrocarbons.

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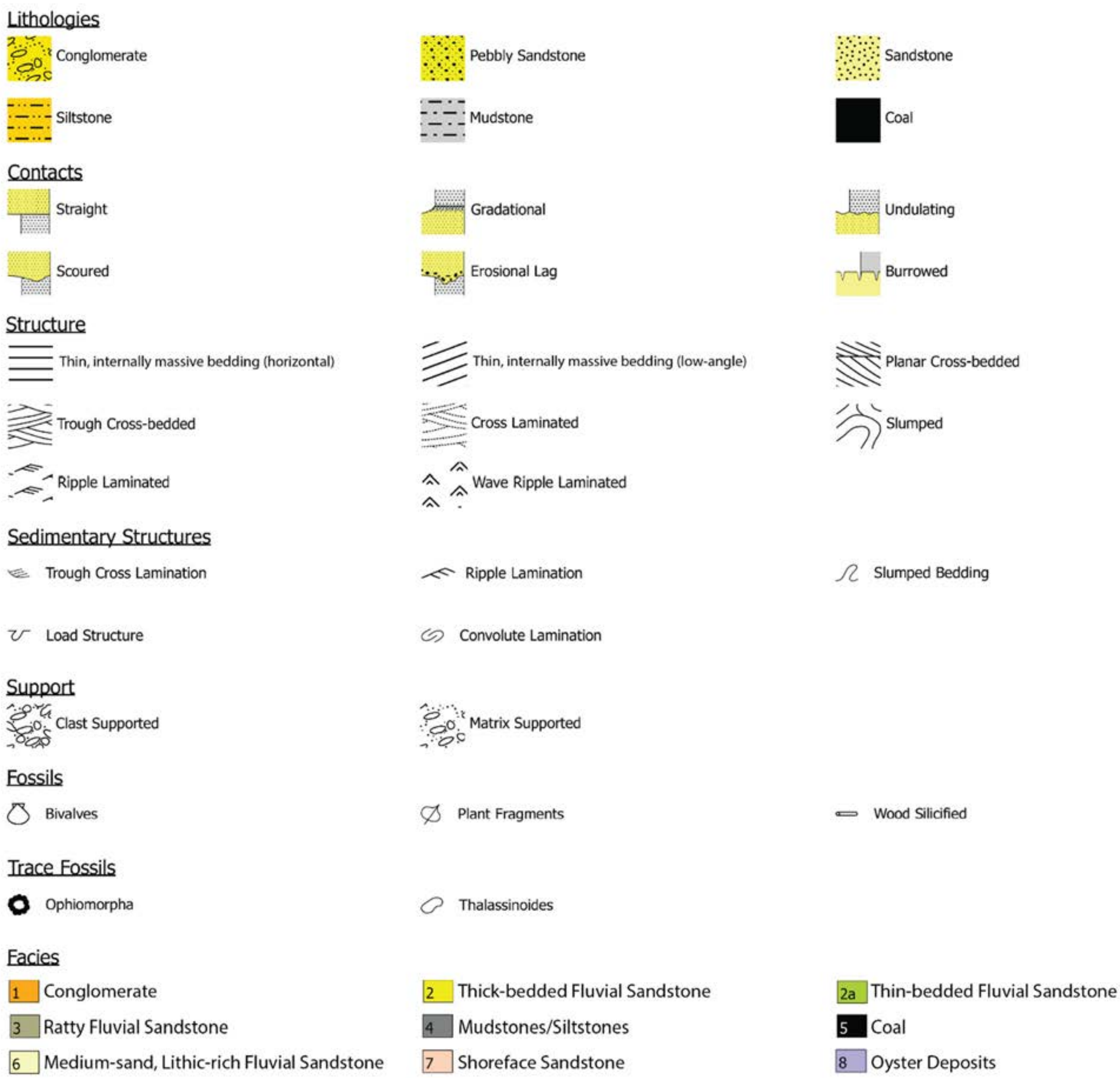
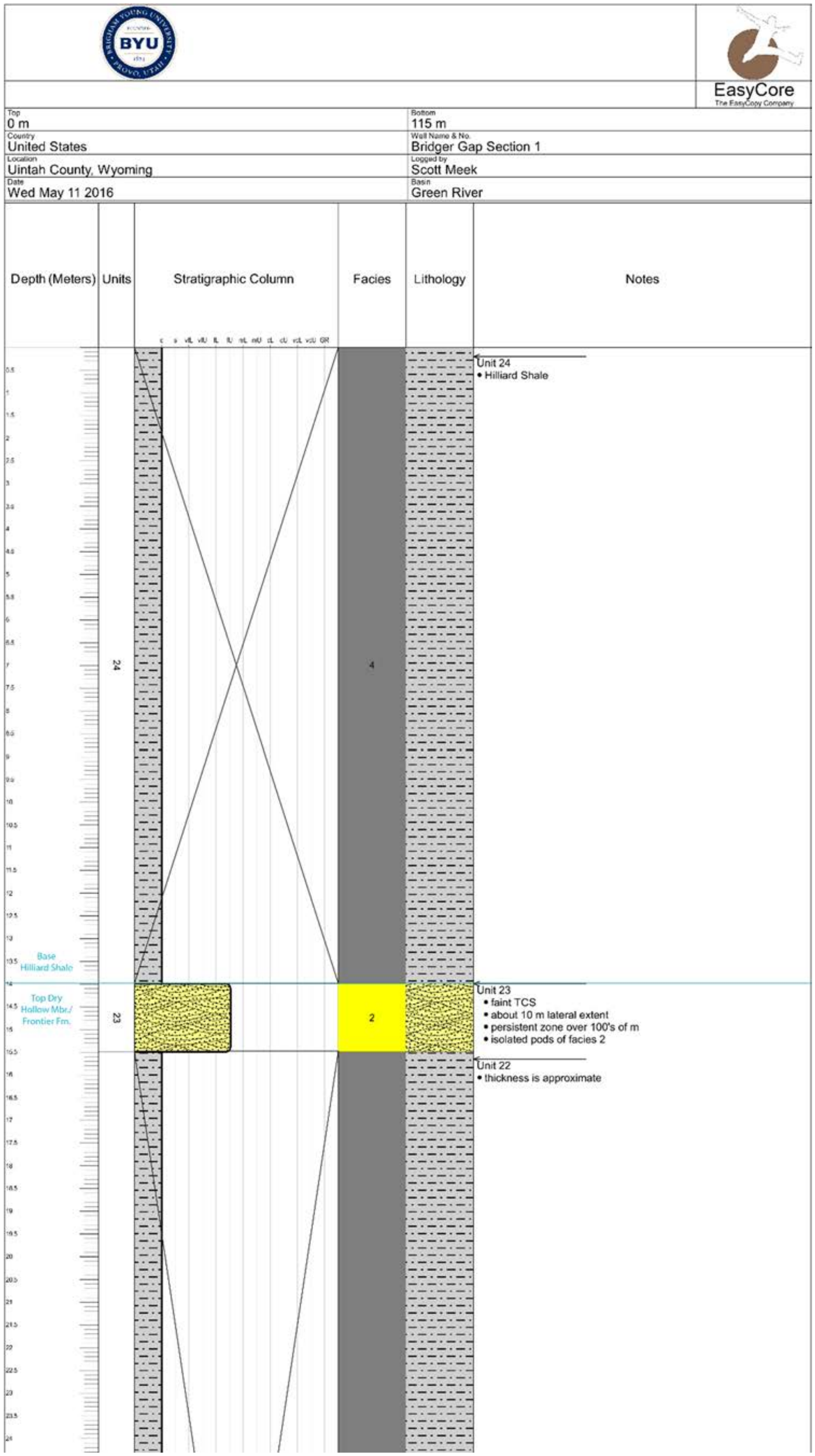
APPENDIX A

DETAILED MEASURED SECTIONS

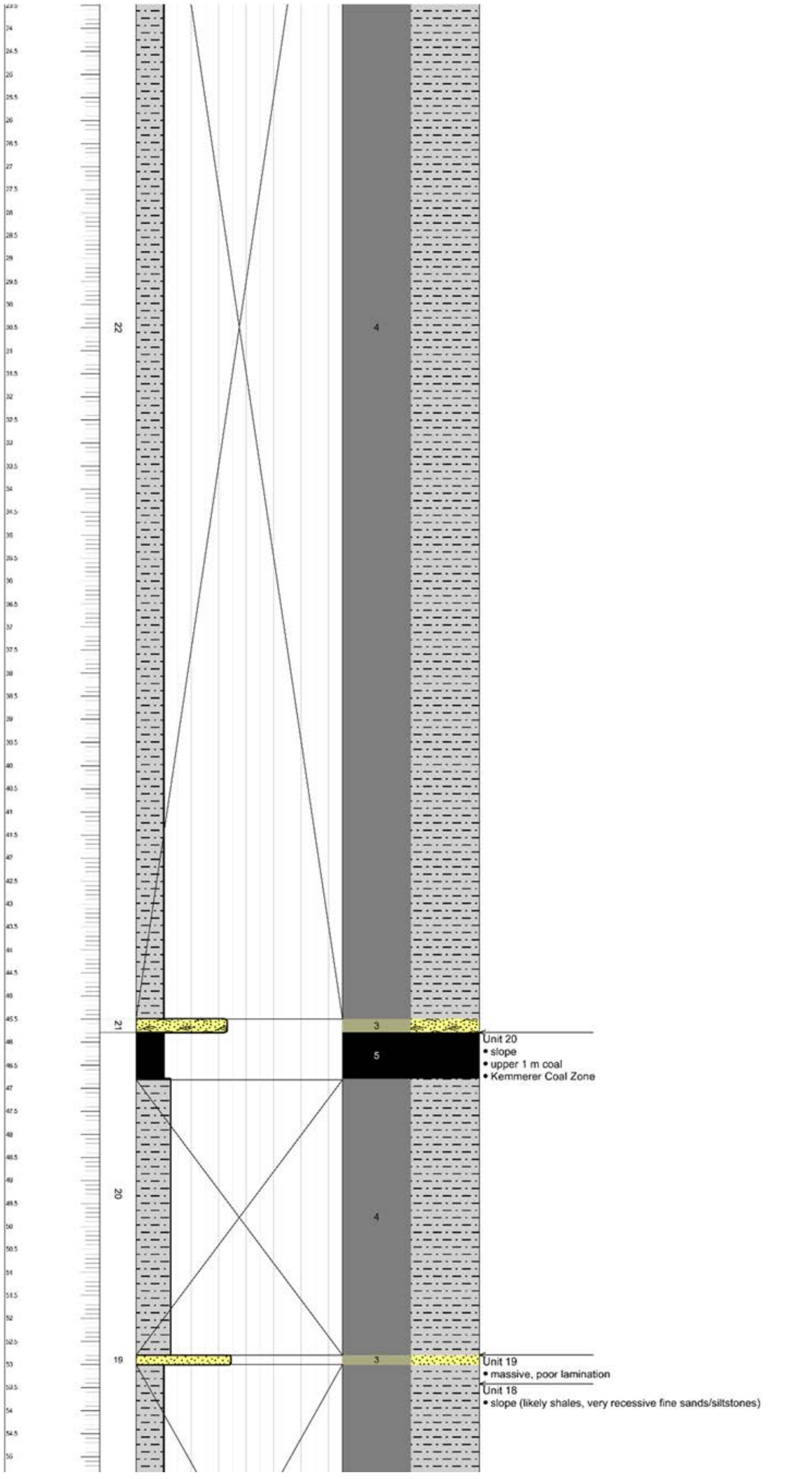
The following are the nine full measured sections from the five key outcrop localities in the study area. Sections were drafted in EasyCore. They are a compilation of field notes and observations and initial interpretation. Many of these interpretations have been revised.

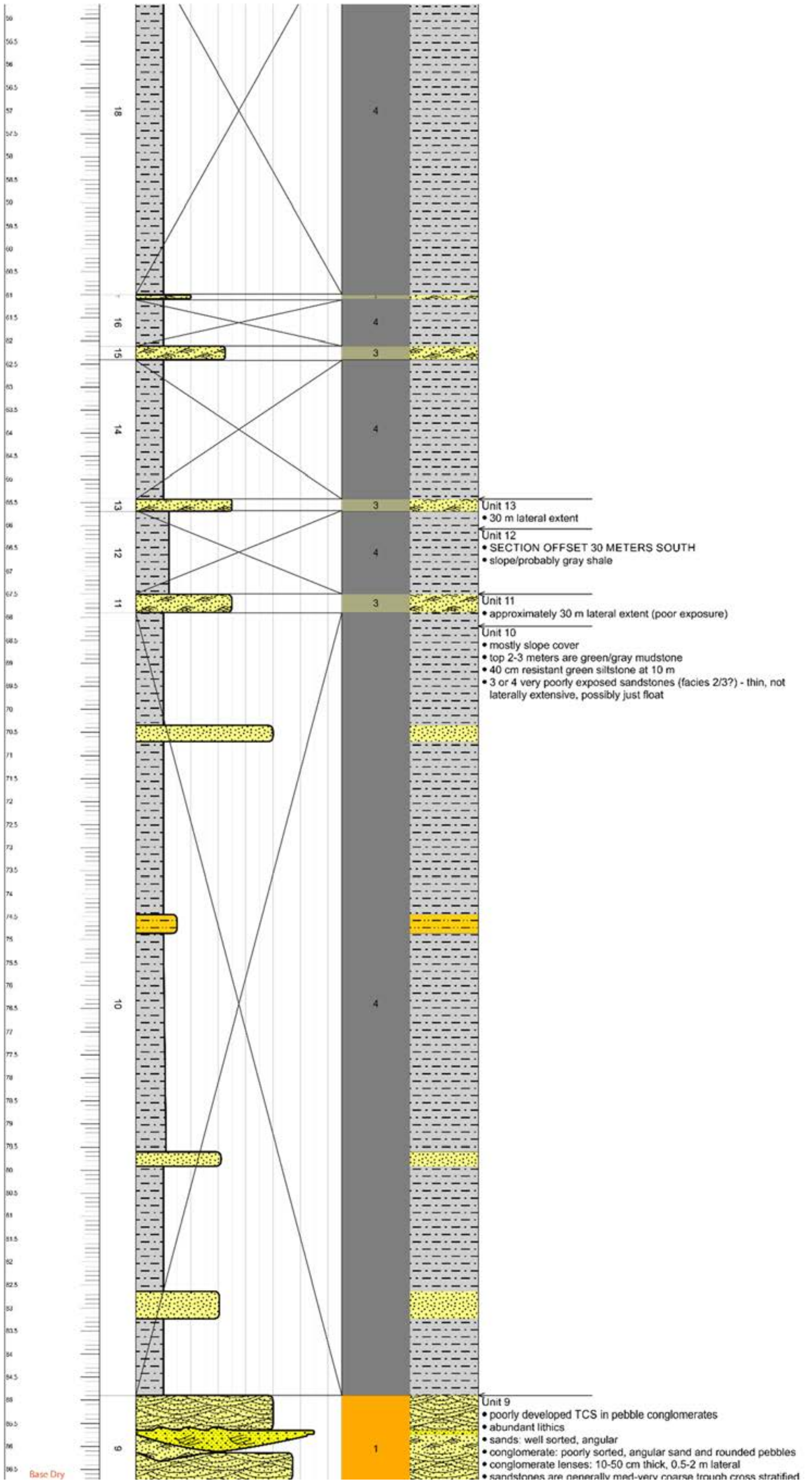
Legend for Measured Sections



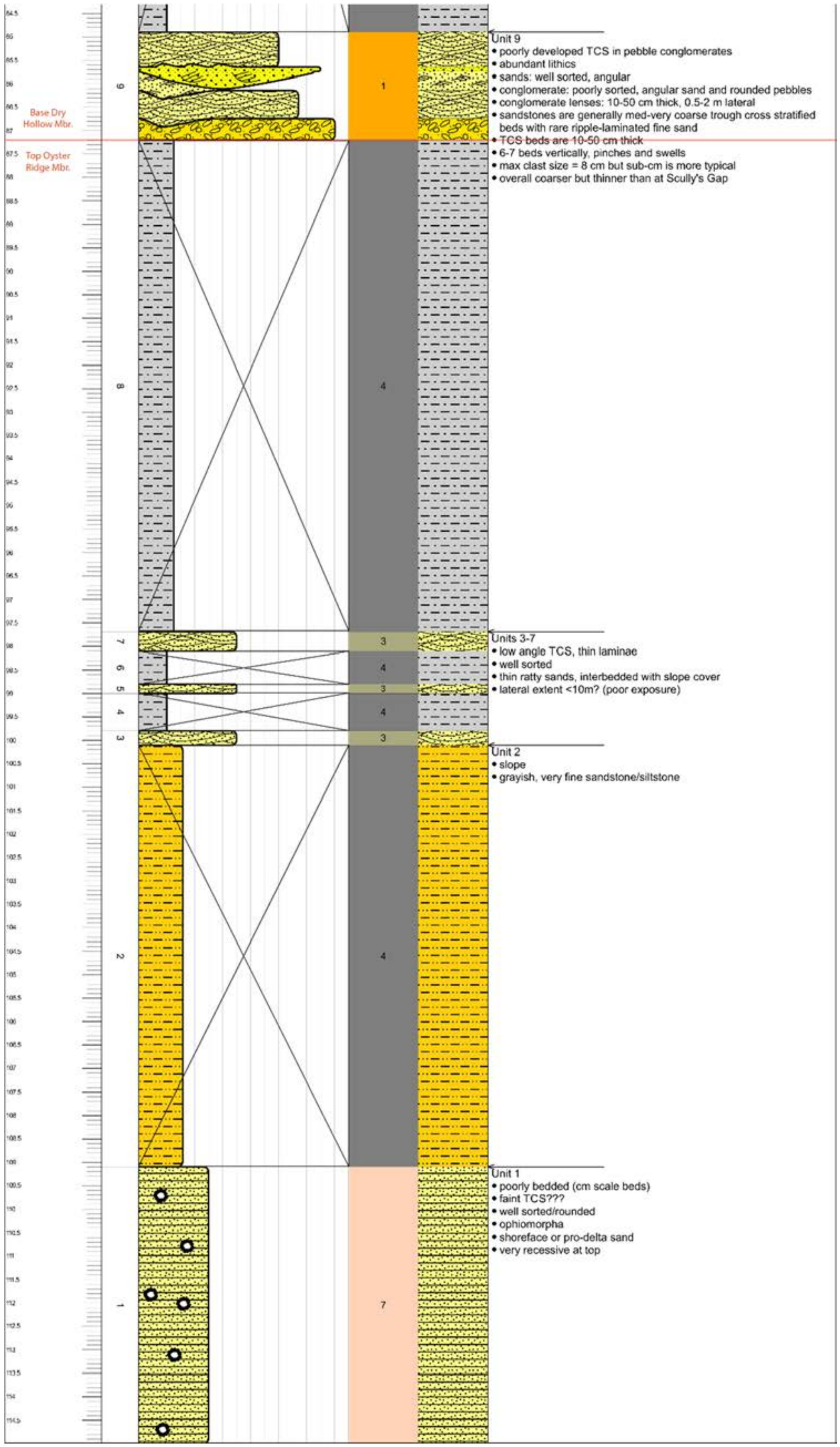


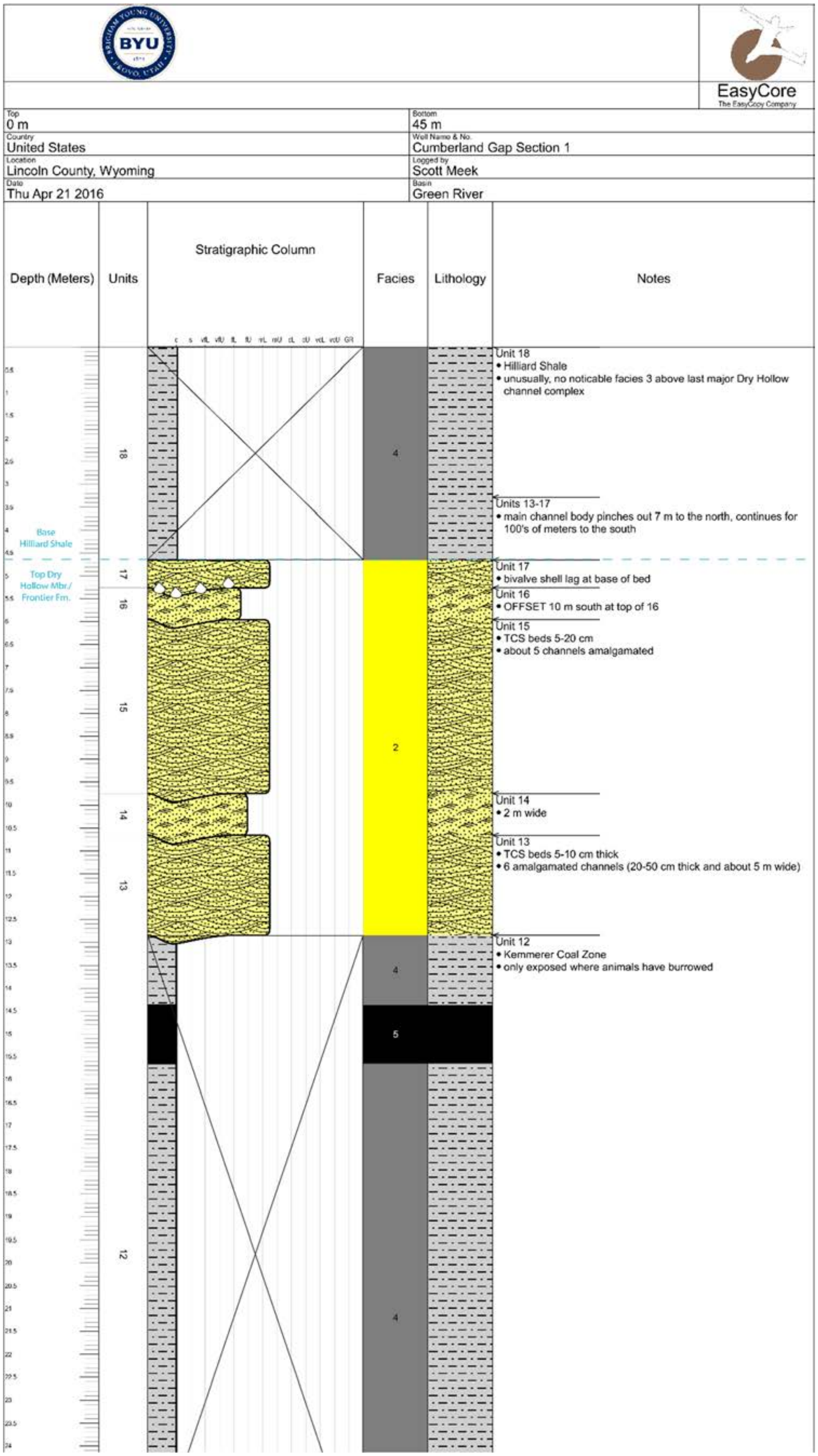
BYU
EasyCore
The EasyCopy Company
Top
0 m
Bottom
115 m
Country
United States
Well Name & No.
Bridger Gap Section 1
Location
Uintah County, Wyoming
Logged by
Scott Meek
Date
Wed May 11 2016
Basin
Green River
Depth (Meters)
Units
Stratigraphic Column
Facies
Lithology
Notes
24
4
Unit 24
• Hilliard Shale
Base Hilliard Shale
Top Dry Hollow Mbr./ Frontier Fm.
23
2
Unit 23
• faint TCS
• about 10 m lateral extent
• persistent zone over 100's of m
• isolated pods of facies 2
Unit 22
• thickness is approximate

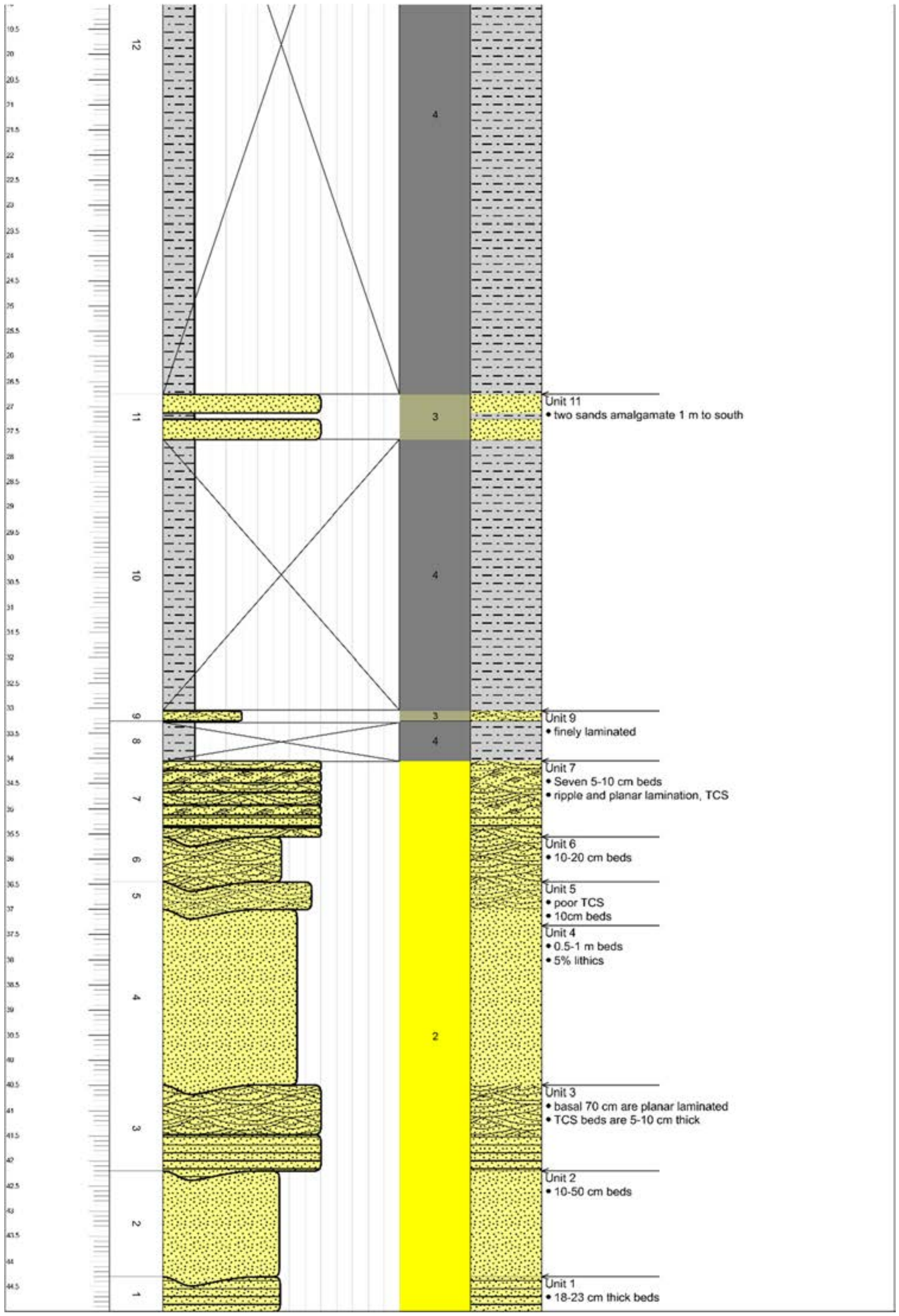

22
4
21
3
Unit 20
• slope
• upper 1 m coal
• Kemmerer Coal Zone
5
20
4
19
3
Unit 19
• massive, poor lamination
Unit 18
• slope (likely shales, very recessive fine sands/siltstones)



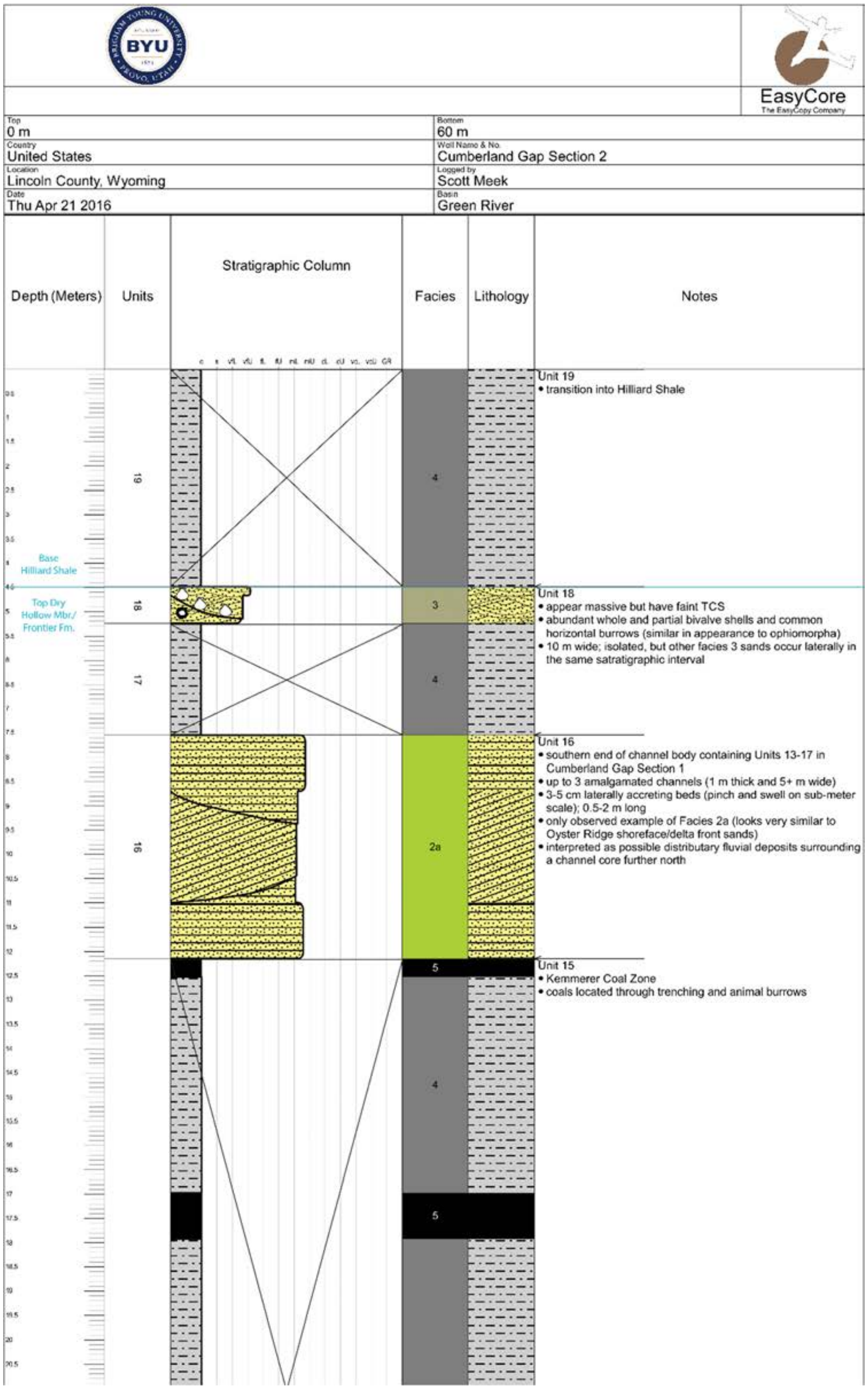
Unit 13
• 30 m lateral extent
Unit 12
• SECTION OFFSET 30 METERS SOUTH
• slope/probably gray shale
Unit 11
• approximately 30 m lateral extent (poor exposure)
Unit 10
• mostly slope cover
• top 2-3 meters are green/gray mudstone
• 40 cm resistant green siltstone at 10 m
• 3 or 4 very poorly exposed sandstones (facies 2/3?) - thin, not laterally extensive, possibly just float
Unit 9
• poorly developed TCS in pebble conglomerates
• abundant lithics
• sands: well sorted, angular
• conglomerate: poorly sorted, angular sand and rounded pebbles
• conglomerate lenses: 10-50 cm thick, 0.5-2 m lateral
• sandstones are generally med-very coarse trough cross stratified
Base Dry

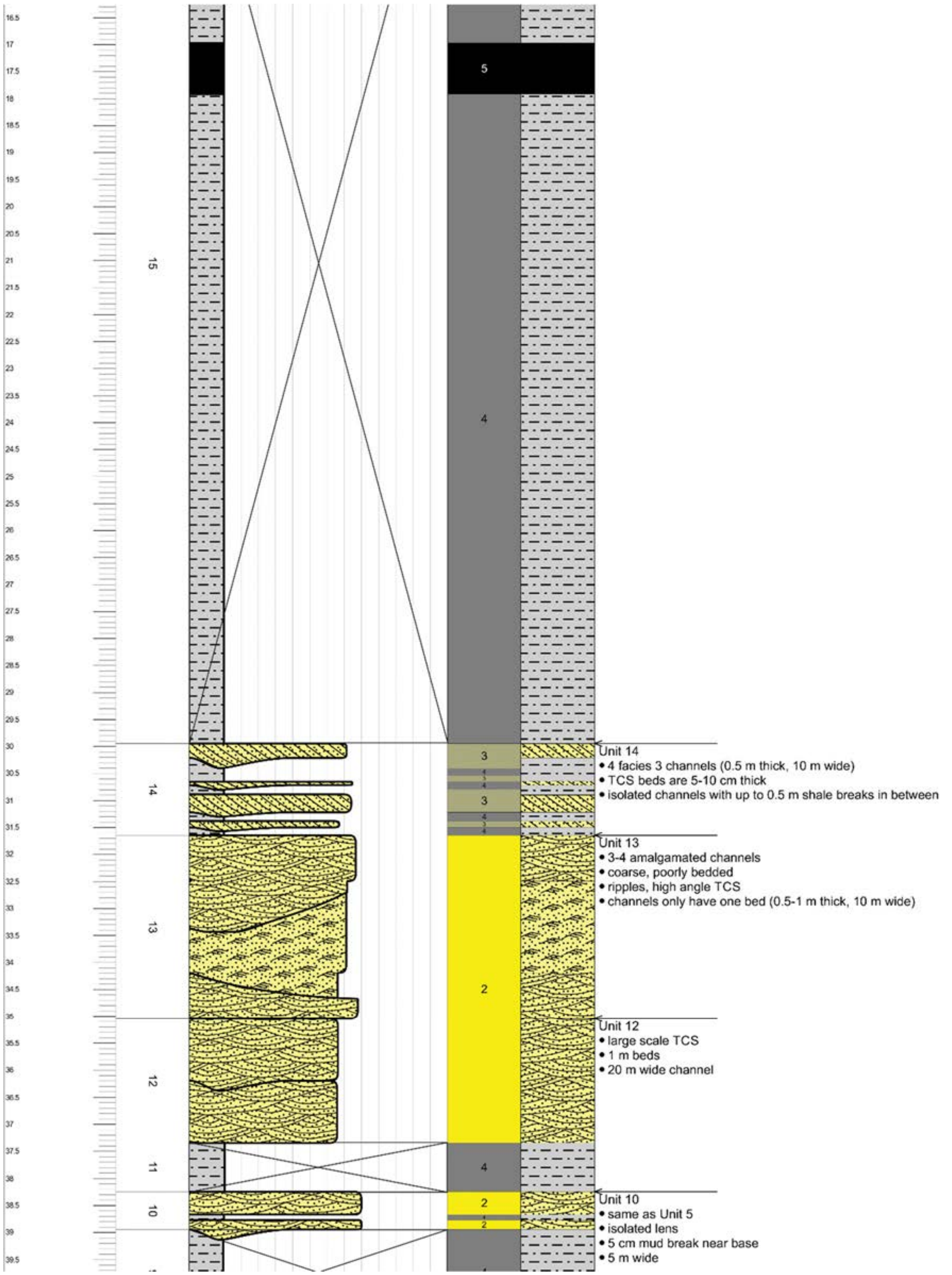

Base Dry Hollow Mbr.
Top Oyster Ridge Mbr.
Unit 9
• poorly developed TCS in pebble conglomerates
• abundant lithics
• sands: well sorted, angular
• conglomerate: poorly sorted, angular sand and rounded pebbles
• conglomerate lenses: 10-50 cm thick, 0.5-2 m lateral
• sandstones are generally med-very coarse trough cross stratified beds with rare ripple-laminated fine sand
• TCS beds are 10-50 cm thick
• 6-7 beds vertically, pinches and swells
• max clast size = 8 cm but sub-cm is more typical
• overall coarser but thinner than at Scully's Gap
Units 3-7
• low angle TCS, thin laminae
• well sorted
• thin ratty sands, interbedded with slope cover
• lateral extent <10m? (poor exposure)
Unit 2
• slope
• grayish, very fine sandstone/siltstone
Unit 1
• poorly bedded (cm scale beds)
• faint TCS???
• well sorted/rounded
• ophiomorpha
• shoreface or pro-delta sand
• very recessive at top


BYU
EasyCore
The EasyCopy Company
Top
0 m
Bottom
45 m
Country
United States
Well Name & No.
Cumberland Gap Section 1
Location
Lincoln County, Wyoming
Logged by
Scott Meek
Date
Thu Apr 21 2016
Basin
Green River
Depth (Meters)
Units
Stratigraphic Column
Facies
Lithology
Notes
Base Hilliard Shale
Top Dry Hollow Mbr./ Frontier Fm.
Unit 18
• Hilliard Shale
• unusually, no noticable facies 3 above last major Dry Hollow channel complex
Units 13-17
• main channel body pinches out 7 m to the north, continues for 100's of meters to the south
Unit 17
• bivalve shell lag at base of bed
Unit 16
• OFFSET 10 m south at top of 16
Unit 15
• TCS beds 5-20 cm
• about 5 channels amalgamated
Unit 14
• 2 m wide
Unit 13
• TCS beds 5-10 cm thick
• 6 amalgamated channels (20-50 cm thick and about 5 m wide)
Unit 12
• Kemmerer Coal Zone
• only exposed where animals have burrowed

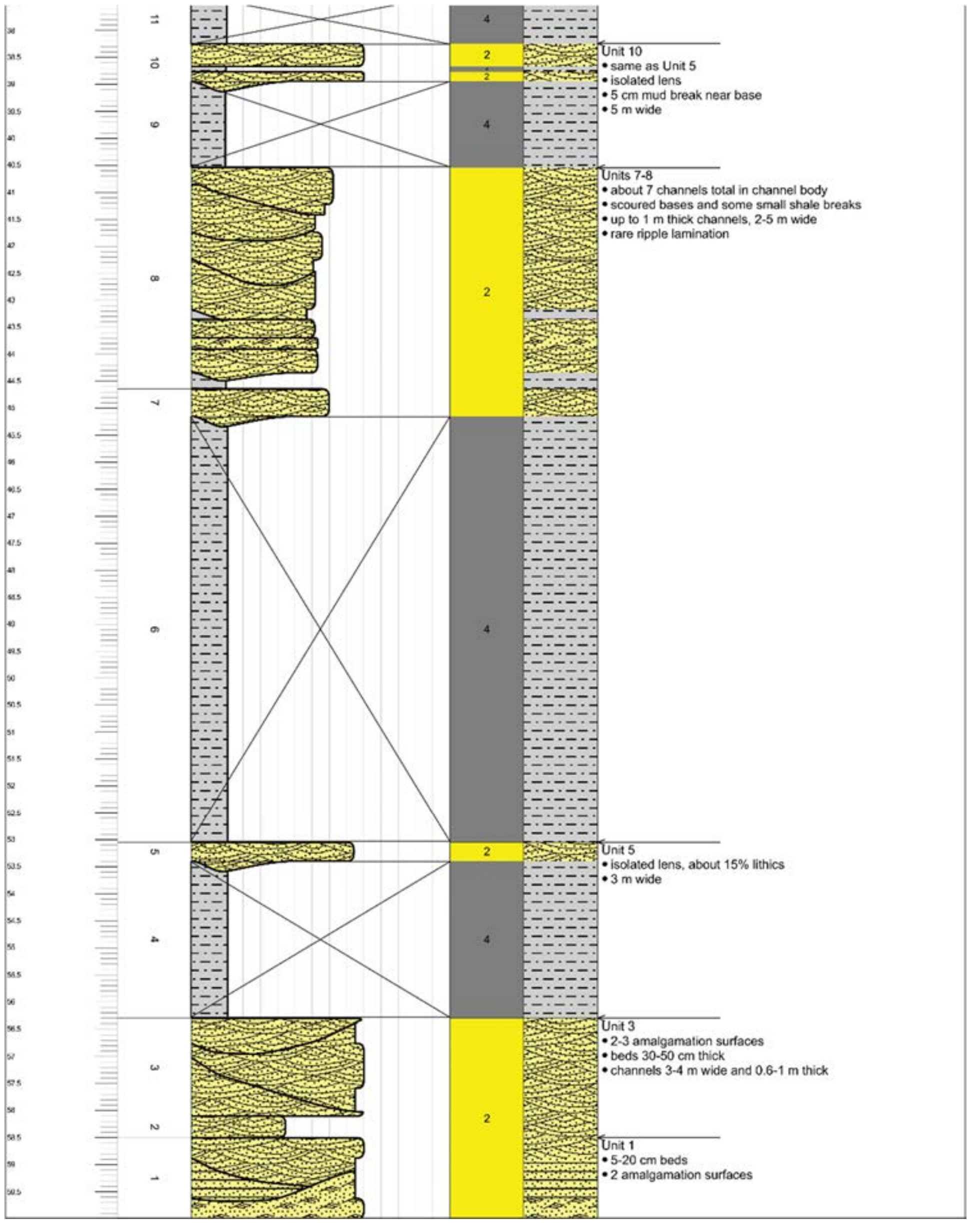


Unit 11
• two sands amalgamate 1 m to south
Unit 9
• finely laminated
Unit 7
• Seven 5-10 cm beds
• ripple and planar lamination, TCS
Unit 6
• 10-20 cm beds
Unit 5
• poor TCS
• 10cm beds
Unit 4
• 0.5-1 m beds
• 5% lithics
Unit 3
• basal 70 cm are planar laminated
• TCS beds are 5-10 cm thick
Unit 2
• 10-50 cm beds
Unit 1
• 18-23 cm thick beds

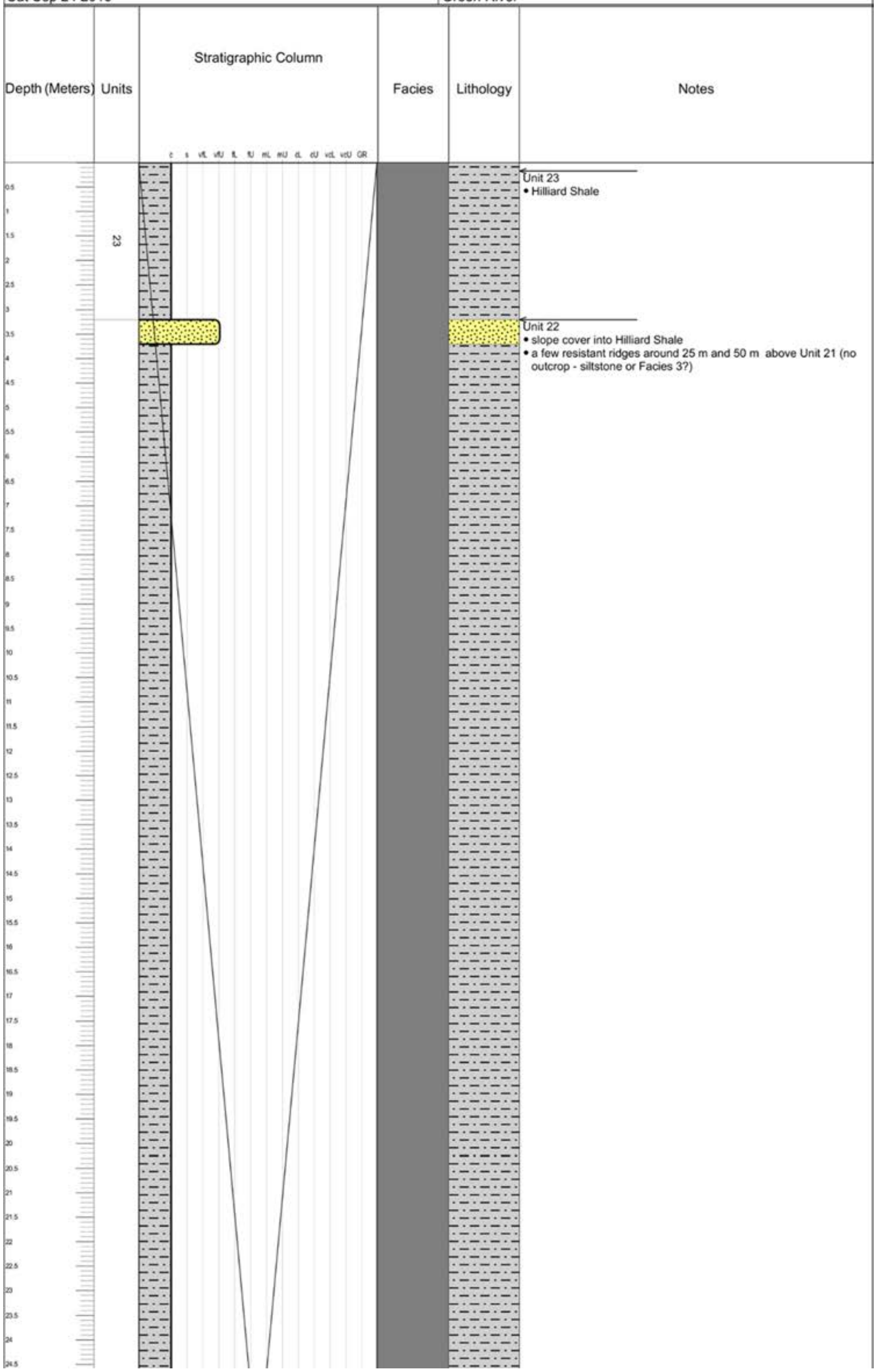

BYU
EasyCore
The EasyCopy Company
Top
0 m
Bottom
60 m
Country
United States
Well Name & No.
Cumberland Gap Section 2
Location
Lincoln County, Wyoming
Logged by
Scott Meek
Date
Thu Apr 21 2016
Basin
Green River
Depth (Meters)
Units
Stratigraphic Column
Facies
Lithology
Notes
Base Hilliard Shale
Top Dry Hollow Mbr./ Frontier Fm.
Unit 19
• transition into Hilliard Shale
Unit 18
• appear massive but have faint TCS
• abundant whole and partial bivalve shells and common horizontal burrows (similar in appearance to ophiomorpha)
• 10 m wide; isolated, but other facies 3 sands occur laterally in the same satratigraphic interval
Unit 16
• southern end of channel body containing Units 13-17 in Cumberland Gap Section 1
• up to 3 amalgamated channels (1 m thick and 5+ m wide)
• 3-5 cm laterally accreting beds (pinch and swell on sub-meter scale); 0.5-2 m long
• only observed example of Facies 2a (looks very similar to Oyster Ridge shoreface/delta front sands)
• interpreted as possible distributary fluvial deposits surrounding a channel core further north
Unit 15
• Kemmerer Coal Zone
• coals located through trenching and animal burrows

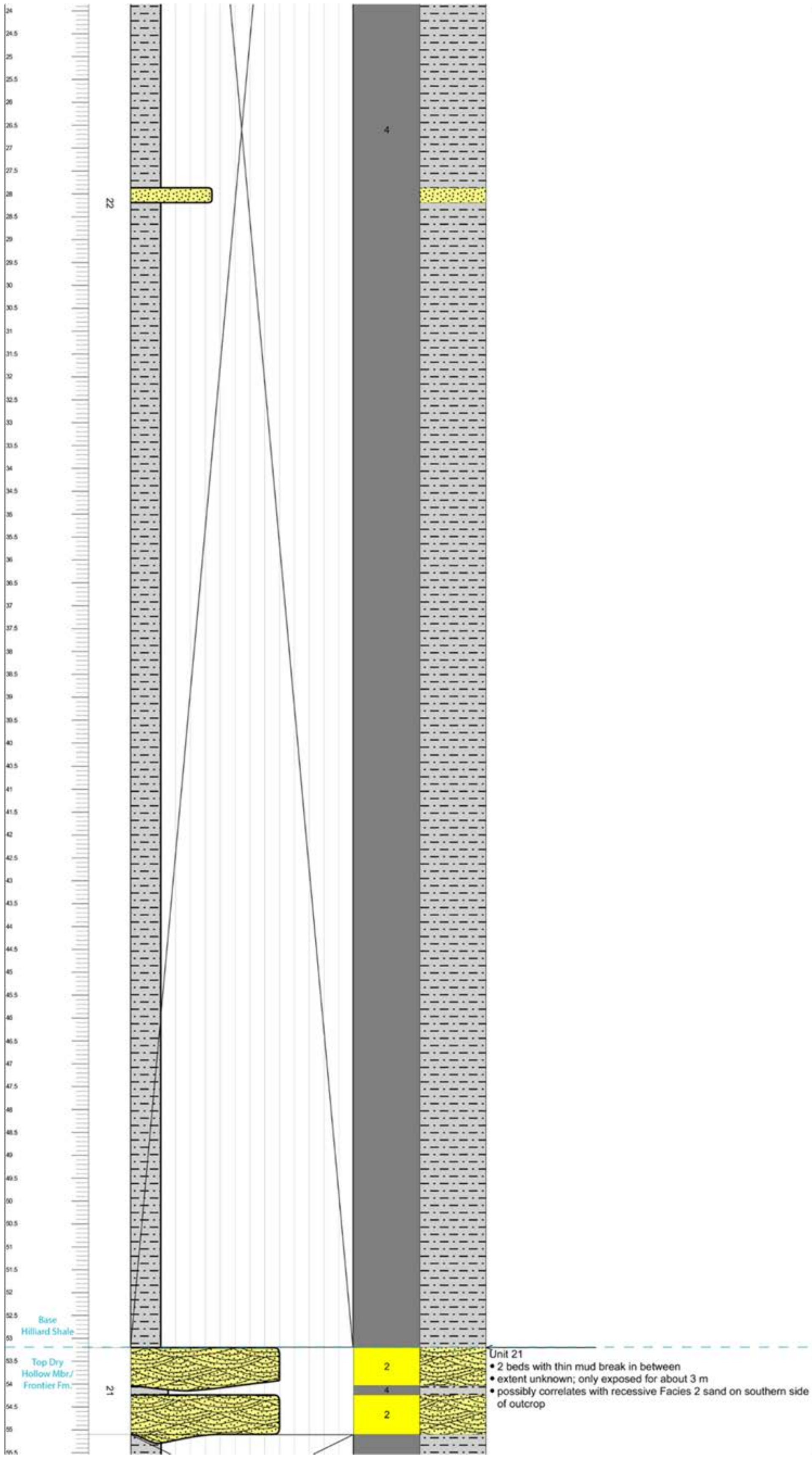


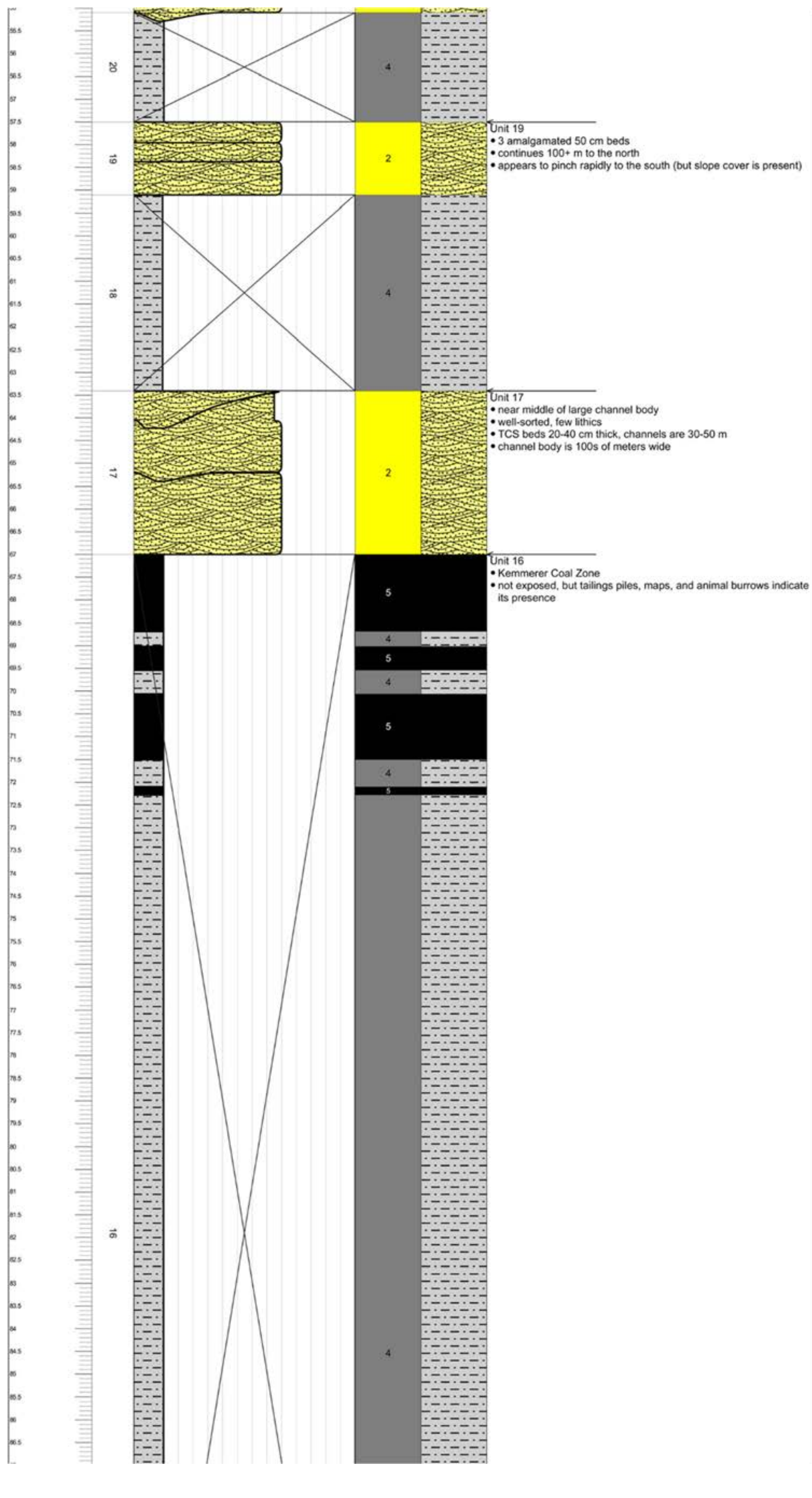
Unit 14
• 4 facies 3 channels (0.5 m thick, 10 m wide)
• TCS beds are 5-10 cm thick
• isolated channels with up to 0.5 m shale breaks in between
Unit 13
• 3-4 amalgamated channels
• coarse, poorly bedded
• ripples, high angle TCS
• channels only have one bed (0.5-1 m thick, 10 m wide)
Unit 12
• large scale TCS
• 1 m beds
• 20 m wide channel
Unit 10
• same as Unit 5
• isolated lens
• 5 cm mud break near base
• 5 m wide
15
14
13
12
11
10
5
4
3
2

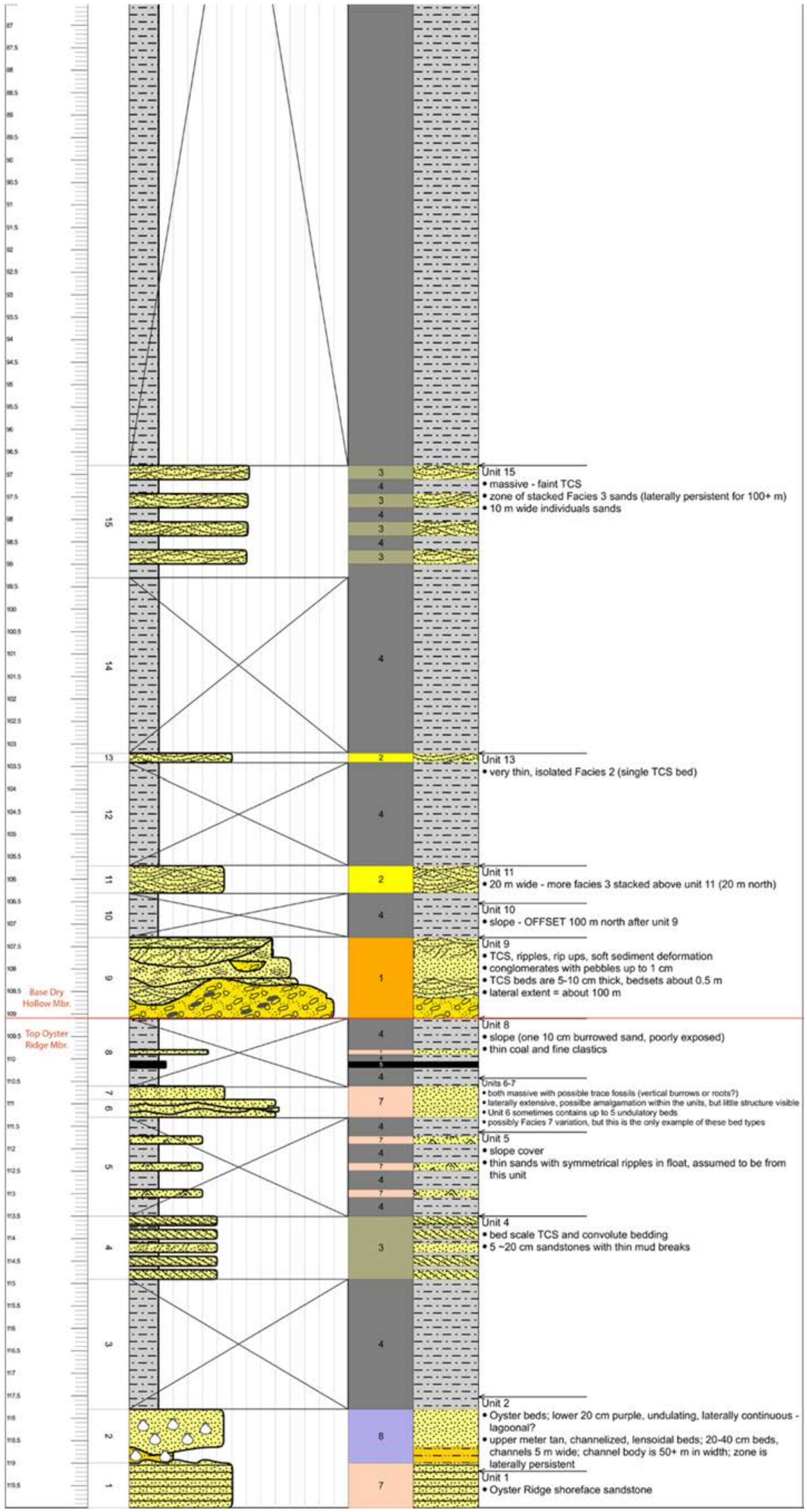

Unit 10
• same as Unit 5
• isolated lens
• 5 cm mud break near base
• 5 m wide
Units 7-8
• about 7 channels total in channel body
• scoured bases and some small shale breaks
• up to 1 m thick channels, 2-5 m wide
• rare ripple lamination
Unit 5
• isolated lens, about 15% lithics
• 3 m wide
Unit 3
• 2-3 amalgamation surfaces
• beds 30-50 cm thick
• channels 3-4 m wide and 0.6-1 m thick
Unit 1
• 5-20 cm beds
• 2 amalgamation surfaces

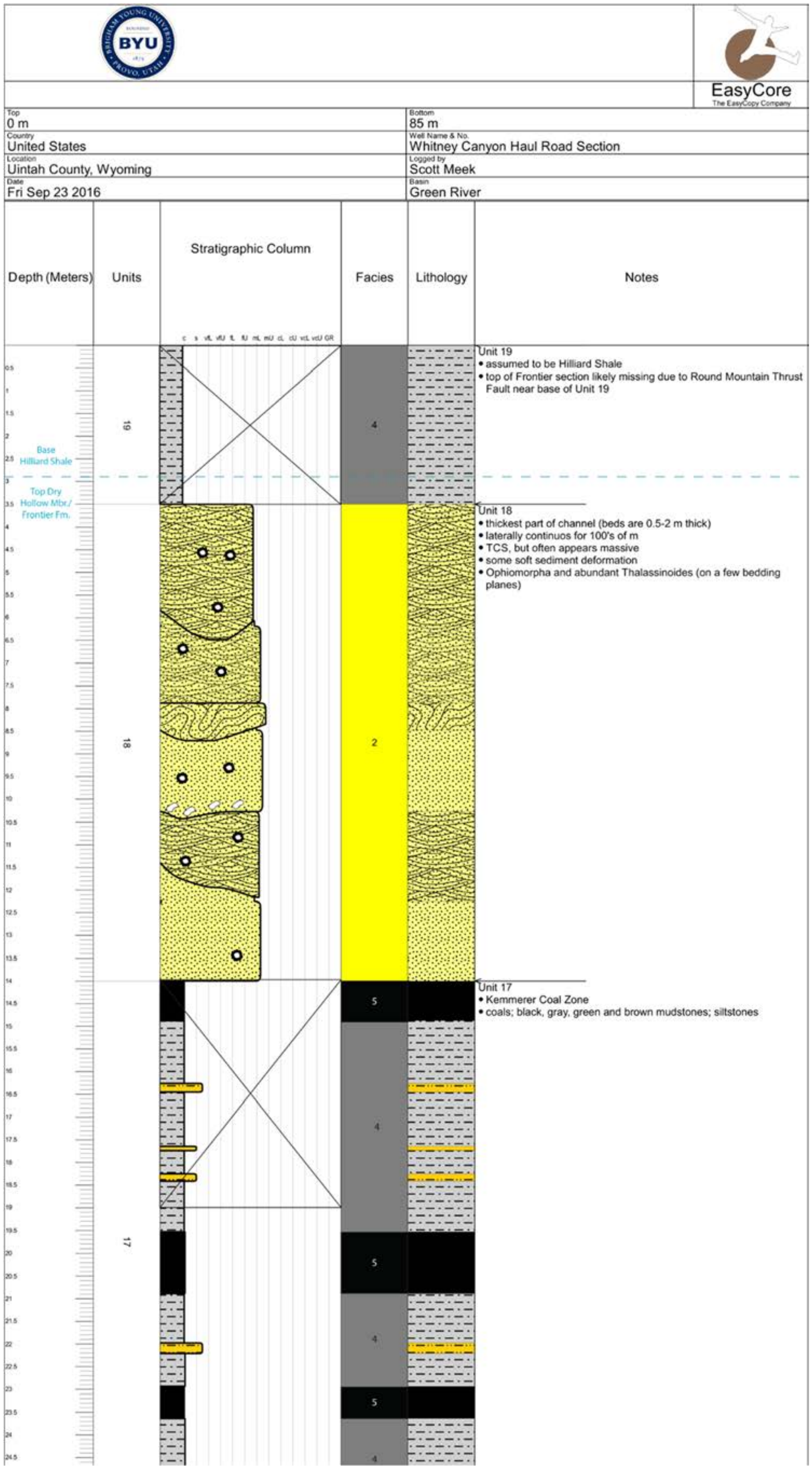
Top 0 m	Bottom 120 m
Country United States	Well Name & No. Cumberland Gap Section 3
Location Lincoln County, Wyoming	Logged by Scott Meek
Date Sat Sep 24 2016	Basin Green River

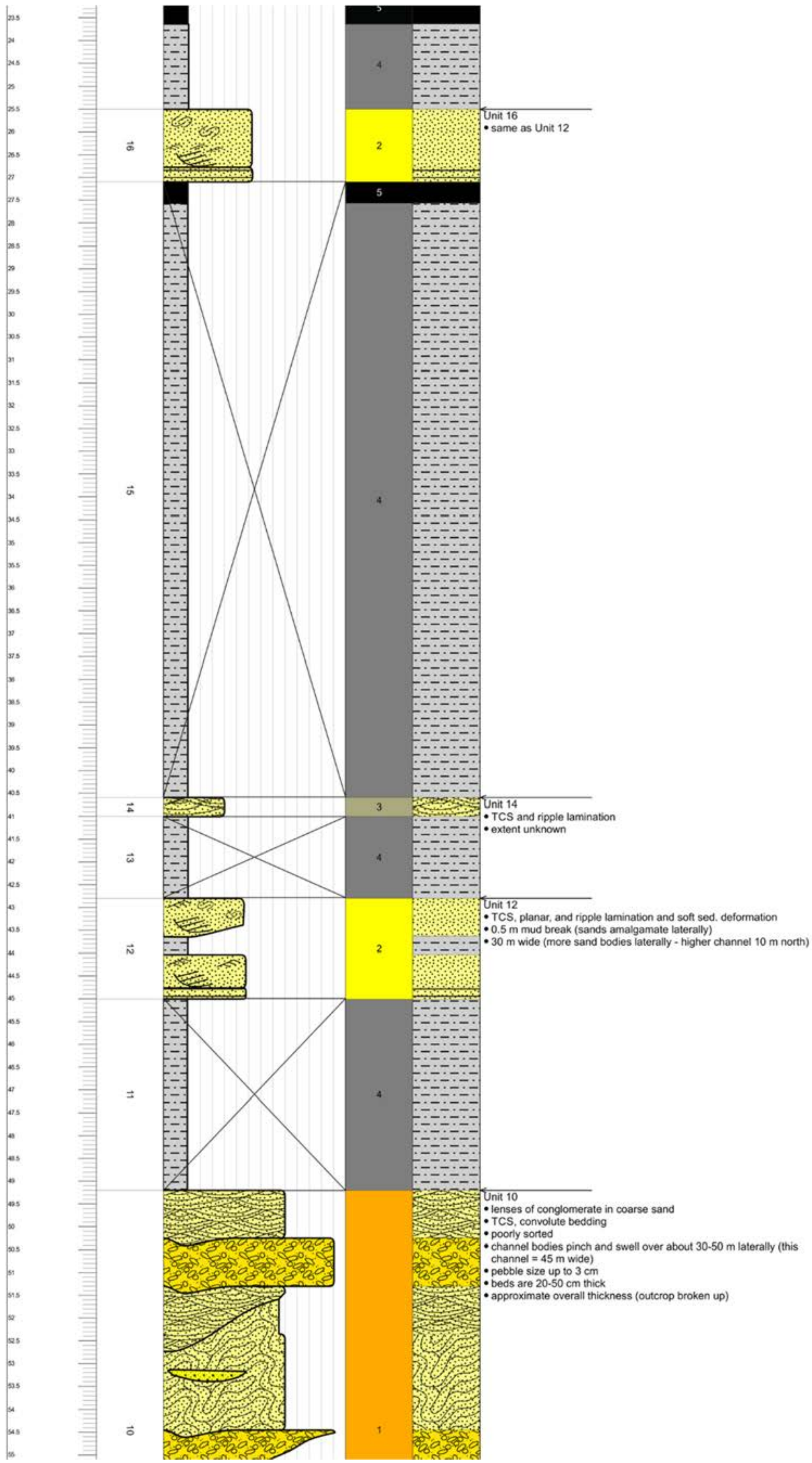


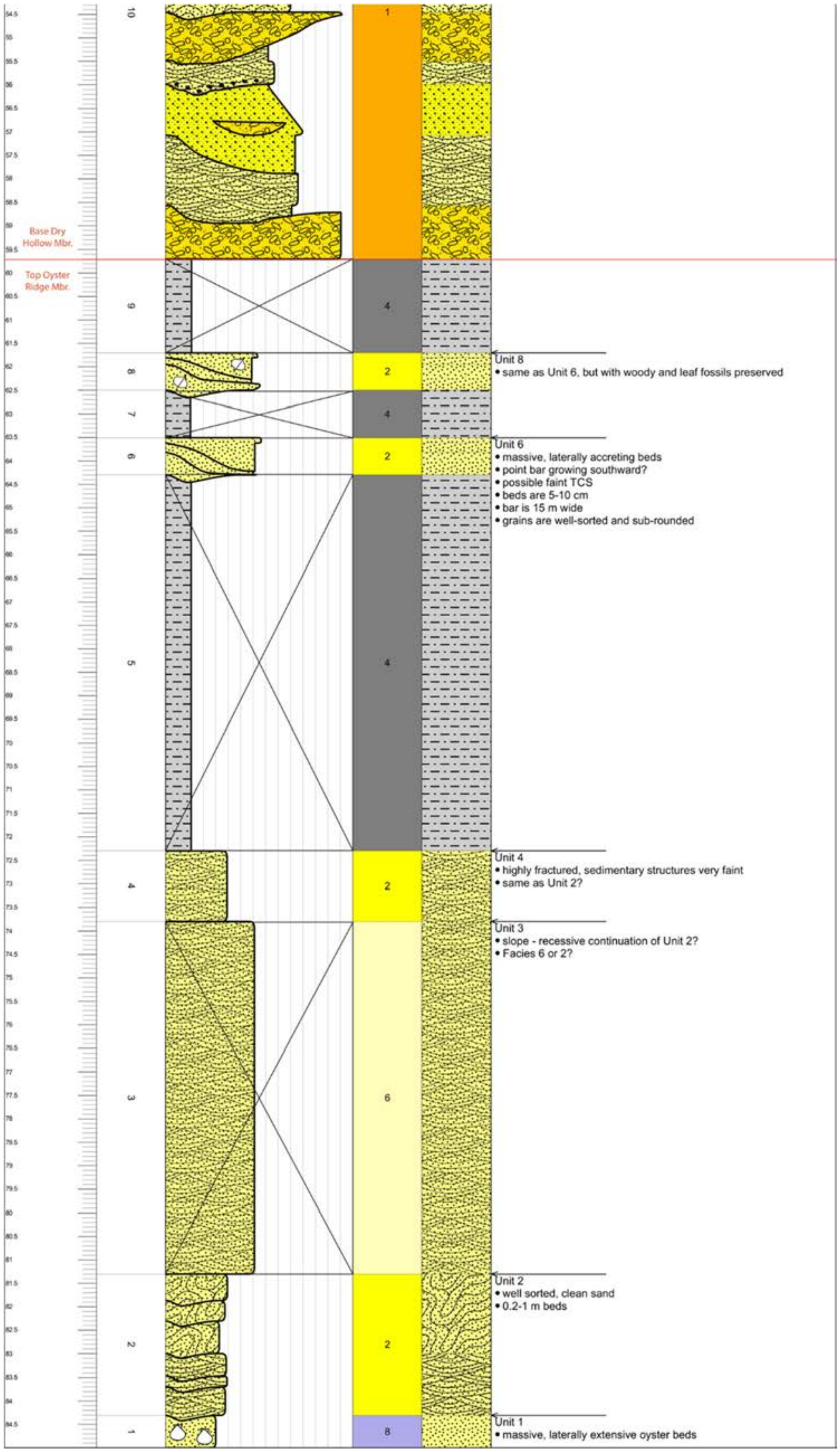

22
4
Base
Hilliard Shale
Top Dry
Hollow Mbr./
Frontier Fm.
21
2
4
2
Unit 21
• 2 beds with thin mud break in between
• extent unknown; only exposed for about 3 m
• possibly correlates with recessive Facies 2 sand on southern side of outcrop

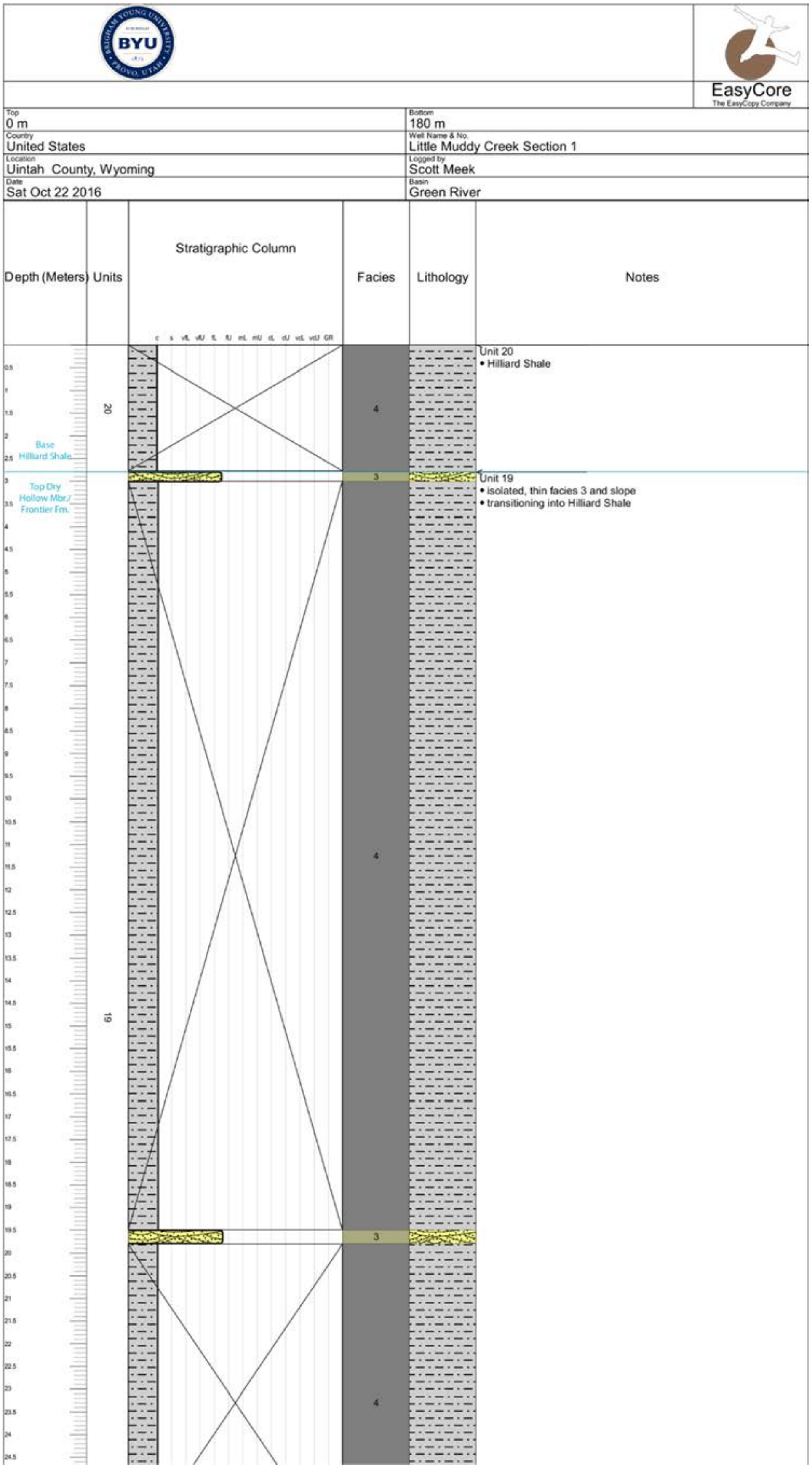

Unit 19
• 3 amalgamated 50 cm beds
• continues 100+ m to the north
• appears to pinch rapidly to the south (but slope cover is present)
Unit 17
• near middle of large channel body
• well-sorted, few lithics
• TCS beds 20-40 cm thick, channels are 30-50 m
• channel body is 100s of meters wide
Unit 16
• Kemmerer Coal Zone
• not exposed, but tailings piles, maps, and animal burrows indicate its presence

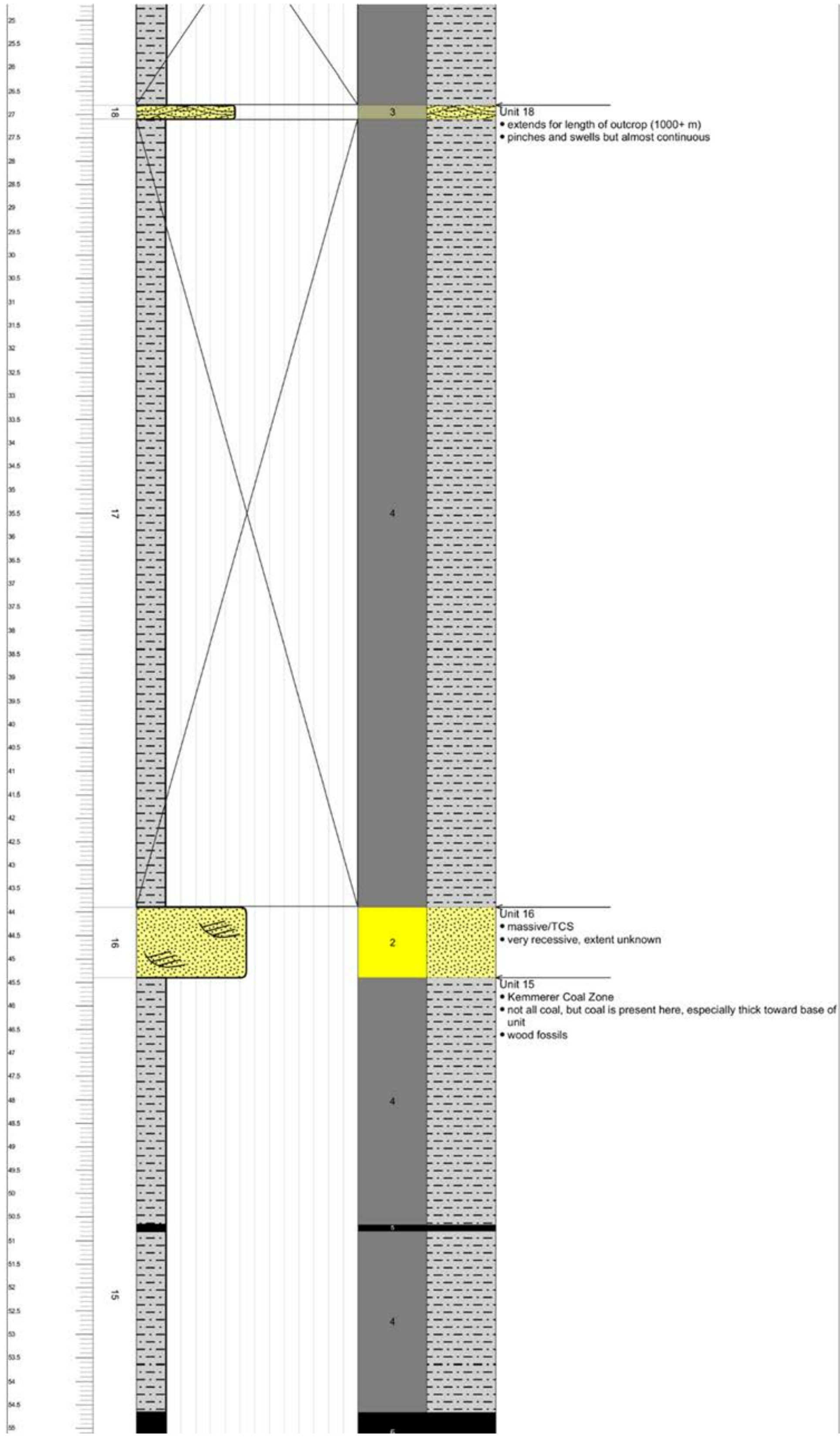

Unit 15
• massive - faint TCS
• zone of stacked Facies 3 sands (laterally persistent for 100+ m)
• 10 m wide individuals sands
Unit 13
• very thin, isolated Facies 2 (single TCS bed)
Unit 11
• 20 m wide - more facies 3 stacked above unit 11 (20 m north)
Unit 10
slope - OFFSET 100 m north after unit 9
Unit 9
• TCS, ripples, rip ups, soft sediment deformation
• conglomerates with pebbles up to 1 cm
• TCS beds are 5-10 cm thick, bedsets about 0.5 m
• lateral extent = about 100 m
Base Dry Hollow Mbr.
Top Oyster Ridge Mbr.
Unit 8
• slope (one 10 cm burrowed sand, poorly exposed)
• thin coal and fine clastics
Units 6-7
• both massive with possible trace fossils (vertical burrows or roots?)
• laterally extensive, possilbe amalgamation within the units, but little structure visible
• Unit 6 sometimes contains up to 5 undulatory beds
• possibly Facies 7 variation, but this is the only example of these bed types
Unit 5
• slope cover
• thin sands with symmetrical ripples in float, assumed to be from this unit
Unit 4
• bed scale TCS and convolute bedding
• 5 ~20 cm sandstones with thin mud breaks
Unit 2
• Oyster beds; lower 20 cm purple, undulating, laterally continuous - lagoonal?
• upper meter tan, channelized, lensoidal beds; 20-40 cm beds, channels 5 m wide; channel body is 50+ m in width; zone is laterally persistent
Unit 1
• Oyster Ridge shoreface sandstone

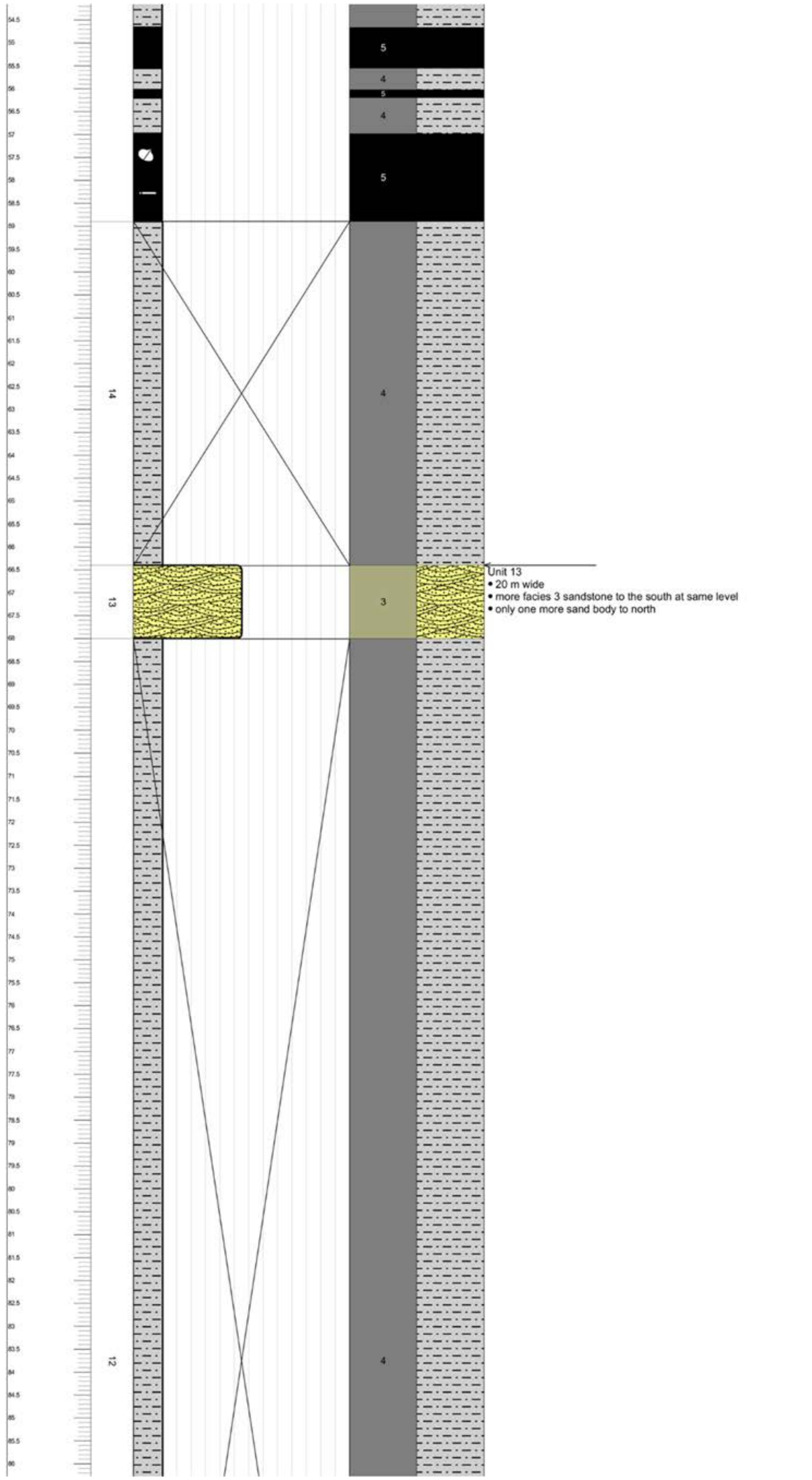

BYU
EasyCore
The EasyCopy Company
Top
0 m
Bottom
85 m
Country
United States
Well Name & No.
Whitney Canyon Haul Road Section
Location
Uintah County, Wyoming
Logged by
Scott Meek
Date
Fri Sep 23 2016
Basin
Green River
Depth (Meters)
Units
Stratigraphic Column
Facies
Lithology
Notes
Base Hilliard Shale
Top Dry Hollow Mbr./ Frontier Fm.
19
18
17
4
2
5
4
5
4
5
4
Unit 19
• assumed to be Hilliard Shale
• top of Frontier section likely missing due to Round Mountain Thrust Fault near base of Unit 19
Unit 18
• thickest part of channel (beds are 0.5-2 m thick)
• laterally continuos for 100's of m
• TCS, but often appears massive
• some soft sediment deformation
• Ophiomorpha and abundant Thalassinoides (on a few bedding planes)
Unit 17
• Kemmerer Coal Zone
• coals; black, gray, green and brown mudstones; siltstones


Unit 16
• same as Unit 12
Unit 14
• TCS and ripple lamination
• extent unknown
Unit 12
• TCS, planar, and ripple lamination and soft sed. deformation
• 0.5 m mud break (sands amalgamate laterally)
• 30 m wide (more sand bodies laterally - higher channel 10 m north)
Unit 10
• lenses of conglomerate in coarse sand
• TCS, convolute bedding
• poorly sorted
• channel bodies pinch and swell over about 30-50 m laterally (this channel = 45 m wide)
• pebble size up to 3 cm
• beds are 20-50 cm thick
• approximate overall thickness (outcrop broken up)

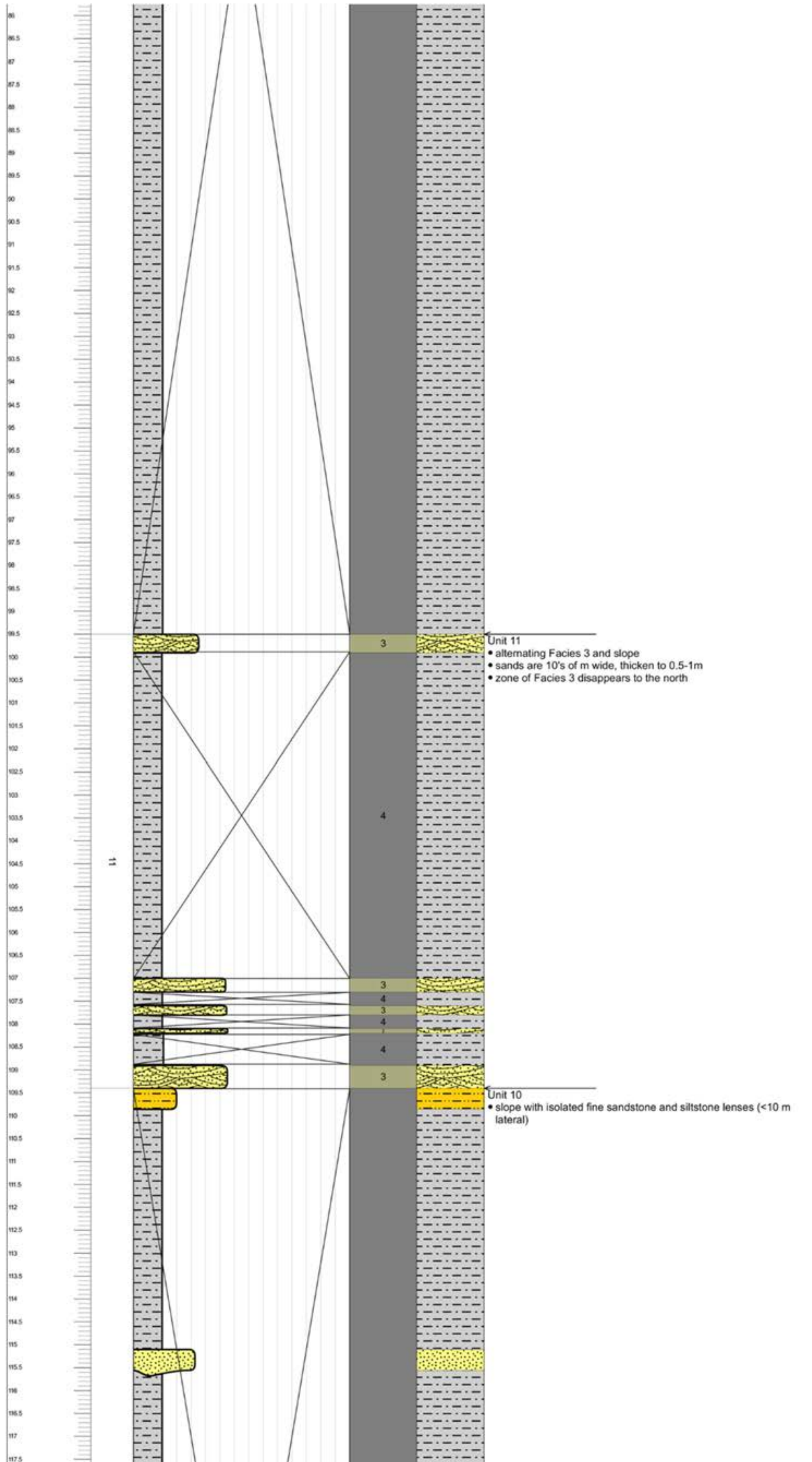

Base Dry Hollow Mbr.
Top Oyster Ridge Mbr.
Unit 8
• same as Unit 6, but with woody and leaf fossils preserved
Unit 6
• massive, laterally accreting beds
• point bar growing southward?
• possible faint TCS
• beds are 5-10 cm
• bar is 15 m wide
• grains are well-sorted and sub-rounded
Unit 4
• highly fractured, sedimentary structures very faint
• same as Unit 2?
Unit 3
• slope - recessive continuation of Unit 2?
• Facies 6 or 2?
Unit 2
• well sorted, clean sand
• 0.2-1 m beds
Unit 1
• massive, laterally extensive oyster beds


EasyCore
The EasyCopy Company
Top
0 m
Bottom
180 m
Country
United States
Well Name & No.
Little Muddy Creek Section 1
Location
Uintah County, Wyoming
Logged by
Scott Meek
Date
Sat Oct 22 2016
Basin
Green River
Depth (Meters)
Units
Stratigraphic Column
Facies
Lithology
Notes
20
19
Base Hilliard Shale
Top Dry Hollow Mbr./ Frontier Fm.
Unit 20
• Hilliard Shale
Unit 19
• isolated, thin facies 3 and slope
• transitioning into Hilliard Shale

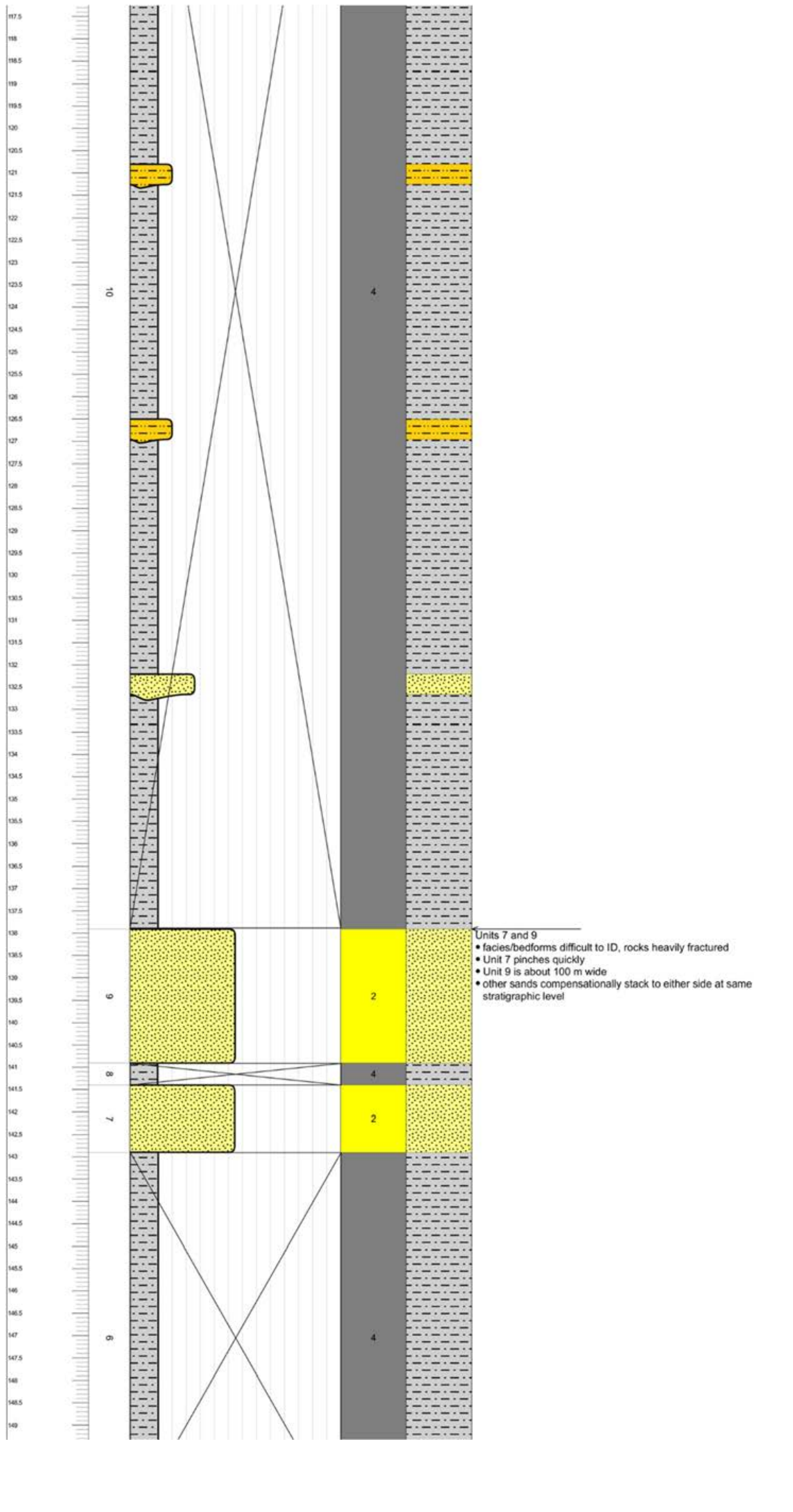

18
17
16
15
3
4
2
4
4
Unit 18
• extends for length of outcrop (1000+ m)
• pinches and swells but almost continuous
Unit 16
• massive/TCS
• very recessive, extent unknown
Unit 15
• Kemmerer Coal Zone
• not all coal, but coal is present here, especially thick toward base of unit
• wood fossils

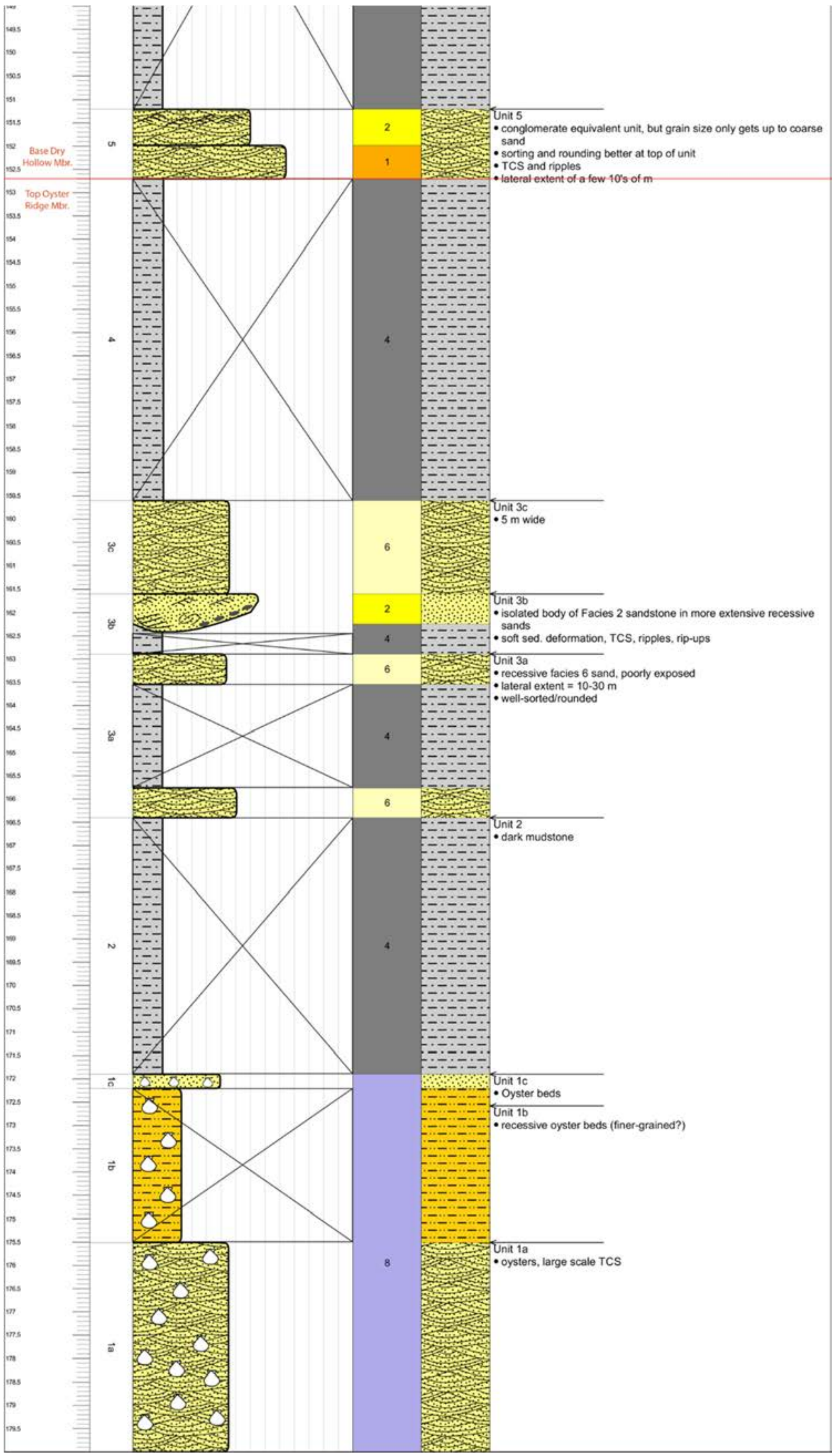


5
4
5
4
5
14
4
Unit 13
• 20 m wide
• more facies 3 sandstone to the south at same level
• only one more sand body to north
13
3
12
4



Unit 11
• alternating Facies 3 and slope
• sands are 10's of m wide, thicken to 0.5-1m
• zone of Facies 3 disappears to the north
11
3
4
3
4
3
4
4
3
Unit 10
• slope with isolated fine sandstone and siltstone lenses (<10 m lateral)


10
4
9
2
8
4
7
2
6
4
Units 7 and 9
• facies/bedforms difficult to ID, rocks heavily fractured
• Unit 7 pinches quickly
• Unit 9 is about 100 m wide
• other sands compensationally stack to either side at same stratigraphic level


Base Dry Hollow Mbr.
Top Oyster Ridge Mbr.
Unit 5
• conglomerate equivalent unit, but grain size only gets up to coarse sand
• sorting and rounding better at top of unit
• TCS and ripples
• lateral extent of a few 10's of m
Unit 3c
• 5 m wide
Unit 3b
• isolated body of Facies 2 sandstone in more extensive recessive sands
• soft sed. deformation, TCS, ripples, rip-ups
Unit 3a
• recessive facies 6 sand, poorly exposed
• lateral extent = 10-30 m
• well-sorted/rounded
Unit 2
• dark mudstone
Unit 1c
• Oyster beds
Unit 1b
• recessive oyster beds (finer-grained?)
Unit 1a
• oysters, large scale TCS

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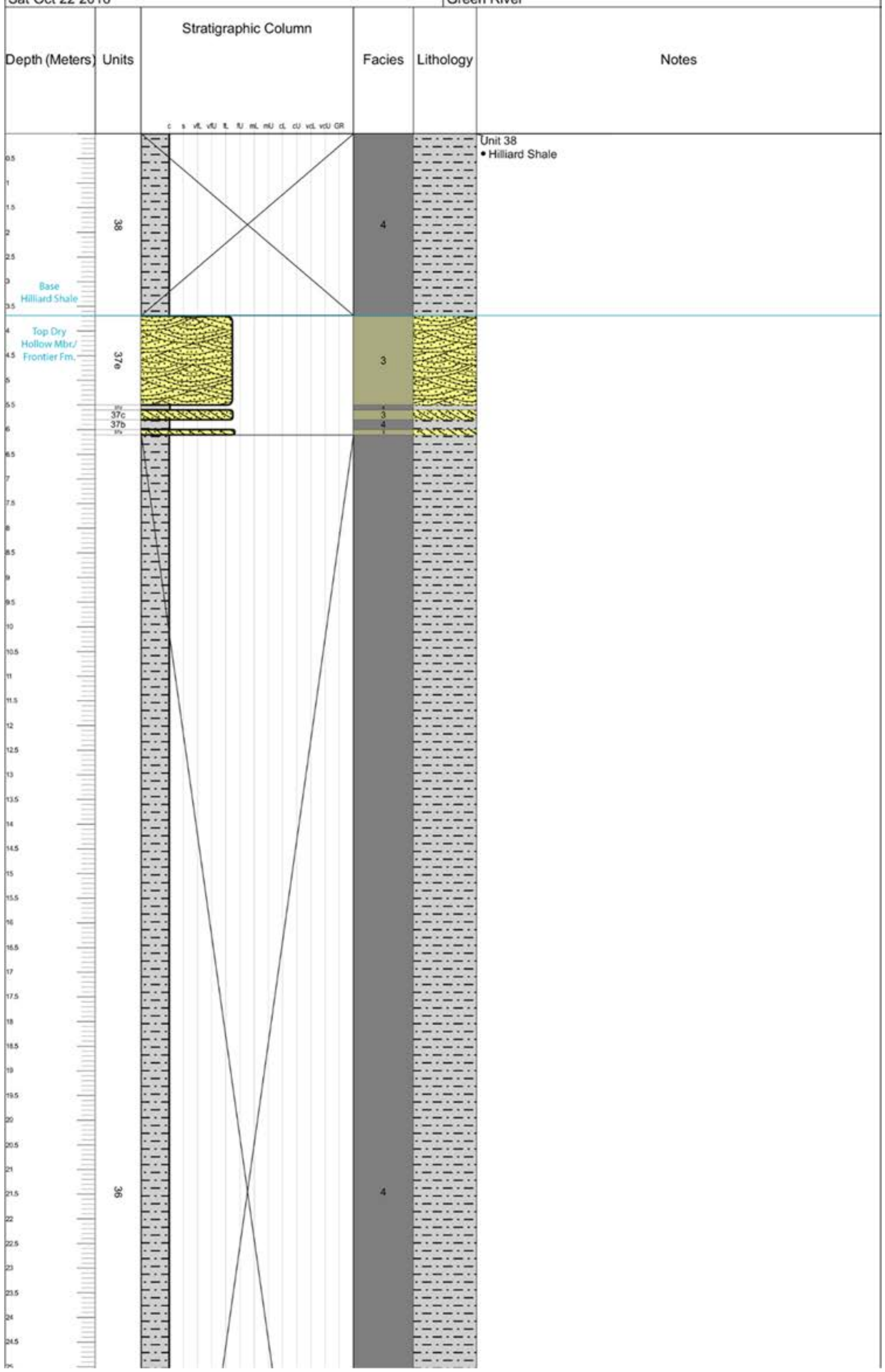
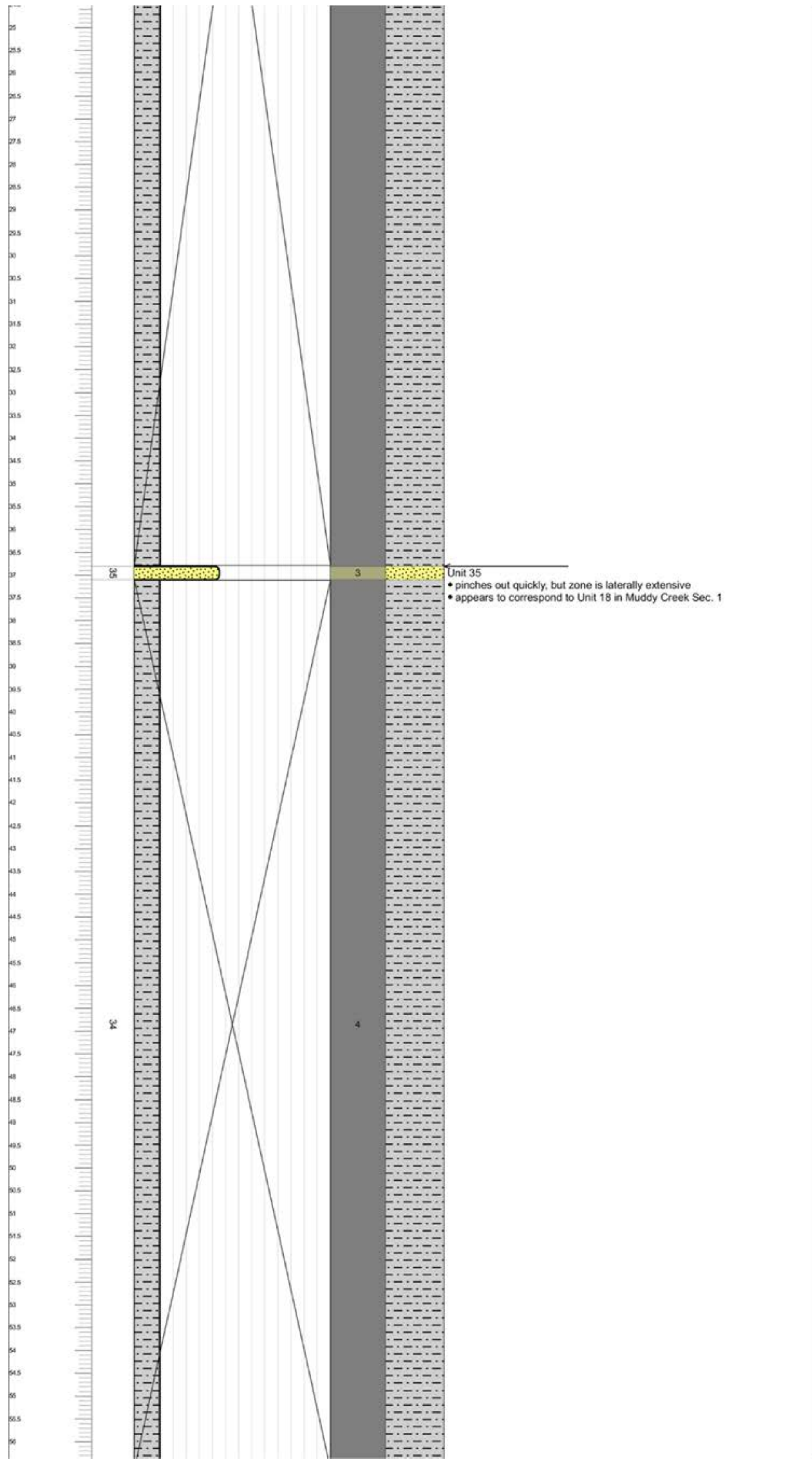
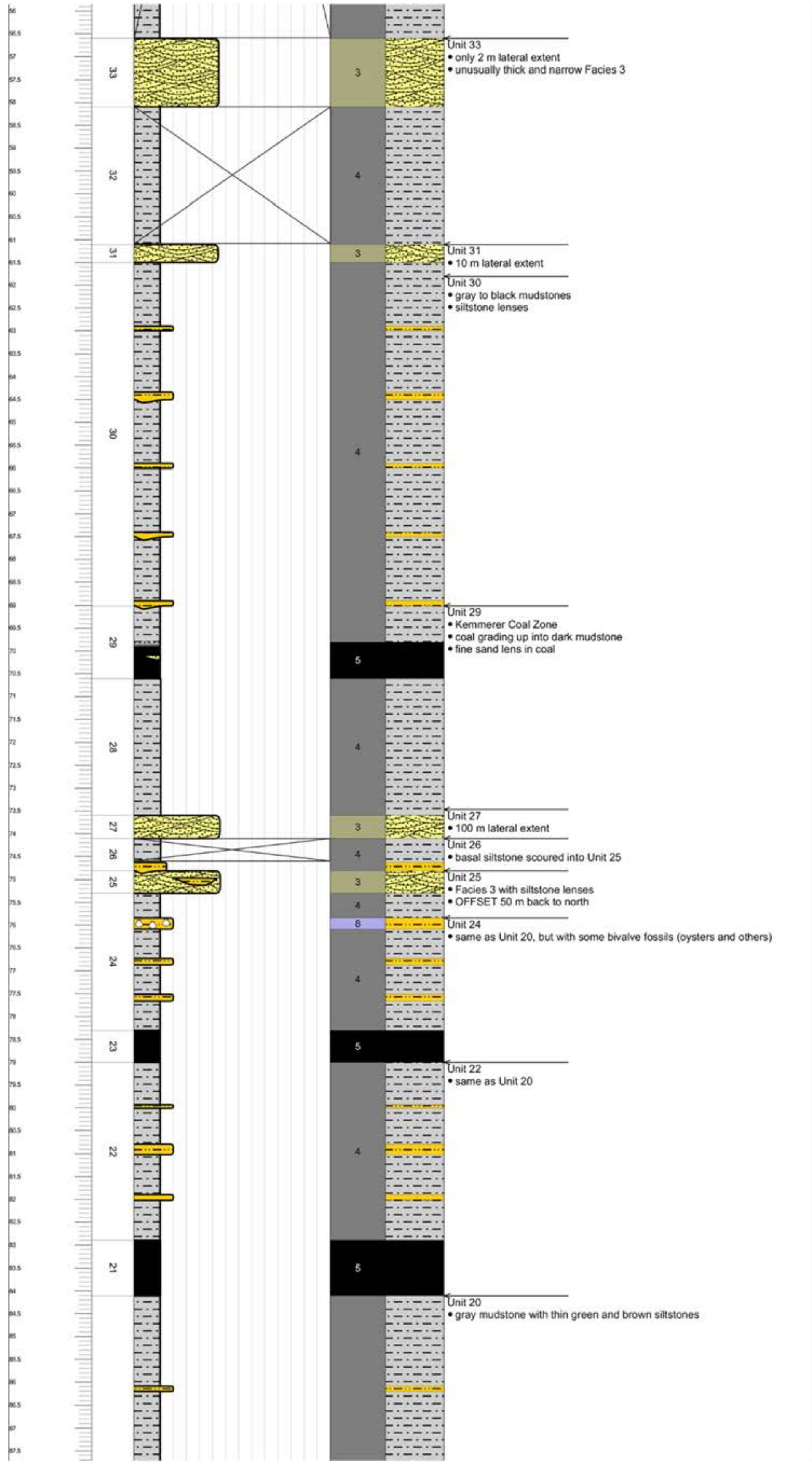
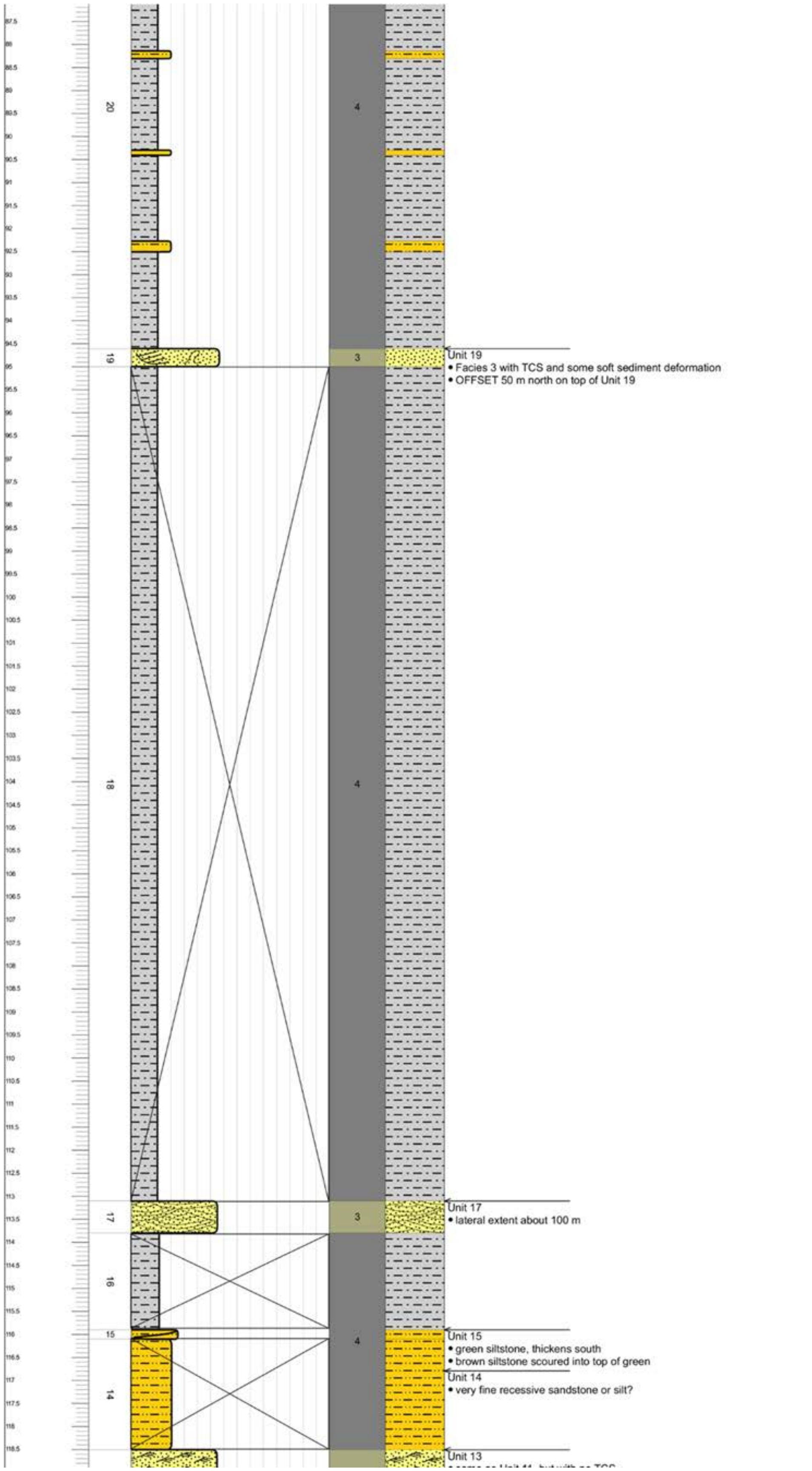
Top 0 m	Bottom 190 m
Country United States	Well Name & No. Little Muddy Creek Section 2
Location Uintah County, Wyoming	Logged by Scott Meek
Date Sat Oct 22 2016	Basin Green River

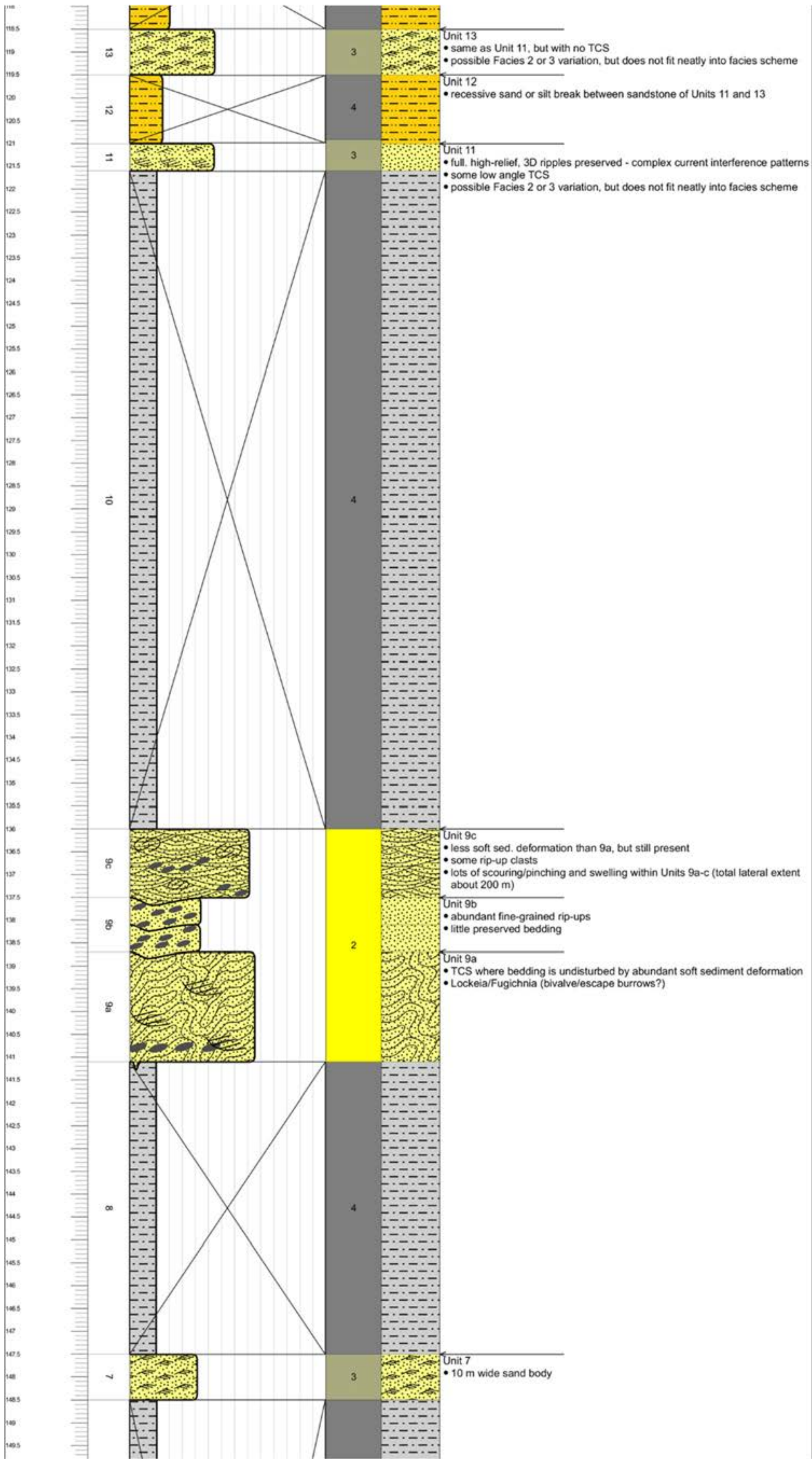


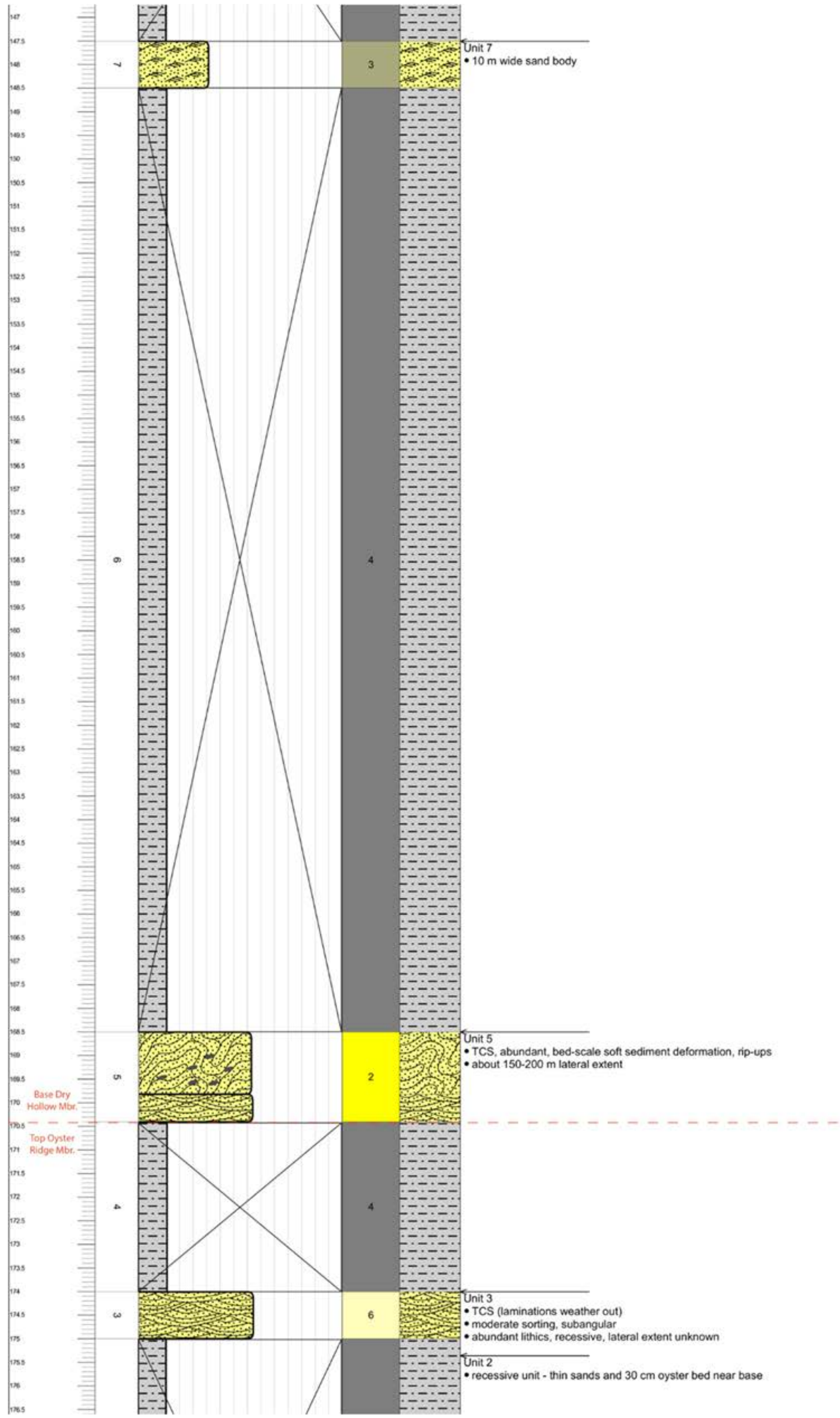

35
3
Unit 35
• pinches out quickly, but zone is laterally extensive
• appears to correspond to Unit 18 in Muddy Creek Sec. 1
34
4

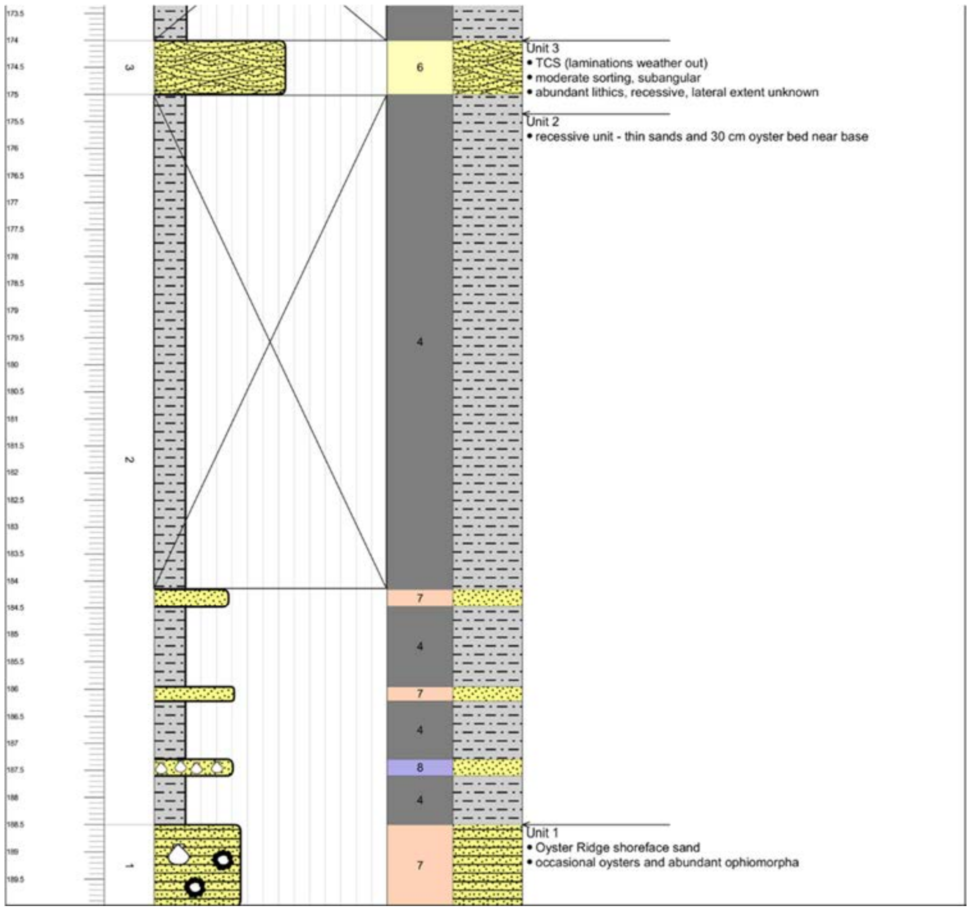


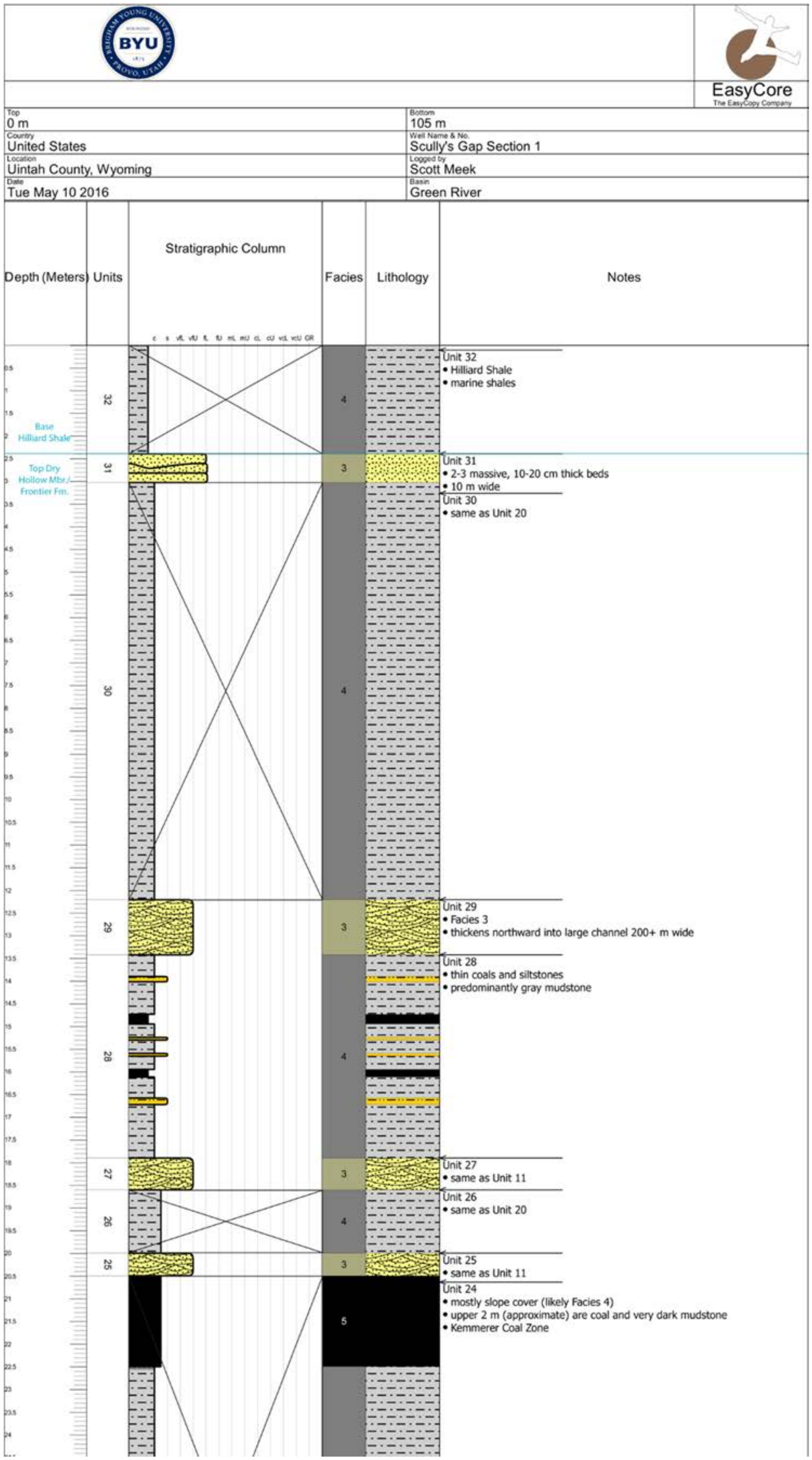
Unit 33
• only 2 m lateral extent
• unusually thick and narrow Facies 3
Unit 31
• 10 m lateral extent
Unit 30
• gray to black mudstones
• siltstone lenses
Unit 29
• Kemmerer Coal Zone
• coal grading up into dark mudstone
• fine sand lens in coal
Unit 27
• 100 m lateral extent
Unit 26
• basal siltstone scoured into Unit 25
Unit 25
• Facies 3 with siltstone lenses
• OFFSET 50 m back to north
Unit 24
• same as Unit 20, but with some bivalve fossils (oysters and others)
Unit 22
• same as Unit 20
Unit 20
• gray mudstone with thin green and brown siltstones

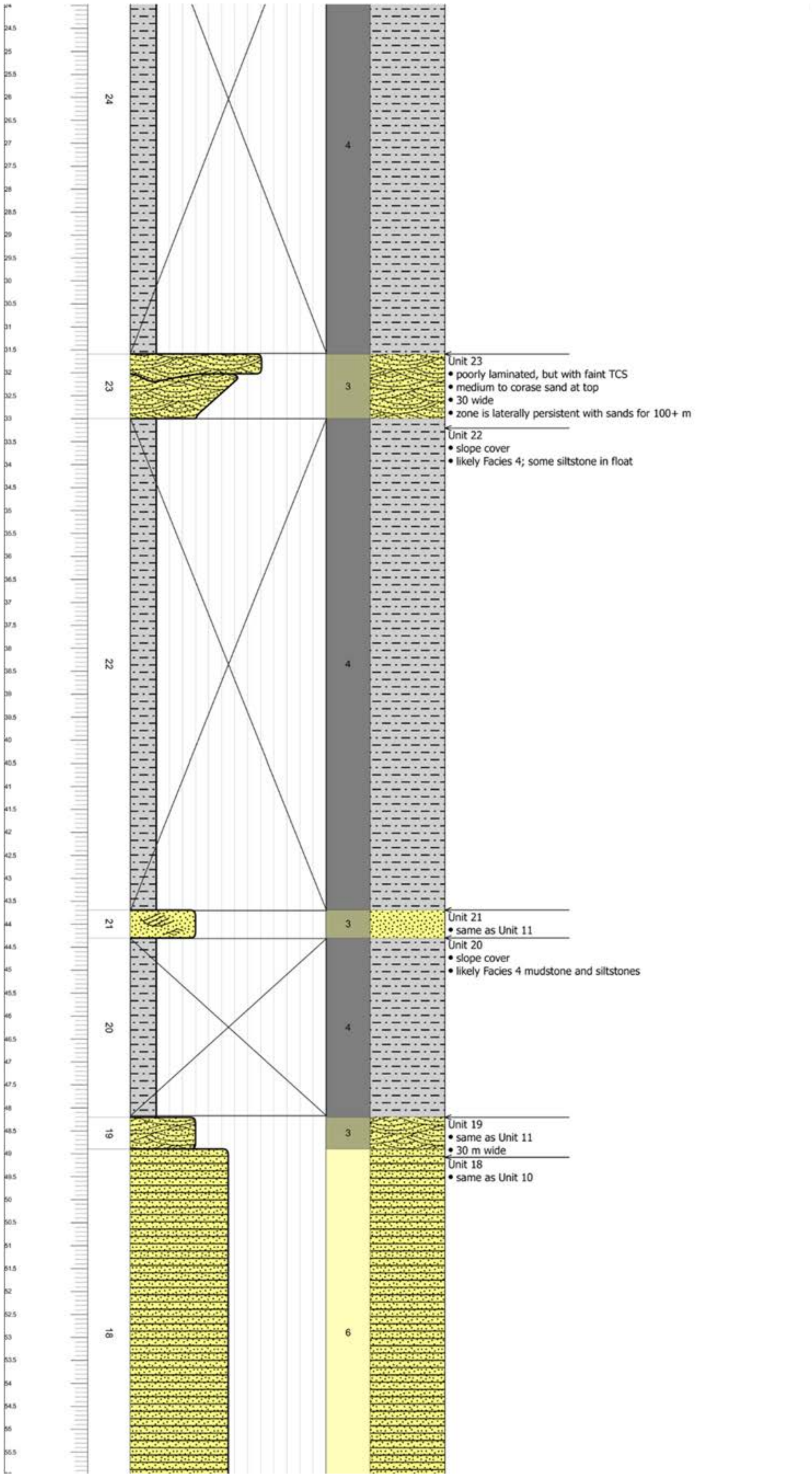

Unit 19
• Facies 3 with TCS and some soft sediment deformation
• OFFSET 50 m north on top of Unit 19
Unit 17
• lateral extent about 100 m
Unit 15
• green siltstone, thickens south
• brown siltstone scoured into top of green
Unit 14
• very fine recessive sandstone or silt?
Unit 13

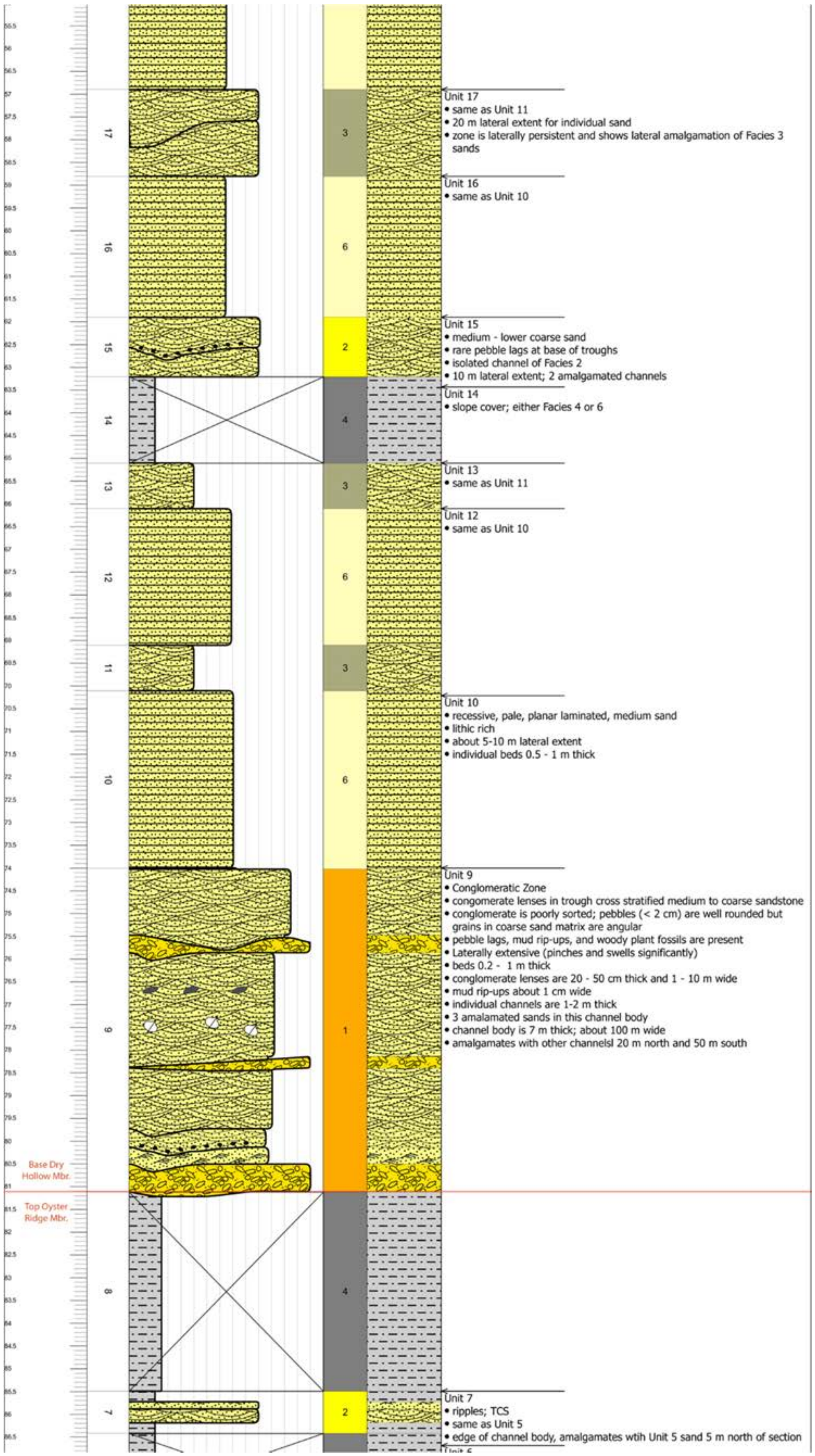

Unit 13
• same as Unit 11, but with no TCS
• possible Facies 2 or 3 variation, but does not fit neatly into facies scheme
Unit 12
• recessive sand or silt break between sandstone of Units 11 and 13
Unit 11
• full. high-relief, 3D ripples preserved - complex current interference patterns
• some low angle TCS
• possible Facies 2 or 3 variation, but does not fit neatly into facies scheme
Unit 9c
• less soft sed. deformation than 9a, but still present
• some rip-up clasts
• lots of scouring/pinching and swelling within Units 9a-c (total lateral extent about 200 m)
Unit 9b
• abundant fine-grained rip-ups
• little preserved bedding
Unit 9a
• TCS where bedding is undisturbed by abundant soft sediment deformation
• Lockeia/Fugichnia (bivalve/escape burrows?)
Unit 7
• 10 m wide sand body
13
12
11
10
9c
9b
9a
8
7

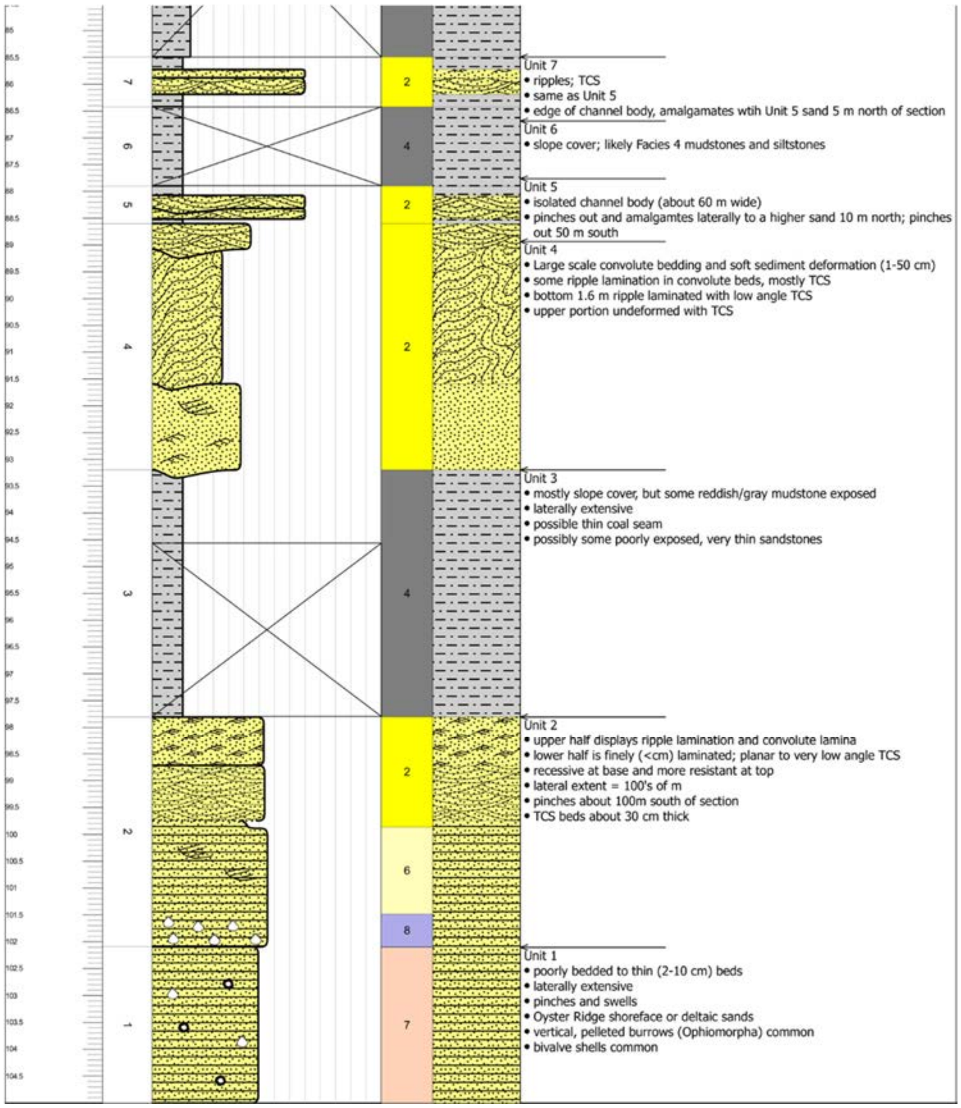

Unit 7
• 10 m wide sand body
Unit 5
• TCS, abundant, bed-scale soft sediment deformation, rip-ups
• about 150-200 m lateral extent
Base Dry Hollow Mbr.
Top Oyster Ridge Mbr.
Unit 3
• TCS (laminations weather out)
• moderate sorting, subangular
• abundant lithics, recessive, lateral extent unknown
Unit 2
• recessive unit - thin sands and 30 cm oyster bed near base


Unit 3
• TCS (laminations weather out)
• moderate sorting, subangular
• abundant lithics, recessive, lateral extent unknown
Unit 2
• recessive unit - thin sands and 30 cm oyster bed near base
Unit 1
• Oyster Ridge shoreface sand
• occasional oysters and abundant ophiomorpha

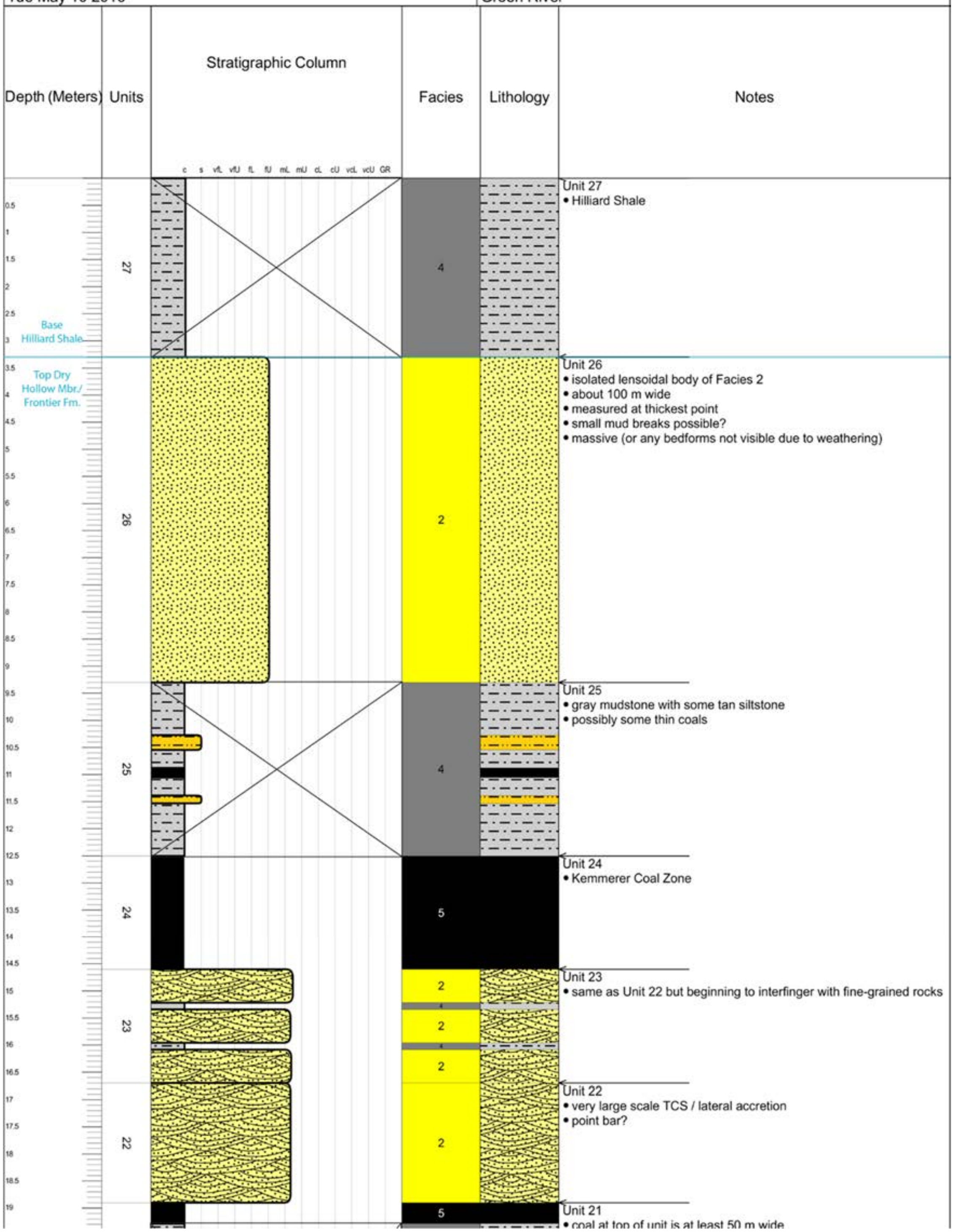

EasyCore
The EasyCopy Company
Top
0 m
Bottom
105 m
Country
United States
Well Name & No.
Scully's Gap Section 1
Location
Uintah County, Wyoming
Logged by
Scott Meek
Date
Tue May 10 2016
Basin
Green River
Depth (Meters)
Units
Stratigraphic Column
Facies
Lithology
Notes
c s vfL vfU fL fU mL mU cL cU vcL vcU GR
Base Hilliard Shale
Top Dry Hollow Mbr./ Frontier Fm.
Unit 32
• Hilliard Shale
• marine shales
Unit 31
• 2-3 massive, 10-20 cm thick beds
• 10 m wide
Unit 30
• same as Unit 20
Unit 29
• Facies 3
• thickens northward into large channel 200+ m wide
Unit 28
• thin coals and siltstones
• predominantly gray mudstone
Unit 27
• same as Unit 11
Unit 26
• same as Unit 20
Unit 25
• same as Unit 11
Unit 24
• mostly slope cover (likely Facies 4)
• upper 2 m (approximate) are coal and very dark mudstone
• Kemmerer Coal Zone

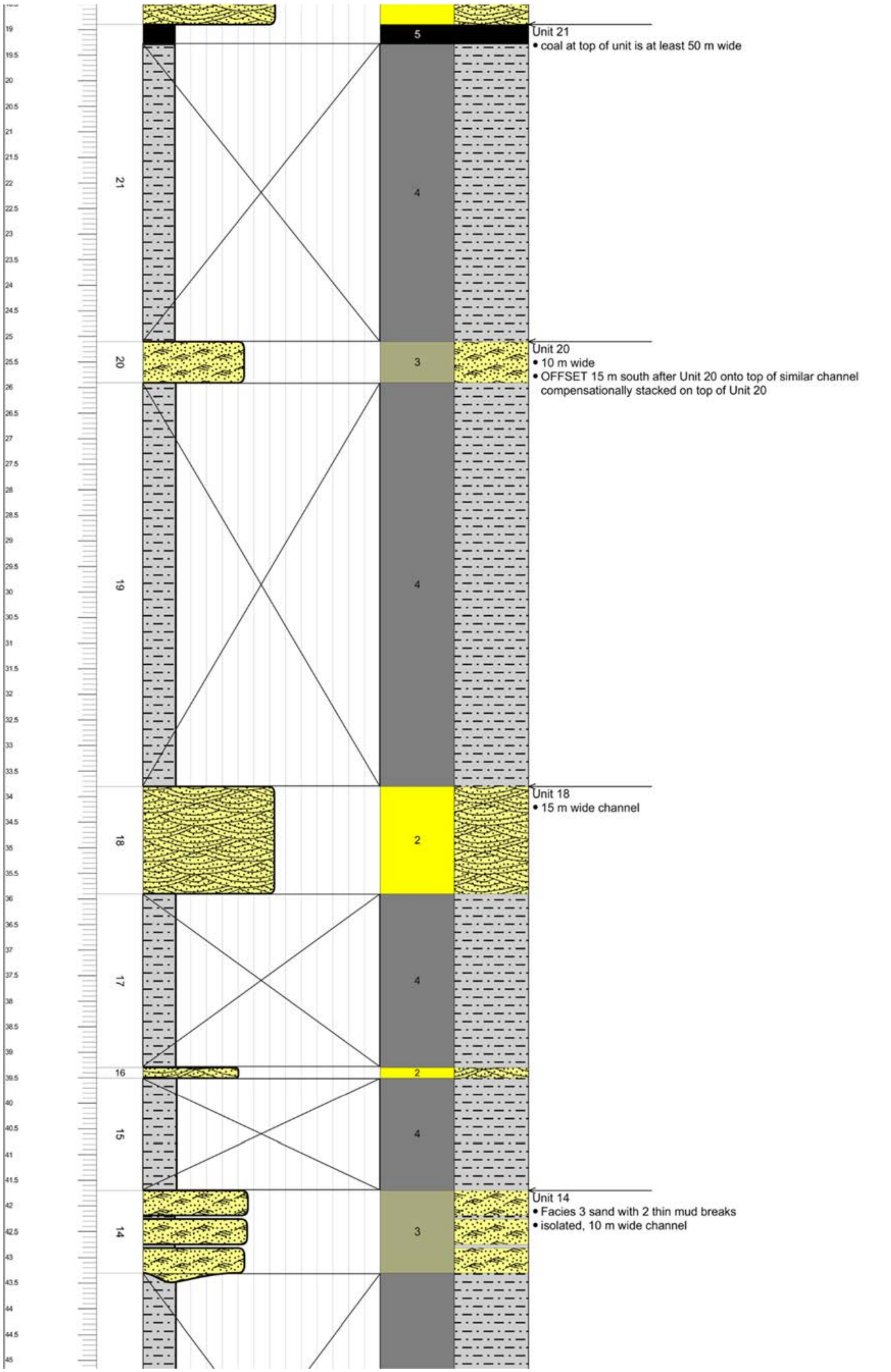

Unit 23
• poorly laminated, but with faint TCS
• medium to corase sand at top
• 30 wide
• zone is laterally persistent with sands for 100+ m
Unit 22
• slope cover
• likely Facies 4; some siltstone in float
Unit 21
• same as Unit 11
Unit 20
• slope cover
• likely Facies 4 mudstone and siltstones
Unit 19
• same as Unit 11
• 30 m wide
Unit 18
• same as Unit 10


Unit 17
• same as Unit 11
• 20 m lateral extent for individual sand
• zone is laterally persistent and shows lateral amalgamation of Facies 3 sands
Unit 16
• same as Unit 10
Unit 15
• medium - lower coarse sand
• rare pebble lags at base of troughs
• isolated channel of Facies 2
• 10 m lateral extent; 2 amalgamated channels
Unit 14
• slope cover; either Facies 4 or 6
Unit 13
• same as Unit 11
Unit 12
• same as Unit 10
Unit 10
• recessive, pale, planar laminated, medium sand
• lithic rich
• about 5-10 m lateral extent
• individual beds 0.5 - 1 m thick
Unit 9
• Conglomeratic Zone
• congomerate lenses in trough cross stratified medium to coarse sandstone
• conglomerate is poorly sorted; pebbles (< 2 cm) are well rounded but grains in coarse sand matrix are angular
• pebble lags, mud rip-ups, and woody plant fossils are present
• Laterally extensive (pinches and swells significantly)
• beds 0.2 - 1 m thick
• conglomerate lenses are 20 - 50 cm thick and 1 - 10 m wide
• mud rip-ups about 1 cm wide
• individual channels are 1-2 m thick
• 3 amalamated sands in this channel body
• channel body is 7 m thick; about 100 m wide
• amalgamates with other channelsl 20 m north and 50 m south
Base Dry Hollow Mbr.
Top Oyster Ridge Mbr.
Unit 7
• ripples; TCS
• same as Unit 5
• edge of channel body, amalgamates wtih Unit 5 sand 5 m north of section

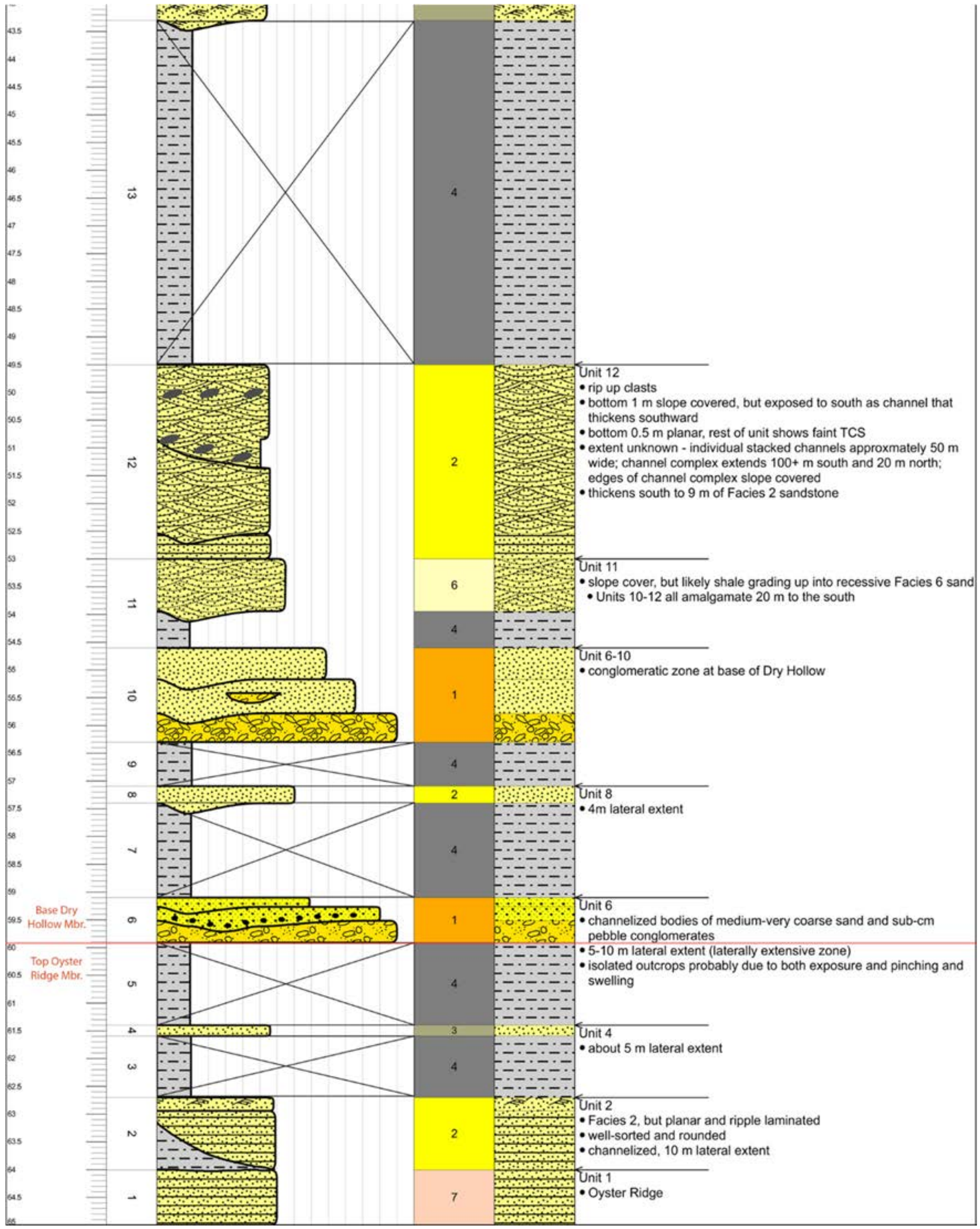

Unit 7
• ripples; TCS
• same as Unit 5
• edge of channel body, amalgamates wtih Unit 5 sand 5 m north of section
Unit 6
• slope cover; likely Facies 4 mudstones and siltstones
Unit 5
• isolated channel body (about 60 m wide)
• pinches out and amalgamtes laterally to a higher sand 10 m north; pinches out 50 m south
Unit 4
• Large scale convolute bedding and soft sediment deformation (1-50 cm)
• some ripple lamination in convolute beds, mostly TCS
• bottom 1.6 m ripple laminated with low angle TCS
• upper portion undeformed with TCS
Unit 3
• mostly slope cover, but some reddish/gray mudstone exposed
• laterally extensive
• possible thin coal seam
• possibly some poorly exposed, very thin sandstones
Unit 2
• upper half displays ripple lamination and convolute lamina
• lower half is finely (<cm) laminated; planar to very low angle TCS
• recessive at base and more resistant at top
• lateral extent = 100's of m
• pinches about 100m south of section
• TCS beds about 30 cm thick
Unit 1
• poorly bedded to thin (2-10 cm) beds
• laterally extensive
• pinches and swells
• Oyster Ridge shoreface or deltaic sands
• vertical, pelleted burrows (Ophiomorpha) common
• bivalve shells common

Top 0 m	Bottom 65 m
Country United States	Well Name & No. Scully's Gap Section 2
Location Uintah County, Wyoming	Logged by Scott Meek
Date Tue May 10 2016	Basin Green River



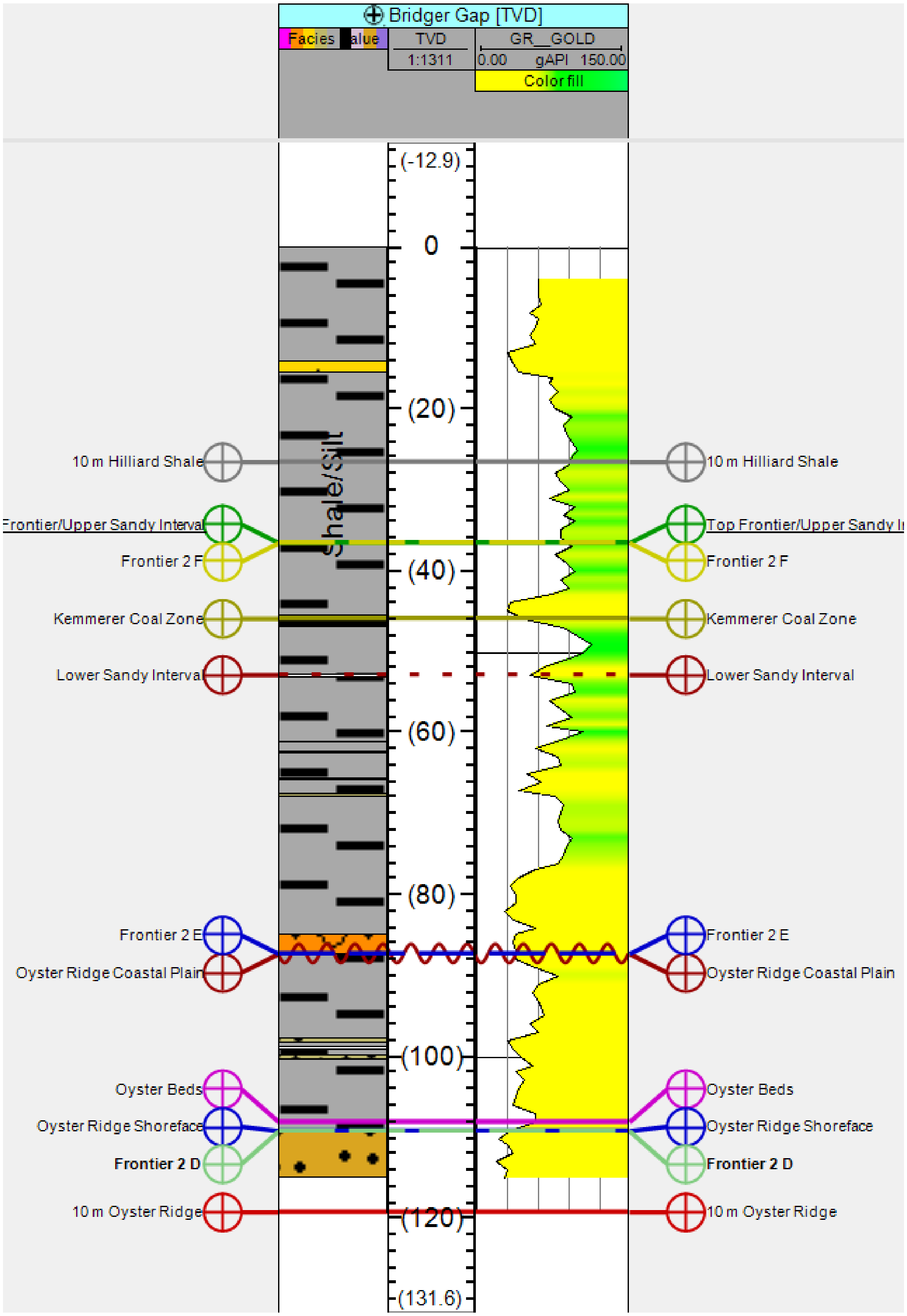


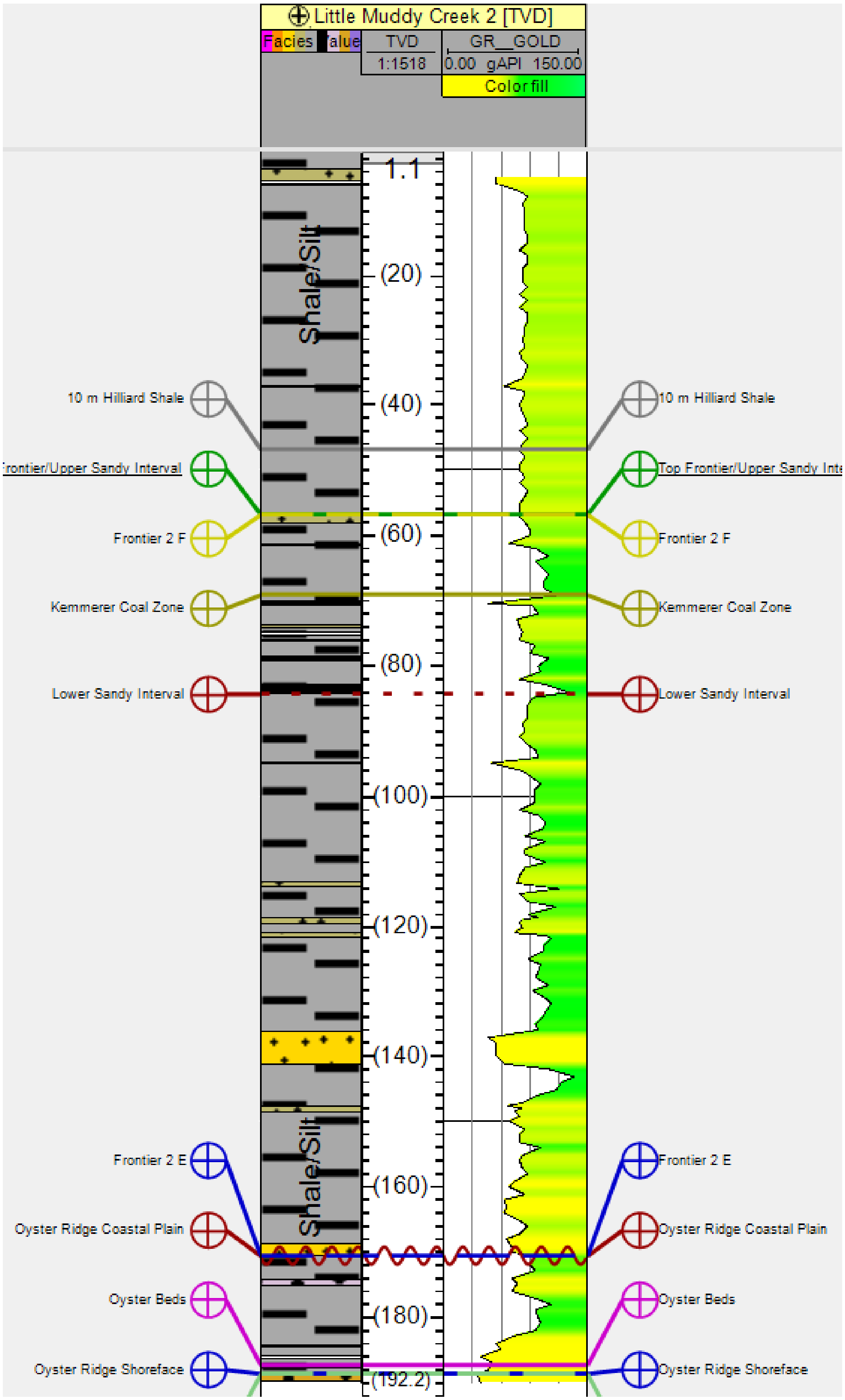
Unit 21
• coal at top of unit is at least 50 m wide
Unit 20
• 10 m wide
• OFFSET 15 m south after Unit 20 onto top of similar channel compensationally stacked on top of Unit 20
Unit 18
• 15 m wide channel
Unit 14
• Facies 3 sand with 2 thin mud breaks
• isolated, 10 m wide channel
21
20
19
18
17
16
15
14
5
4
3
4
2
4
2
4
3

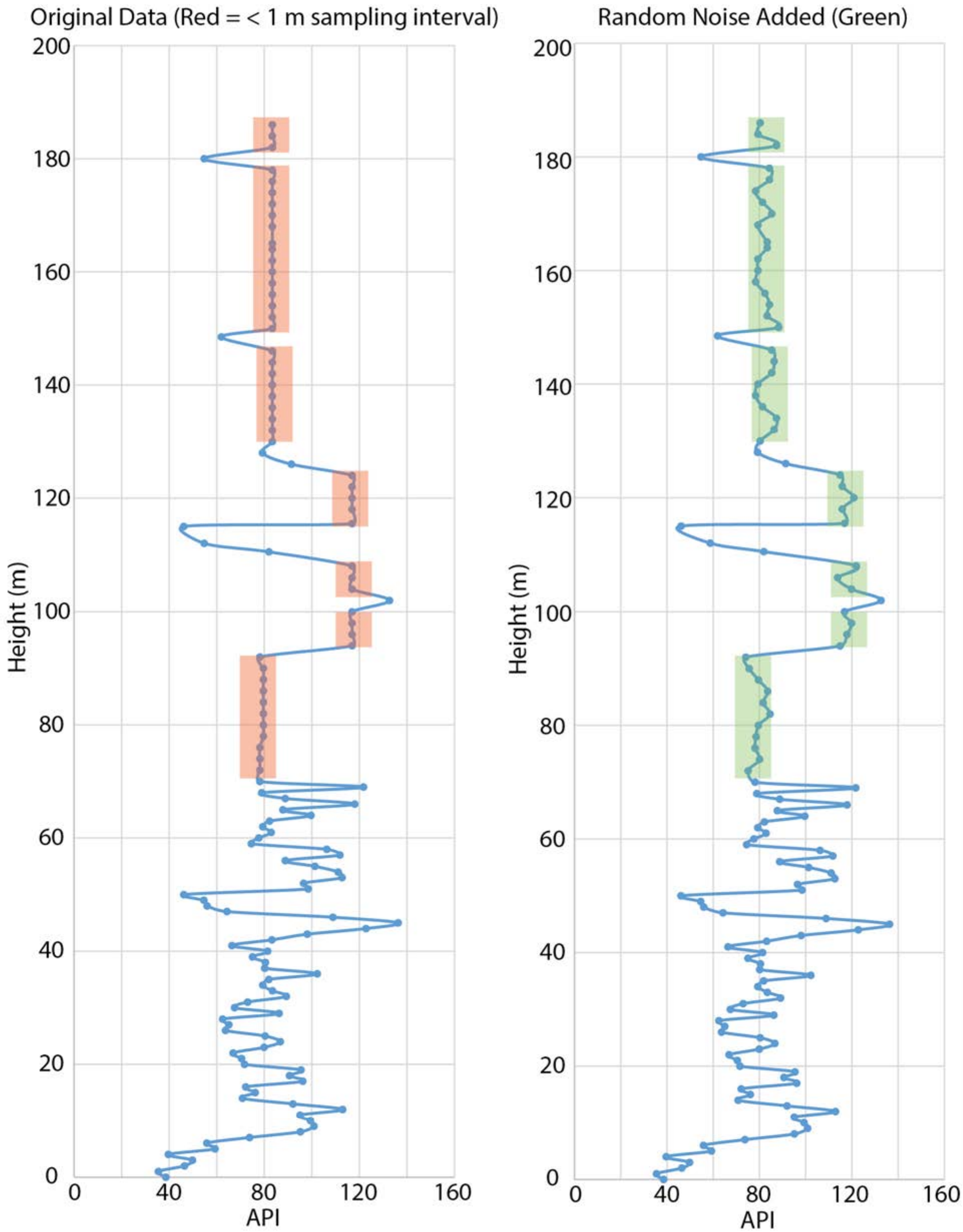

Unit 12
• rip up clasts
• bottom 1 m slope covered, but exposed to south as channel that thickens southward
• bottom 0.5 m planar, rest of unit shows faint TCS
• extent unknown - individual stacked channels approxmately 50 m wide; channel complex extends 100+ m south and 20 m north; edges of channel complex slope covered
• thickens south to 9 m of Facies 2 sandstone
Unit 11
• slope cover, but likely shale grading up into recessive Facies 6 sand
• Units 10-12 all amalgamate 20 m to the south
Unit 6-10
• conglomeratic zone at base of Dry Hollow
Unit 8
• 4m lateral extent
Base Dry Hollow Mbr.
Top Oyster Ridge Mbr.
Unit 6
• channelized bodies of medium-very coarse sand and sub-cm pebble conglomerates
• 5-10 m lateral extent (laterally extensive zone)
• isolated outcrops probably due to both exposure and pinching and swelling
Unit 4
• about 5 m lateral extent
Unit 2
• Facies 2, but planar and ripple laminated
• well-sorted and rounded
• channelized, 10 m lateral extent
Unit 1
• Oyster Ridge

APPENDIX B

GAMMA RAY SPECTROMETER LOGS




Little Muddy Creek 2 [TVD]
Facies
Value
TVD
1:1518
GR__GOLD
0.00 gAPI 150.00
Color fill
1.1
(20)
(40)
(60)
(80)
(100)
(120)
(140)
(160)
(180)
(192.2)
Shale/Silt
Shale/Silt
10 m Hilliard Shale
Top Frontier/Upper Sandy Interval
Frontier 2 F
Kemmerer Coal Zone
Lower Sandy Interval
Frontier 2 E
Oyster Ridge Coastal Plain
Oyster Beds
Oyster Ridge Shoreface

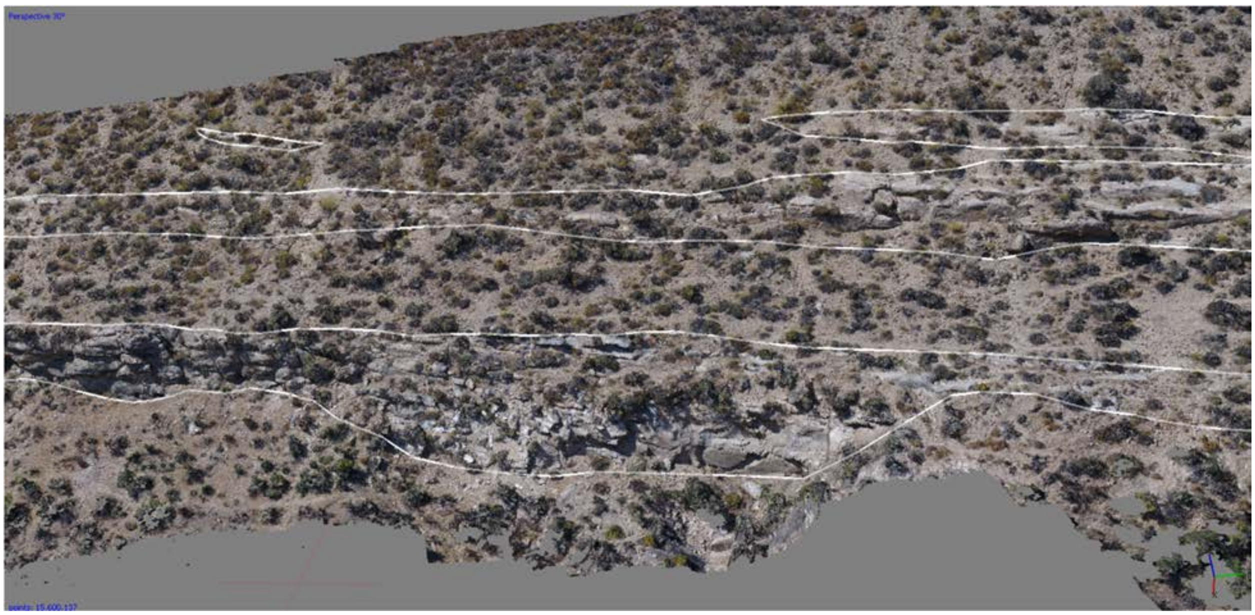


Random noise added to Little Muddy Creek Section 2 to create more realistic profiles where data was sparse (>1 m sampling interval) - noise was based on similar mud-rich units

APPENDIX C

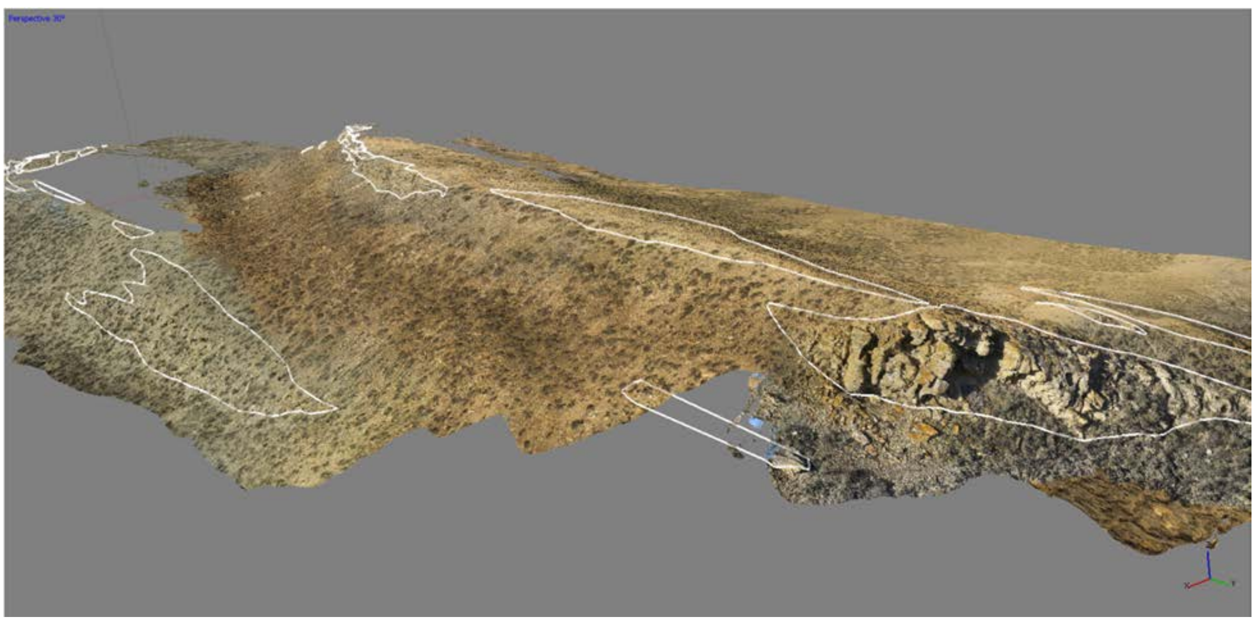
EXAMPLES OF PHOTOGRAMMETRIC MODELS

These images are meant to serve as examples of the photogrammetric models constructed for this study. Only the photogrammetric models from Cumberland Gap were incorporated into the geocellular model in Petrel.

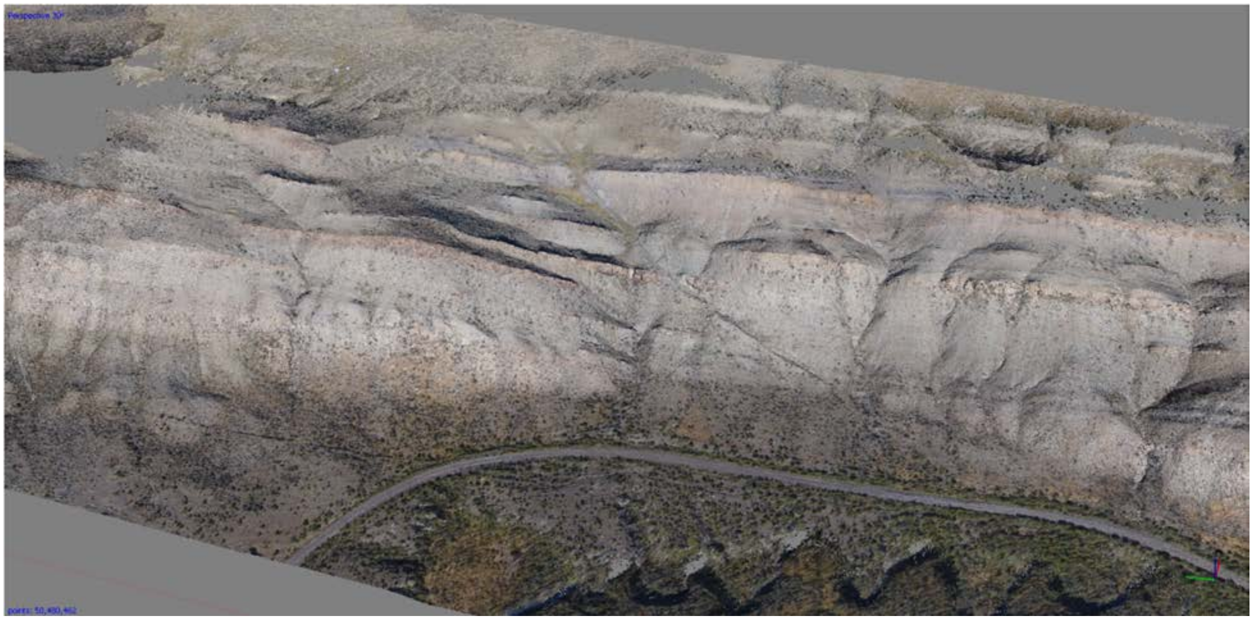


Cumberland Gap (between section 1 and 3)

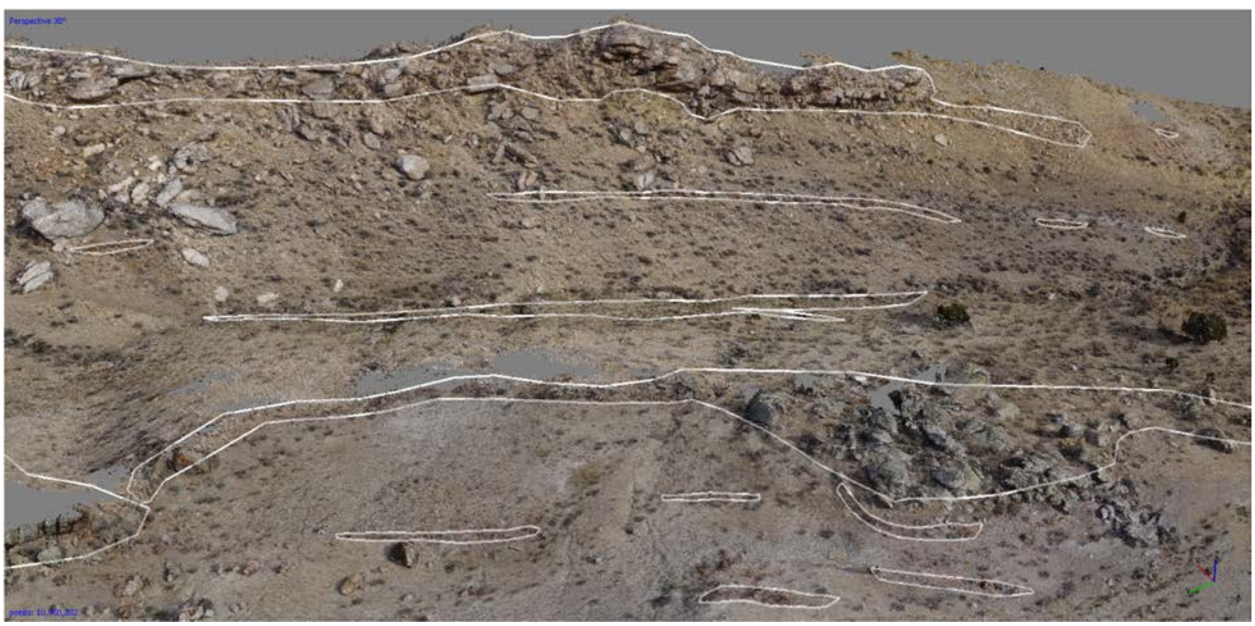
Scully's Gap Section 1 outrops



Cumberland Gap Section 1 and 2 outcrops



Little Muddy Creek outcrop



Whitney Canyon Haul Road outcrop