STRATIGRAPHY OF THE EOCENE GREEN RIVER FORMATION, SOUTHEASTERN UINTA BASIN, UTAH – OUTCROP TO SUBSURFACE CORRELATION

by

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A thesis submitted to the Faculty and Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science (Geology)

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ABSTRACT

A stratigraphic correlation was constructed for the Eocene Green River Formation in the area of the southeastern Uinta basin, Utah that integrated centimeter-to-decimeter scale outcrop and core measurements with 12 well logs. Green River Formation strata from the Uteland Butte tongue to the Mahogany Marker were examined. This correlation connects existing outcrop and subsurface studies and provides facies-to-log calibration for the characteristically unusual log responses of Green River Formation strata. The correlation utilized nine markers that were consistently present in the study area and which tie into existing studies (Hogan, 2015).

Log calibration of lacustrine facies has traditionally been difficult due to facies and stratigraphic complexities. This study utilizes gamma ray assay measurements of described outcrop as well as gamma ray, bulk density, and neutron porosity of described cores to provide a general calibration of log response to facies association. This identified five groupings of calibrated facies associations: FA1 – Fluvial sandstones, FA2/FA6 – Floodplain and littoral mudstones, FA3 – Deltaic deposits, FA4/FA5 – Carbonate deposits, and FA7 – Oil shale. These calibrations are useful in determining facies distribution and depositional environment where the only (or predominant) data source is well logs.

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CHAPTER 1

INTRODUCTION

This study focuses on the Eocene Green River Formation in the southeastern Uinta basin, Utah. The Green River Formation is an excellent example of lacustrine deposits and lake-basin development. It is of interest to industry because it is known to contain large “carbonate-rich, kerogen-bearing shales” (Pitman, 1996) or oil shale deposits in addition to conventional oil and gas deposits.

1.1 – Research Problem

Difficulty in subsurface analysis of the Green River Formation arises from the unconventional and sometime irregular characteristics that the strata show in logs. These irregularities are due in part to unusual distributions and concentrations of organic material and carbonate content in the lacustrine deposits, and the mineralogically immature provenance of the fluvial deposits. These unusual log responses require a more in depth study of the various strata in order to obtain a facies-based log calibration for the various intervals.

1.2 – Previous Work

Stratigraphic descriptions of the Green River Formation in the Uinta basin began as early as the late 19th century. During an expedition of the Yale College Scientific party, Marsh (1871) initially named the Uinta basin (Uintah Basin by his spelling) and described deposits of what we now call the Green River Formation. The first systematic descriptions of Green River stratigraphy were made by Peale (1879) who refers to the Green River Group in the Green River Basin and provides a generalized stratigraphic section.

Woodruff and Day (1915) surveyed the thickness of Green River Formation oil shales in the Uinta Basin and mapped their extent. Winchester (1919) did the same in addition to providing several measured sections. Williams (1950) gives descriptions of the Green River Formation (and surrounding strata) in different regions of the Uinta basin, and includes a geologic map of the Tertiary formations in the Uinta basin.

Dane (1954) provides the first modern stratigraphic correlation of Uinta basin Green River stratigraphy. He measured and correlated 12 sections along the southwestern outcrop belt of the basin. Picard (1955) provides two diagrammatic cross sections (one north-south, one east-west) that stretch across nearly the entire basin. This study introduces and defines the "black shale facies" with a type section and detailed description. Picard also provides a chart correlating the various nomenclatures that were in use up to that point. Picard (1959) focused on the western portion of the basin, provides interpreted logs and additional correlations, and gives an updated nomenclature chart. Cashion (1967) focused mainly on the southeastern portion of the basin and provides detailed discussions of each member of the Green River Formation. This study also gives an isopach for the oil shale deposits of the formation.

Cashion and Donnell (1972) correlate between the Uinta and Piceance Creek basins via a cross section covering 10 locations. Roehler (1974) primarily focuses on Piceance Creek stratigraphy, but includes a diagrammatic chart correlating the Uinta, Piceance Creek, Sand Wash, Washakie, and Green River basins.

Fouch (1975) gives a Uinta-specific cross section running generally north-south across the western portion of the basin. This cross section is a structural cross section and has continued to be utilized to the present day. Fouch also includes a series of maps showing generalized facies distributions at different stratigraphic levels, allowing for some interpretation of environment of deposition.

Ryder et al. (1976) update the nomenclature once again by creating a chart that combines generalized stratigraphy and common nomenclature. They also include three cross sections focused on the western and southwestern portions of the basin.

Moncure and Surdam (1980) shifted focus back to the eastern margin with their correlated measured sections across the Douglas Creek Arch. Scott, Jr. and Pantea (1982) provide a detailed description of the Coyote Wash-1 Core, drilled through nearly 3500 feet of eastern Uinta basin strata.

The Long Point Bed is formally described by Johnson (1984). This study focuses on the Piceance Creek basin, but later studies show the bed to be correlative in the Uinta basin (Johnson, 1985). Johnson (1985) provides a 47-point cross section that correlates the Uinta and Piceance Creek basins. The study also provides detailed discussion of the lake level variability and the influence on sedimentation, as well as a set of facies distribution maps that are interpreted for depositional environment. Johnson et al. (2010) calculated an in-place resource total of 1.32 trillion barrels for the Uinta basin oil shales.

Ruble and Philp (1998) give another update to the nomenclature by including past usages and their correlations on a generalized stratigraphy chart of the Green River Formation. They also include descriptions of the various intervals of the Green River and RockEval data from samples taken from the western portion of the basin.

Keighley et al. (2003) were the first to publish an application of sequence stratigraphic principles to the basin. They measured numerous sections in Nine Mile Canyon (southern margin of the basin) and created a sequence stratigraphic framework for the facies observed. They also created a depositional model for the lakes based on this framework.

Morgan et al. (2003) studied the reservoir properties of a number of intervals in the Green River. This study includes discussion of depositional environment/lake basin development, numerous maps of the various reservoir intervals, and rock property evaluations.

A series of outcrop and core studies characterize most of the recent Uinta basin stratigraphic studies. Schomacker et al. (2010) conducted an outcrop-based study in Nine Mile and Argyle Canyons (southern margin of the basin). The study includes measured sections, facies charts, cross sections, and a depositional model. Birgenheier and Vanden Berg (2011) provide a detailed stratigraphic, sedimentological, and geochemical study based on four cores in a basin-center transect. The four cores examined in this study each come with log suites, so log calibration could be made, however, the focus of their study was on the organic richness of the oil shale itself, and log response was not discussed. O'Hara (2013) studied two sandstone intervals in the Parachute Creek Member of Evacuation Creek (eastern basin margin). The study includes a cross section of the measured sections, detailed facies descriptions, and a model for deposition. Rosenberg (2013) studies Evacuation Creek as well, creating a cross section that incorporates Evacuation Creek with the Asphalt Wash-1 core.

Burton et al. (2014) are the first to attempt to interpret environment of deposition from well logs in the Uinta basin. They remark on the rarity and increased complexity of doing such in a lacustrine setting. The study includes a cross section across a portion of the western basin, calibrated by a measured section from the nearby Hwy 191 road cut in Willow Creek Canyon, although the well logs they use as proxy logs for the measured section are from a well five miles northeast.

Hogan (2015) provides the predecessor to the current study. Two cross sections that extend from a number of eastern margin measured sections out into the basin center are provided, with well log/facies/depositional environment calibration coming from core descriptions (with attendant well logs) and spectral gamma ray assays that were taken on outcrop. The same methods are followed in the current study, and this study is integrated with Hogan (2015).

1.3 – Study Objectives

The four primary objectives of this study are:

(1) Construct an outcrop-to-subsurface correlation of the Green River Formation in the southeastern part of the basin, connecting existing and ongoing outcrop studies to existing basin center and eastern margin studies.

(2) Contribute to a basin-specific facies model to be used in ongoing and further studies of the Green River Formation.

(3) Contribute to a basin-specific log calibration methodology that will allow more accurate correlation of facies with well logs given the unusual nature of Green River Formation log responses.

(4) Contribute to the understanding of the vertical and lateral distribution of fluvial and lacustrine facies along the cross-sections created.

CHAPTER 2

BACKGROUND GEOLOGY

The Uinta basin is found in northeastern Utah and northwestern Colorado. It is separated from the neighboring Piceance Creek basin by the Douglas Creek Arch. The study area for this study is located in southeastern Uinta Basin, extending from the Hay Canyon outcrop in the south (about 20 miles north of I-70; Fig 2.1) to the basin center.

2.1 – Regional Structure

The Uinta basin of NE Utah (Fig. 2.1) was formed during two major orogenic events: the Sevier Orogeny and the Laramide Orogeny. The Sevier Orogeny (100-80 Ma) was primarily thin-skinned, was compressional, and created a relative high to the west ("Meso-Codilleran foothills") and a foreland-basin to the east (Armstrong, 1968; Decelles, 1994; Decelles et al., 1995; Slim, 2007). The highlands were the source for the clastic material (e.g. the fluvial clastics of the Mesaverde Group) and this foreland-basin was the pathway for the Cretaceous Interior Seaway and its associated marine sediments (e.g. the Mancos Shale and the nearshore clastics of the Mesaverde Group).

The Laramide Orogeny (88-40 Ma) was primarily thick-skinned, was also compressional, and created the major uplifts that bound the Uinta basin (Beck et al., 1988; Dickinson et al., 1988; Slim, 2007; Lawton, 2008; Bader, 2009; Davis et al., 2009). These include the Uinta Mountains to the north, the Douglas Creek Arch to the east, the Uncompahgre Uplift to the south, the San Rafael Swell to the southwest, and the Wasatch Mountains to the west (Fig. 2.2).

2.2 – Regional Stratigraphy and Depositional Environment

The Eocene Green River Formation of the Uinta basin is a sequence of carbonate- and organic-rich mudrocks of lacustrine origin interbedded with fluvially-derived sandstones. It provides an excellent example of lacustrine depositional environments and lake-basin development (Fig 2.3). Economically the formation is understood to contain large deposits of oil shale, and in areas where it is mature it is currently being produced for its oil and gas accumulations.

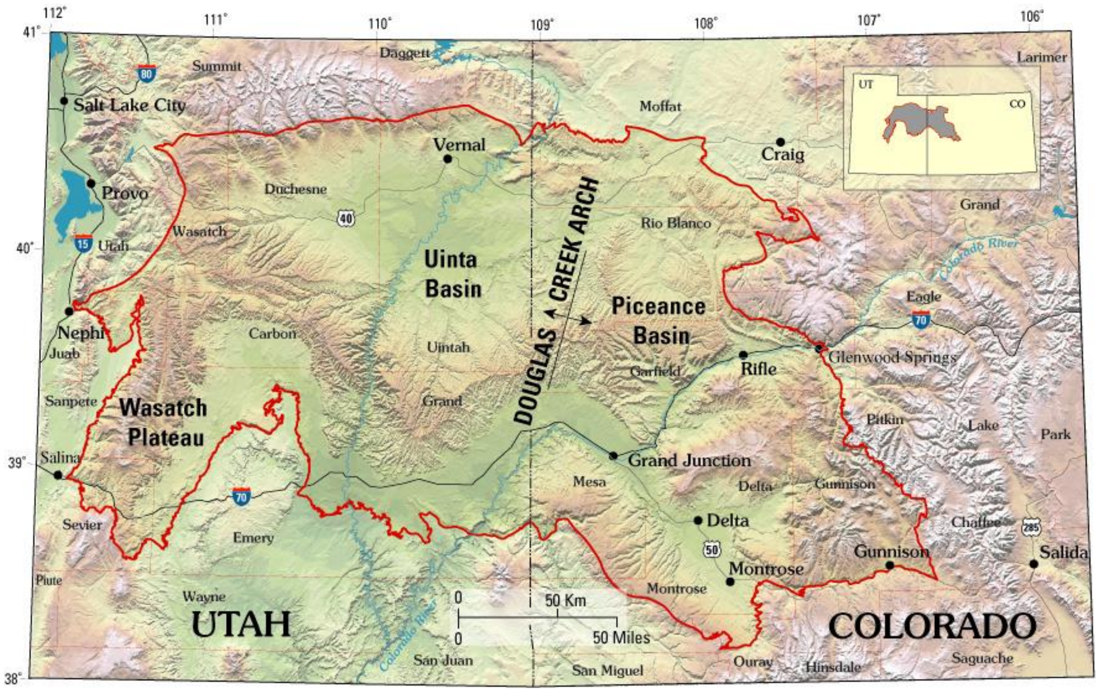

Figure 2.1 - Uinta and Piceance Creek basins (USGS, 2003)

The Green River Formation is bounded by contacts with the Wasatch and Uinta Formations. The lowest portion of the formation is the first major lacustrine transgression, which in the southeast of the basin interfingers with the uppermost Wasatch Formation (Cashion, 1967). The upper boundary of the Green River Formation is marked by the transition of lacustrine oil shales and littoral to sublittoral siliciclastics and carbonates (the uppermost beds of the Green River Formation) to dominantly fluvial sandstones and floodplain mudstones (Cashion, 1967).

The Green River Formation in this area consists of five members: the Uteland Butte member, the Black Shale facies, the Garden Gulch Member, the Douglas Creek Member, and the Parachute Creek Member (Fig. 2.4). The Uteland Butte member is a package of mixed carbonate and siliciclastic deposits representing the first major pulse of lacustrine activity. This is the portion of the Green River Formation that interfingers with the Colton Tongue of the Wasatch Formation. The Black Shale facies was originally defined by Picard (1955) as being dominated by "dark gray or black" shales with "grayish green shales…common in some areas." In Hay Canyon, this interval seems to be dominated by the gray-green shales with dark gray and black shales being more localized. Carbonates are also present in this unit. The Garden Gulch Member is dominated by floodplain mudstones with some fluvial channels. The Douglas Creek Member is dominated by more fluvial deposits, but includes interbeds of carbonate wackestones to grainstones and microbialites along with floodplain and littoral to sublittoral siliciclastics. The Parachute Creek Member is dominated by the characteristic Green River oil shales, sequences of finely laminated, organic rich brown to nearly black mudstones.

The Green River Formation in the basin was deposited during the early to middle Eocene, during which time the basin was filled by Lake Uinta (Fig. 2.3). The currently accepted model for Lake Uinta deposition (including that of the Green River Formation) incorporates a combination of rising and falling lake stages, climatic controls, and lacustrine stratification to explain the strata that are observed (Carroll and Bohacs, 1999; Bohacs et al., 2000; Rhodes, 2002; Keighley et al., 2003; Pietras and Carroll, 2006; Smith et al., 2008; Davis et al., 2009; Buchheim et al., 2012; Tänavsuu-Milkeviciene and Sarg, 2012, Boak et al., 2013; Burton et al., 2014).

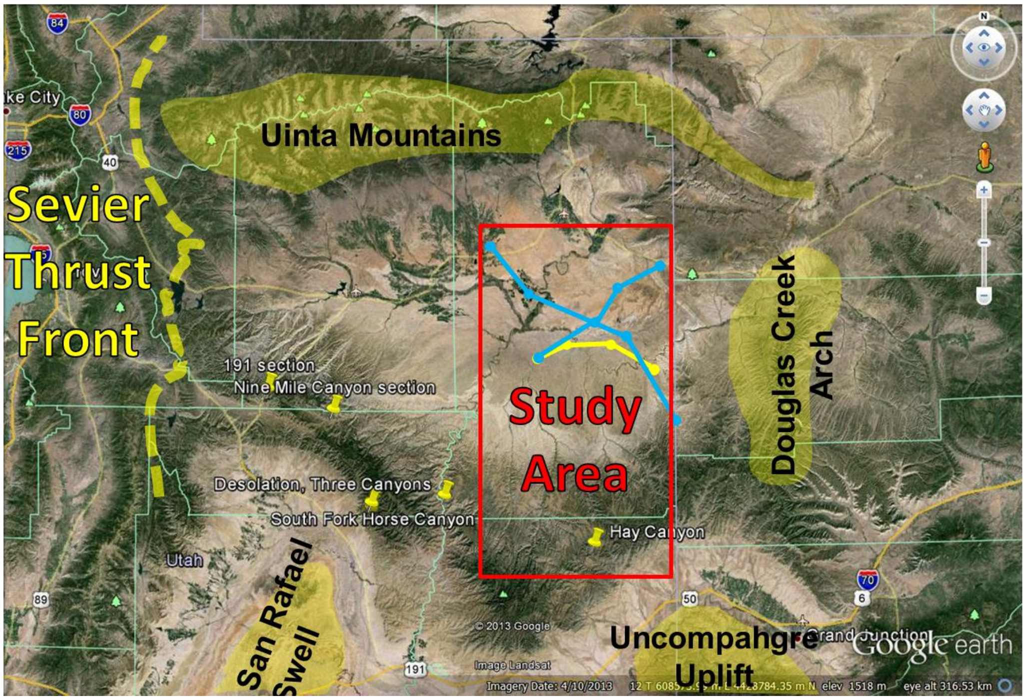

Figure 2.2 - Bounding structures of the Uinta basin with key locations, cross sections that connect to the current study, and the study area for the current study. Blue cross sections are from Hogan 2015; yellow cross section is from Birgenheier and Vanden Berg (2011) (adapted from Google Maps, 2014).

Figure 2.3 - Paleogeographic reconstruction of Lake Uinta (adapted from Blakey, 2009)

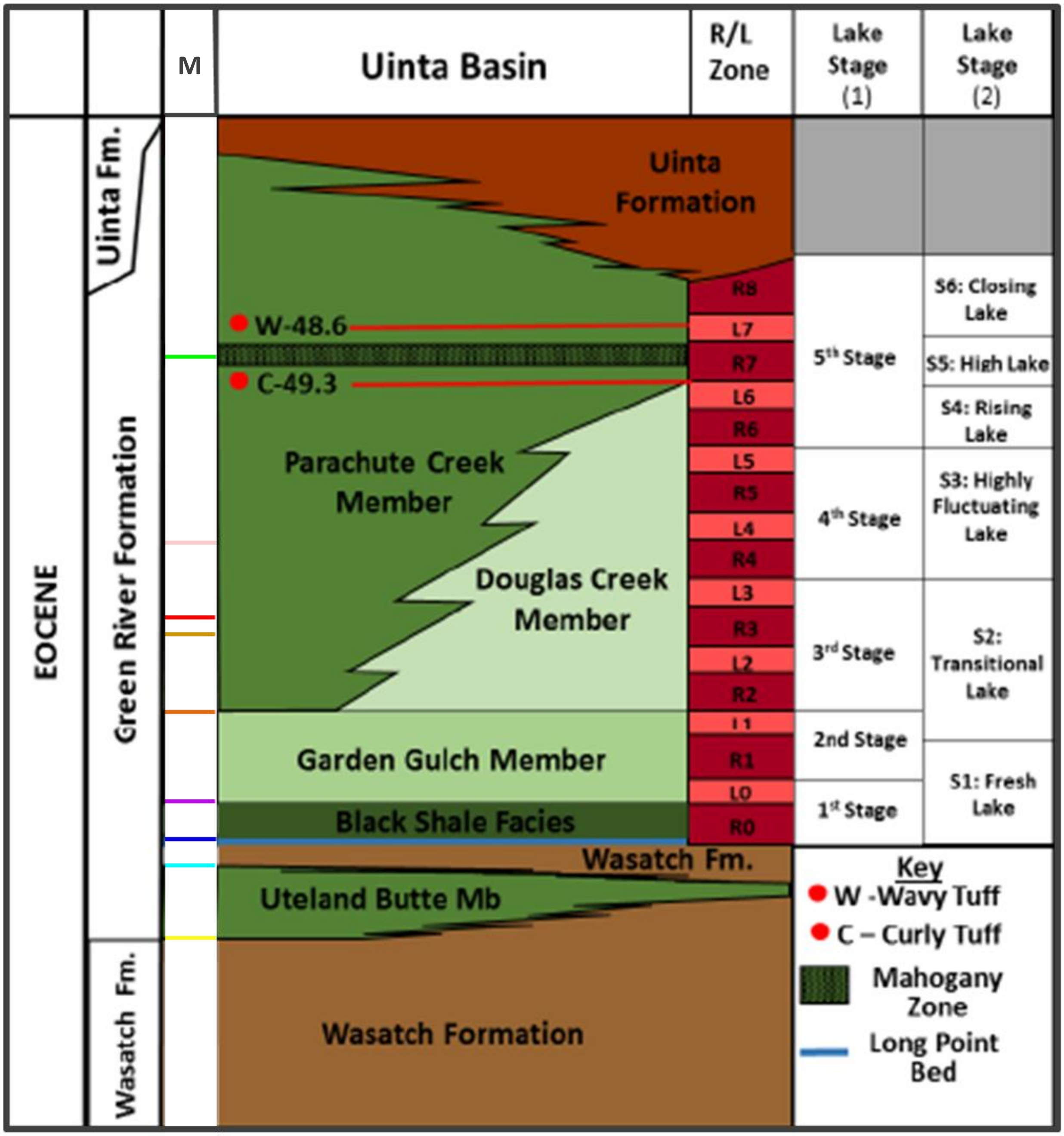

Figure 2.4 - Stratigraphy of the Green River Formation in the Uinta basin with rich and lean zones, and lake stages delineated. Lake Stage (1) after Johnson (1985). Lake Stage (2) after Tanavsuu-Milkeviciene and Sarg (2012). W and C are the ages of the Wavy and Curly Tuffs respectively (after Smith et al., 2008). Colored lines in column "M" represent approximate location of markers used in cross sections C-C' and D-D' (see section 5.2): yellow – Wasatch, cyan – Uteland Butte, blue – Castle Peak, purple – Black Shale, orange – Three Point, brown – Douglas Creek, red – TGR3, pink – Marker 8, green – Mahogany. Adapted from Hogan (2015).

CHAPTER 3

DATA COLLECTION

Primary data for this study were collected from an outcrop measured section, and two described cores, the 11 S Uinta Basin core and the EX-1 Utah core. The outcrop is located in Hay Canyon, Utah, on the southeastern margin of the basin. Both cores are archived at the U.S. Geological Survey Core Research Center. Secondary data was collected from well logs.

3.1 – Study Area

Focus was placed on the southeastern portion of the Uinta basin in order to connect to existing/ongoing studies. Detailed studies of the basin center and eastern margin of the basin have been previously completed (see section 1.2 – Previous Work). Studies of the southern outcrop belt have also been completed, and further studies are ongoing as a part of the CSM Green River Research Consortium. This study connects to the outcrop belt via the Hay Canyon measured section and connects to the basin center/eastern margin via the EX-1 Utah core and multiple shared wells (Fig. 3.1). Correlation of these studies allows for a comparison of facies types and transitions across the southern to eastern margins of the basin.

Stratigraphically, the study focuses on the Green River Formation below the Mahogany Zone. The Mahogany Zone was chosen as an upper limit because much of the overlying section is missing in the southern wells, and the Mahogany Zone and some underlying beds frequently outcrop at the surface to the north of the southern outcrop zone and are missing from the outcrop. Limiting the study to this stratigraphic interval still allows for a correlation of significant Green River Formation stratigraphy.

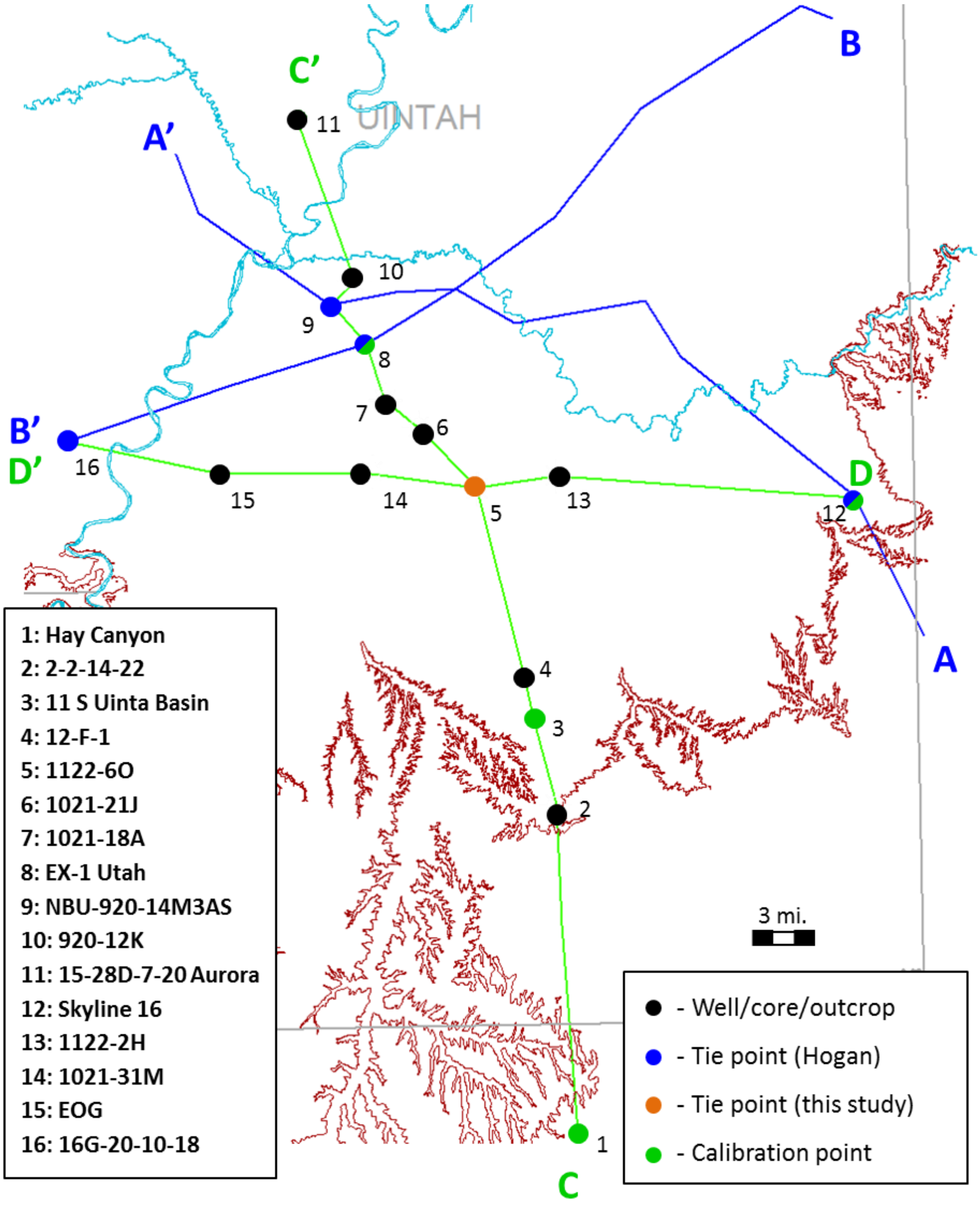

Figure 3.1 - Location of cross sections A-A' and B-B' from Hogan (2015) (in blue); cross sections C-C' and D-D' from the current study (in green). Well names listed by number.

3.2 – Outcrop

An outcrop section was measured and described in Hay Canyon. This section includes strata from the Wasatch/Green River contact to the lower portion of the Douglas Creek Member. Four traverses were made as shown on the map in Fig 3.2.

Most of the section was measured along the road. This method was chosen for two main reasons: accessibility and outcrop quality. Accessibility was an issue for non-road outcrop because of numerous, laterally continuous, cliff/ledge-forming sandstone channels or channel amalgamations in the section (5-10 m high). Some of these channels could be traversed, but some were impassable. Outcrop quality was an issue for non-road outcrop because of the tendency of the mudstones (typical of the lake or floodplain facies) to form extensively weathered talus slopes. Along the road cut, a nearly continuous section of much fresher outcrop could be measured and described.

Measurements were made of each bed (or, in places, bed sets), with detailed facies descriptions included. The resulting lithology log includes 276 described units covering 383.7 m of vertical section (Fig. 3.3a, 3.3b, and 3.4).

A spectral gamma survey was also taken along the majority of the outcrop (Fig. 3.3a). This was conducted with the Radiation Solutions RS125 handheld gamma spectrometer. This tool provides total count as well as counts for potassium, thorium, and uranium, but does not provide an API value.

The survey was taken using 30 second assays every 30 cm within beds, as well as immediately above and below bed contacts. This was to provide complete coverage of the

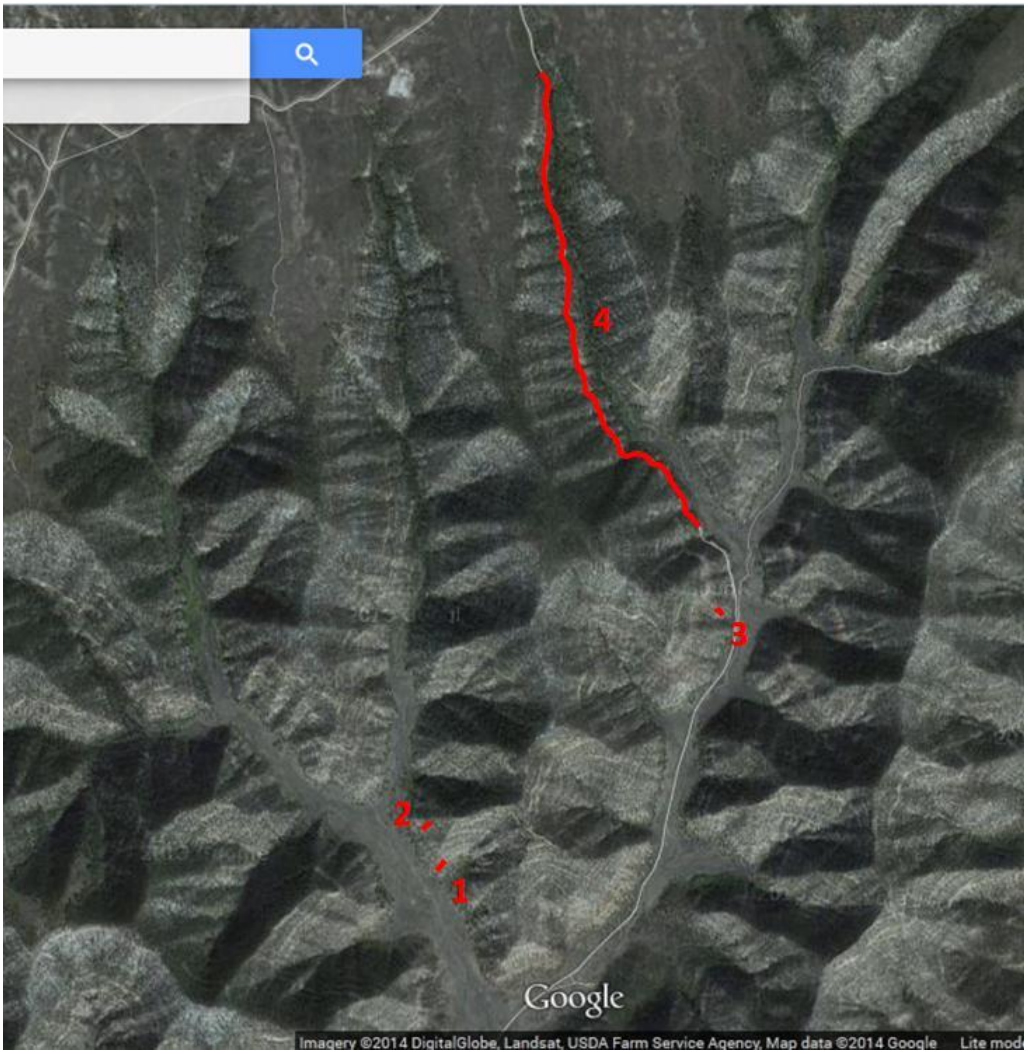

Figure 3.2 - Transects taken in measuring Hay Canyon outcrop (modified from Google Maps, 2014).

section given the 30 cm sensing radius of the tool (Fig. 3.5). Clean surfaces were generally available, but trenching was sometimes required to reach unweathered rock (especially in the mudstones).

From the values provided by the survey, a three-point rolling average was calculated to remove some of the noise. The resulting values were used to construct a total counts per minute (CPM) gamma curve whose curves could be compared to the API gamma curves from the

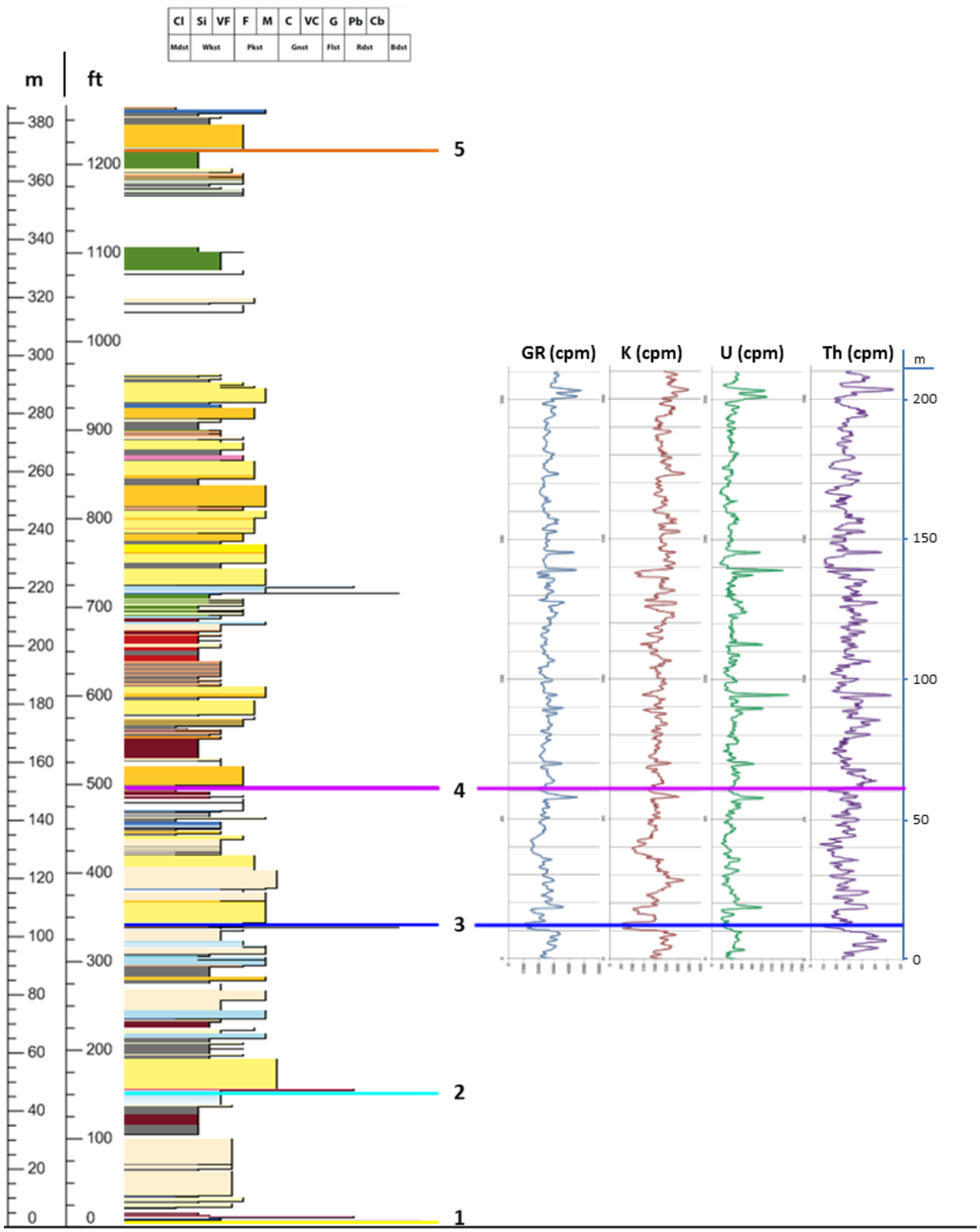

Figure 3.3a - Hay Canyon outcrop measured section. Lithology log is color coded to the CSM Green River Research Consortium's facies model (Fig. 3.2b). Spectral gamma ray logs are included on a counts per minute (cpm) scale. Colored lines represent markers used in cross sections C-C' and D-D' (see section 5.2): 1 – Wasatch, 2 – Uteland Butte, 3 – Castle Peak, 4 – Black Shale, 5 – Three Point.

Figure 3.3b - Legend for Green River Research Consortium facies model used in measured sections.

various wells/cores of the study (since CPM to API values vary for different types of gamma tool, no direct conversion is possible).

3.3 – Core

Two cores were described: the 11 S Uinta Basin core and the EX-1 Utah core. Both of these cores are housed at the US Geological Society Core Research Center in Lakewood, CO.

Figure 3.4 – Hay Canyon outcrop with stratigraphic column; colored lines represent markers used in cross sections C-C' and D-D' (see section 5.2); yellow – Wasatch, cyan – Uteland Butte, blue – Castle Peak, purple – Black Shale; white line represents an observable lithology change in Hay Canyon, but is not a marker used in the cross sections.

The entirety of the 11 S Uinta Basin core was described. The EX-1 Utah core was described from its base to the Mahogany marker bed.

3.3.1 – 11 S Uinta Basin (U682)

This core was taken by the US Energy Research and Development Administration (the predecessor of the Department of Energy [Buck, 1982]). The date is unknown, but the ERDA existed from 1975-1977. The core library number is U682. The core was chosen because it is one of the only cores of significant length between the Hay Canyon outcrop and the basin center.

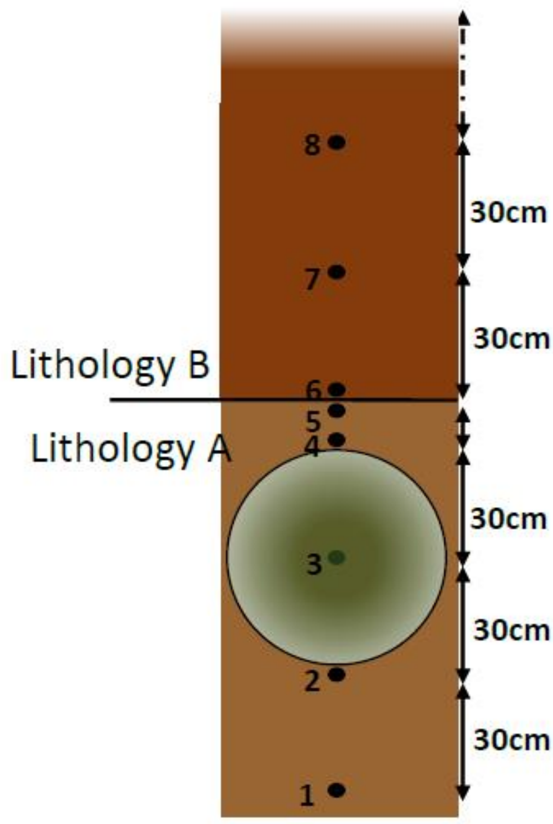

Figure 3.5 - Model of gamma ray assay methodology. Circle indicates the extent of the tool reading. Points 1-8 represent locations where assay measurements re taken. Points 5 and 6 are taken immediately on either side of a lithologic boundary. From Hogan (2015).

The core is ~130 m long, and covers the interval from the Mahogany Zone into the upper Douglas Creek Member. It is predominantly composed of rich and lean oil shale, with occasional siliciclastic interbeds (especially towards to the bottom of the core). Measurements and descriptions were made of each bed (down to a cm-scale resolution), resulting in a lithology log with 190 described units (Fig. 3.6).

This core has very little additional data that accompanies it. There are no log suites available. As the only core of length in the area, it was still desirable to describe this core, but given the lack of logs for calibration, the nearby (~3.7 km) 12-F-1 well (Fig. 3.1) was used as a proxy log suite. This well has gamma ray, bulk density, and sonic logs.

3.3.2 – EX-1 Utah (U631)

This core was taken by the USGS in 1969 (Birgenheier and Vanden Berg, 2011). The core library number is U631. This core was chosen because it covers a significant portion of the stratigraphy under consideration and ties into two previous studies (Birgenheier and Vanden Berg, 2011; Hogan, 2015).

The core is ~370 m long in total, however only ~235 m were described (from the Mahogany Zone to the base). This section covers the stratigraphic interval from the Mahogany Zone down into the upper Douglas Creek Member (between the TGR3 marker and Marker 8; see Hogan [2015] for definition of Marker 8). It is predominantly composed of rich and lean oil shales with some siliciclastic and/or carbonate pulses. The same resolution was used as for the 11 S Uinta Basin core, resulting in a lithology log with 420 described units (Fig. 3.7).

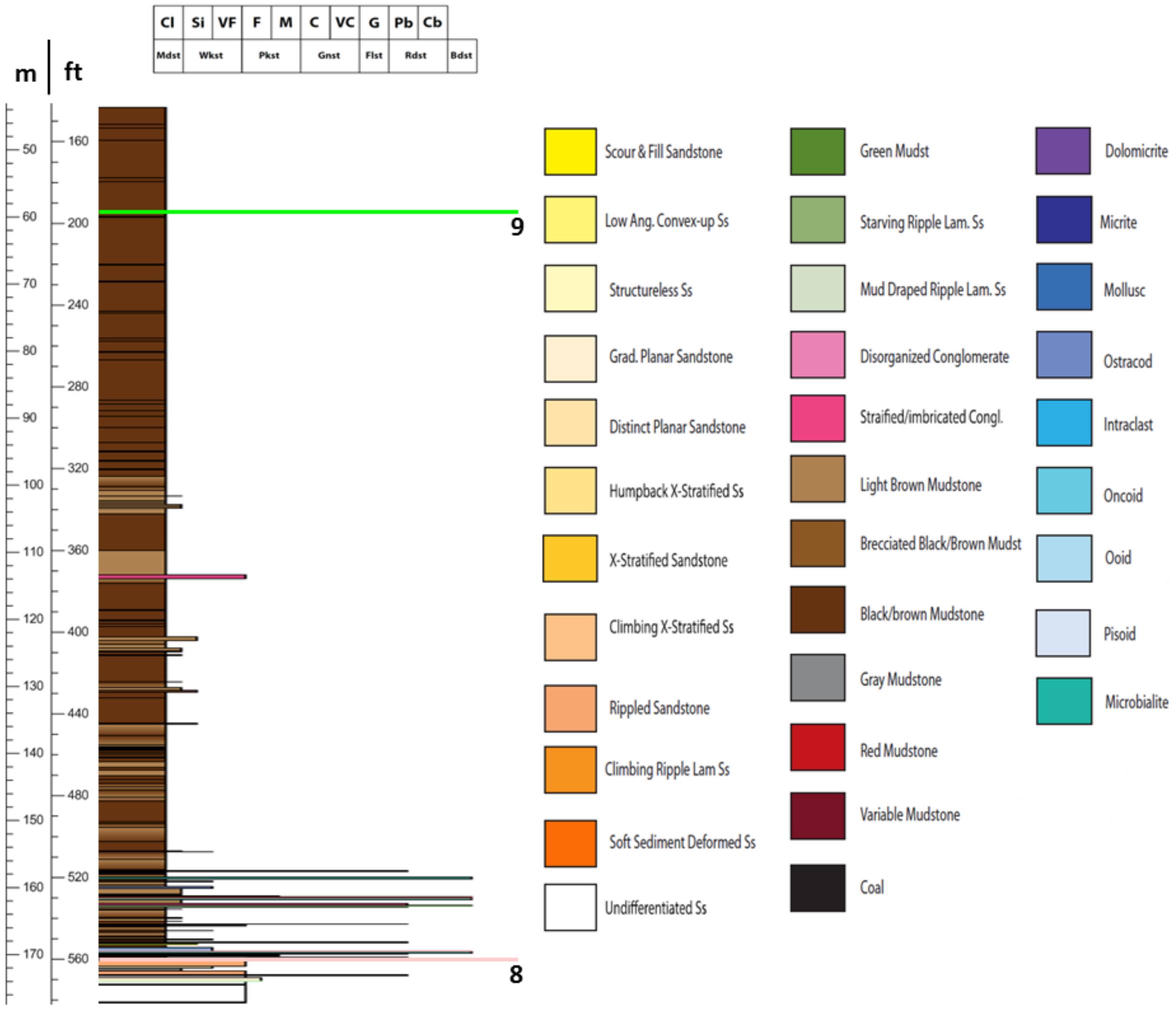

Figure 3.6 – 11 S Uinta Basin core measured section. Lithology log is color coded to the CSM Green River Research Consortium's facies model (legend on right). Colored lines represent markers used in cross sections C-C' and D-D' (see section 5.2): 8 – Marker 8, 9 – Mahogany.

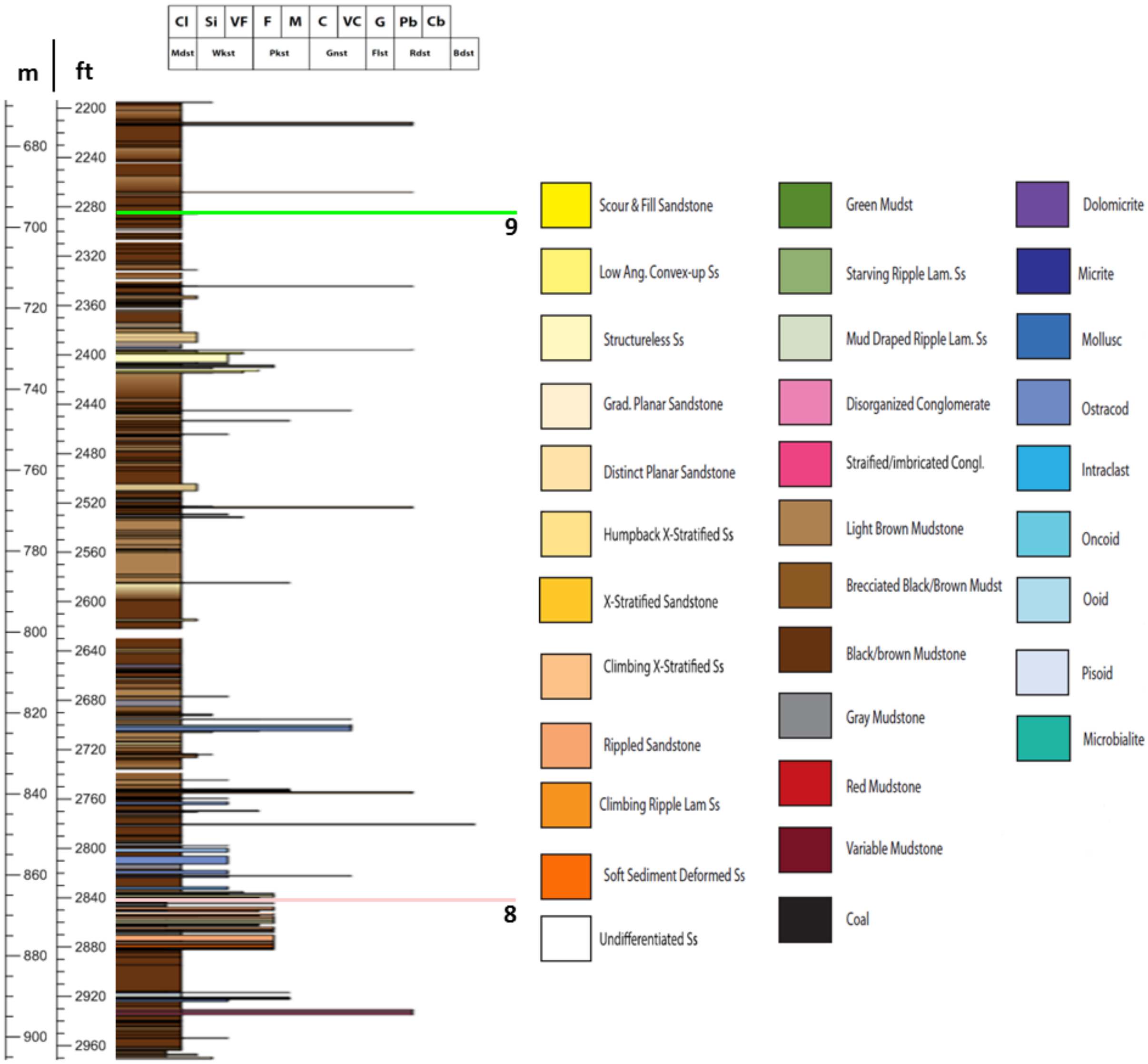

Figure 3.7 - EX-1 Utah core measured section. Lithology log is color coded to the CSM Green River Research Consortium's facies model (legend on right). Colored lines represent markers used in cross sections C-C' and D-D' (see section 5.2): 8 – Marker 8, 9 – Mahogany.

CHAPTER 4

FACIES AND FACIES ASSOCIATIONS

From the detailed core and outcrop descriptions listed in the previous chapter, twenty-nine facies have been identified. These are listed and described in Table 4.1. Seven facies associations are also identified and have been described in this chapter (Table 4.2).

Facies were predominantly distinguished according to lithologic characteristics and sedimentary structures. However, for some of the mudstone facies (specifically F14-F20), color was a primary distinguishing factor. While color is not universally a good indication of depositional environment, in this particular study, variations in color based on oxidation (red and gray to green) are a consistent indicator of subaerial vs. subaqueous deposition for otherwise identical mudstones. Furthermore, variations in the light brown to dark brown/black mudstones provide a consistent indicator of the organic richness of the lacustrine oil shales. These rich/lean variations do not necessarily indicate environment of deposition, but do have implications regarding lake chemistry, and have been used as correlative markers in academic studies and industry (Bill Barrett tops provided via CSM Green River Research Consortium; Tanavsuu-Milkeviciene and Sarg, 2012).

In this CSM Green River Research Consortium facies model, carbonates are defined based on their dominant grain type. Additional grain types are designated via appropriate symbols wherever detailed sections are given; however, in lengthy sections (such as the ones in this study) these symbols are omitted because the scale is too large to include symbols for individual beds.

Table 4.1 - Facies identified in measured sections

#	Facies	Texture/Lithology	Structures	Facies Association
1	Scour and fill sandstone	Fine to medium sand	Scours filled with decreasing angle laminae	FA1
2	Low-angle convex-up sandstone	Fine to coarse sand	Low-angle convex-up laminae, sometimes inclined parallel	FA1
3	Structureless sandstone	Very fine to medium sand	Homogenous, massive	FA1, FA2, FA3
4	Gradational planar laminated sandstone	Fine to coarse sand	Indistinct, graded planar laminae	FA1, FA2, FA3, FA6
5	Distinct planar laminated sandstone	Very fine sand	Distinct planar laminae (few grains thick)	FA2
6	Cross-stratified sandstone	Very fine to coarse sand	Planar or trough-cross stratification	FA1
7	Ripple laminated sandstone	Silt to medium sand	Ripple laminae (asymmetrical and symmetrical)	FA1, FA2, FA3, FA6
8	Climbing ripple laminated sandstone	Very fine to medium sand	Climbing sets of ripple laminae (asymmetrical)	FA1, FA2, FA3
9	Soft sediment deformed sandstone	Very fine sand	Displaced chaotic bedding	FA3
10	Undifferentiated sandstone	Very fine to medium sand	No structures visible due to poor exposure or patina	FA1, FA2, FA3
11	Disorganized conglomerate	Granule to pebble	Matrix to clast supported with no preferred grain orientation	FA1
12	Stratified/imbricated conglomerate	Granule to pebble	Matrix to clast supported with preferred grain orientation	FA1
13	Mud-draped ripple laminated sandstone	Fine sand	Ripple laminae with mud drapes	FA1, FA2
14	Green mudstone	Clay to silt	Usually finely laminated; sometimes soft-sediment deformed (pillow and ball structures common); often contain burrow traces that in outcrop are rust-colored	FA6
15	Gray mudstone	Clay to silt	Usually finely laminated; sometimes soft-sediment deformed (pillow and ball structures common)	FA2, FA3
16	Red mudstone	Clay to silt	Usually finely laminated; sometimes soft-sediment deformed (pillow and ball structures common); sometimes massive	FA2

#	Facies	Texture/Lithology	Structures	Facies Association
17	Variable mudstone	Clay to silt	Variations of red to gray; usually finely laminated; sometimes soft-sediment deformed (pillow and ball structures common); sometimes massive	FA2
18	Black/brown mudstone	Clay to silt; sometimes contains carbonate grains	Usually finely laminated; laminations occasionally wavy, rippled, or scoured	FA7
19	Brecciated black/brown mudstone	Clay to silt	Usually disorganized conglomerate in the granule to pebble clast size range	FA7
20	Light brown mudstone	Clay to silt; sometimes contains carbonate grains	Usually finely laminated; laminations occasionally wavy, rippled, or scoured	FA7
21	Coal	N/A	Some poor quality section near bed boundary, but high quality coal in center; cleats present	FA2
22	Micritic carbonate	Micrite	Massive with some fractures	FA5
23	Molluscan carbonate	Wacke- to packstone; frequently contains other carbonate and/or siliciclastic grains	Massive or gradational planar laminae	FA5
24	Ostracod-bearing carbonate	Wacke- to grainstone; frequently contains other carbonate or siliciclastic grains	Massive or gradational planar laminae	FA5
25	Intraclastic carbonate	Wacke- to packstone; frequently contains other carbonate or siliciclastic grains	Massive	FA5
26	Ooid-bearing carbonate	Wacke- to grainstone; frequently contains other carbonate or siliciclastic grains	Massive, gradational planar laminae, or occasionally ripple laminae	FA5

#	Facies	Texture/Lithology	Structures	Facies Association
27	Pisoid-bearing carbonate	Packstone	Massive	FA5
28	Microbialite	Boundstone with algal mats or heads; frequently with other carbonate grains as a matrix	Mats and/or domes with finely laminated, dendritic, and/or thrombolitic textures	FA4

Table 4.2 - Summary of facies associations

Facies Association	General Description	Included Facies
FA1-Fluvial channels	Channel/amalgamated channel sandstones with high to moderate flow regime structures	1, 2, 3, 4, 6, 7, 8, 10, 11, 12, 13
FA2-Floodplain deposits	Thick tabular beds of red to gray floodplain mudstones and siltstones with thin crevasse splays	3, 4, 5, 7, 8, 10, 13, 15, 16, 17, 21
FA3-Deltaic deposits	Tabular beds of mouth bar/foreset and turbidite sandstones	3, 4, 7, 8, 9, 10, 15
FA4-Microbial carbonates	Algal mats, domes, and mounds	28
FA5-Littoral to sublittoral carbonates	Tabular beds of carbonate wacke-grainstones and micrite; includes skeletal and non-skeletal components	22, 23, 24, 25, 26, 27
FA6-Littoral to sublittoral siliciclastics	Thick tabular beds of green, bioturbated mudstone with thin fine-grained sandstones	4, 7, 14
FA7-Oil shales	Thick, finely-laminated, organic-rich deposits of oil shale; variations in richness and leanness	18, 19, 20

4.1 FA1 – Fluvial Channels

Faces association 1 is composed of F1 – Scour and fill sandstone (Fig. 4.1), F2 – Low-angle convex-up sandstone (Fig. 4.2), F3 – Structureless sandstone (Fig. 4.3), F4 – Gradational planar laminated sandstone (Fig. 4.4), F6 – Cross-stratified sandstones (Fig. 4.1), F7 – Ripple laminated sandstone (Fig. 4.5), F8 – Climbing ripple laminated sandstone (Fig. 4.6), F10 –

Undifferentiated sandstone (Fig. 4.7), F11 – Disorganized conglomerate (Fig. 4.8), F12 – Stratified/imbricated conglomerate (Fig. 4.9), and F13 – Mud-draped ripple laminated sandstone (Fig. 4.10). The facies do not typically manifest any vertical or horizontal pattern in their appearance, although higher flow regime structures (F1 or F2) changing vertically into lower flow regime structures (F6 or F7) at the top of a channel were observed in a few places. Thin (1-2 dm thick) conglomerate packages are interpreted as cut bank collapses resulting in debris flows (F11 – Disorganized conglomerate) and traction flow conglomerates (F12 – Stratified/imbricated conglomerate). FA1 facies are most commonly found in channels or vertically and horizontally amalgamated packages of channels. Occasionally these packages do not show incision along the road because of limited lateral exposure, but these packages contain internal erosion surfaces, in places they have scoured bases, and they show clear incision along cliff faces. Facies association 1 is found predominantly at the basin margin, although a few channels were observed in the more basinward cores. While it can be found in vertical/lateral association with any of the marginal to littoral facies associations, it is most frequently observed in association with FA2 – Floodplain deposits.

Interpretation: High to moderate flow regime, traction current deposits in channels indicate that this facies association represents fluvial channel deposits. The primarily lake margin distribution supports this interpretation. Gradational planar laminations and climbing ripple sets point to periods of high deposition, while imbricated and disorganized conglomerates (usually at/near the channel base) point to cut banks and bank collapse/slump. The mineralogically immature composition of these channel fill sandstones despite the significant transport distance of the sediments (~750 km , Dickinson, et al., 2012) indicates seasonal rainfall in an arid

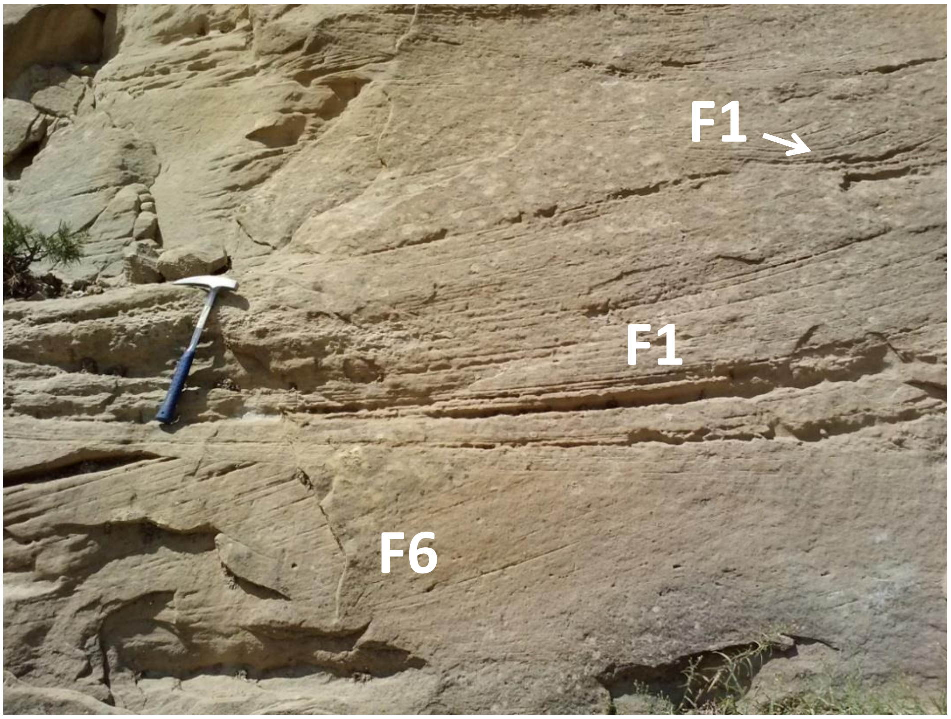

Figure 4.1 - Examples of F1 – Scour and fill sandstone and F6 – Cross stratified sandstone (rock hammer for scale).

Figure 4.2 - Example of F2 - Low-angle convex-up sandstone (rock hammer for scale).

Figure 4.3 - Example of F3 - Structureless sandstone (rock hammer for scale).

Figure 4.4 - Example of F4 – Gradational planar laminated sandstone (rock hammer for scale).

Figure 4.5 - Example of F7 – Ripple laminated sandstone (pencil for scale); this example shows symmetrical ripples

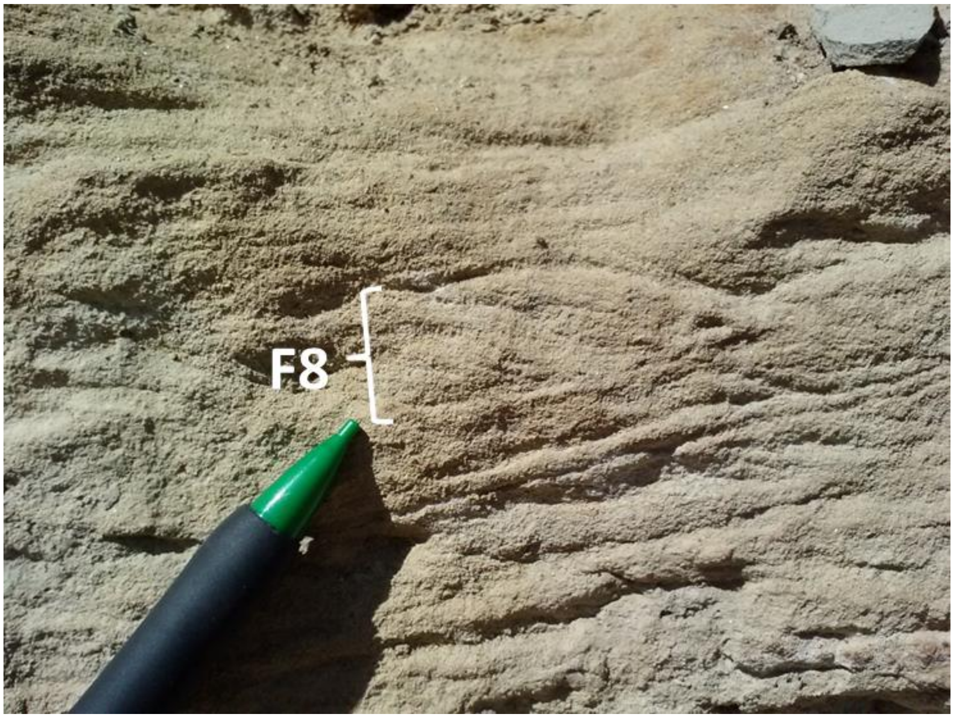

Figure 4.6 - Example of F8 – Climbing ripple laminated sandstone (pencil for scale).

Figure 4.7 - Example of F10 - Undifferentiated sandstone (rock hammer for scale).

Figure 4.8 - Example of F11 - Disorganized conglomerate.

Figure 4.9 - Example of F12 - Stratified/imbricated conglomerate.

Figure 4.10 - Example of F13 - Mud-draped ripple laminated sandstone.

environment, which allows most of the transport distance to be covered during short periods of heavy rainfall with minimal weathering.

4.2 FA2 – Floodplain Deposits

Facies association 2 is composed of F3 – Structureless sandstone (Fig. 4.3), F4 – Gradational planar laminated sandstone (Fig. 4.4), F5 – Distinct planar laminated sandstone (Fig. 4.11), F7 – Ripple laminated sandstone (Fig. 4.5), F8 – Climbing ripple laminated sandstone (Fig. 4.6), F10 – Undifferentiated sandstone (Fig. 4.7), F13 – Mud-draped ripple laminated sandstone (Fig. 4.10), F15 – Gray mudstone (Fig. 4.12), F16 – Red mudstone (Fig. 4.13), F17 – Variable mudstone (Fig. 4.14), and F21 – Coal (Fig. 4.15). These facies are arranged in tabular beds. The sandstones are generally centimeters to a few decimeters thick, while the mudstones can be centimeters to greater than 10 meters thick. Only one thin coal was observed in a shallowing up littoral-floodplain-channel package. The sandstones are typically fine-grained (even silty in places), and interbedded packages of sandstone and mudstone are typical. They are most frequently observed in association with the FA1 – Fluvial channel deposits, but also occur with littoral to marginal deposits (FA2-6). This facies association is found predominantly at the basin margin, but, in places, is recognized in the cores.

Interpretation: The interbedding of relatively thin beds of fine grained sandstones and siltstones with thicker deposits of mudstones is interpreted as floodplain deposited mudstones with occasional muds and silts from levee breaching/overflow. The frequent association with FA1 – Fluvial channel deposits supports this interpretation as does the characteristic red-purple color of many of the mudstones (indicating sub-aerial exposure and subsequent oxidation). The secondary association of this facies association with marginal/littoral deposits (FA2-6) also supports its interpretation as a near-shore flood plain, as any lake level fluctuations would deposit these facies types in lateral and vertical association.

4.3 FA3 – Deltaic Deposits

Facies association 3 is composed of F3 – Structureless sandstone (Fig. 4.3), F4 – Gradational planar laminated sandstone (Fig. 4.4), F7 – Ripple laminated sandstone (Fig. 4.5), F8 – Climbing ripple laminated sandstone (Fig. 4.6), F9 – Soft sediment deformed sandstone (Fig. 4.16), F10 – Undifferentiated sandstone (Fig. 4.13), and F15 – Gray mudstone (Fig. 4.12). The facies are primarily arranged in tabular sandstone beds – some a few meters thick, most a few centimeters to decimeters thick. The thicker beds tend to be poorly to moderately sorted. The thinner beds tend to be fine grained and vary among normally graded, ungraded, or capped with a thin mudstone. They are predominantly found in association with littoral or marginal deposits (FA4-FA6) or oil shales (FA7). While FA3 does not comprise a large portion volumetrically of the Green River Formation in the Uinta basin, it is more widespread than the previous two facies associations, being observed in at least some form from outcrop to basin center.

Interpretation: The association of these sandstones with predominantly lacustrine sediments (FA4-FA7) indicates a deltaic deposition. The thicker beds are interpreted as mouth bar deposits based on a combination of structure, composition, and association with lacustrine sediments; these are equivalent to the sharp-based mouth bars of O'Hara (2013). The thinner beds (mostly comprised of F3 – Structureless sandstone) are interpreted as turbidite deposits based on their distal location, and thinner, grading up to normally graded, well-sorted sandstone beds. Some of the thin, fine-grained, siliciclastic pulses observed in the cores (especially the basin-center EX-1 Utah core) are most easily explained as the most distal portion of turbidites.

Tänavsuu-Milkeviciene and Sarg (2012) also include both mouth bars and turbidites in their "delta deposits" facies association.

4.4 FA4 – Microbial Carbonates

Facies association 4 is composed exclusively of F28 – Microbialite (Fig. 4.17). The microbialites form algal mats or heads, and frequently have trapped other carbonate or siliciclastic grains between the algal layers or between mounds. Meso-textures range from finely laminated to dendritic to thrombolitic. This facies association is most commonly observed in association with other carbonate facies (FA5 – Littoral to sublittoral carbonates), but is also found overlying siliciclastics (both FA1 – Fluvial channel and FA6 – Littoral to sublittoral

Figure 4.11 - Example of F5 – Distinct planar laminated sandstone (laminations only faintly visible; rock hammer for scale).

Figure 4.12 - Example of F15 - Gray mudstone (rock hammer for scale).

Figure 4.13 - Example of F16 - Red mudstone (pencil for scale); modern weathering pattern changes from fragmented at base to massive at top, but lithology appears to be the same throughout.

Figure 4.14 – Example of F17 – Variable mudstone (rock hammer for scale). Note the different modern weathering patterns (fragmented in the center grading to massive at the top). The lithology appears to be the same throughout.

Figure 4.15 - Example of F21 - Coal (field notebook for scale).

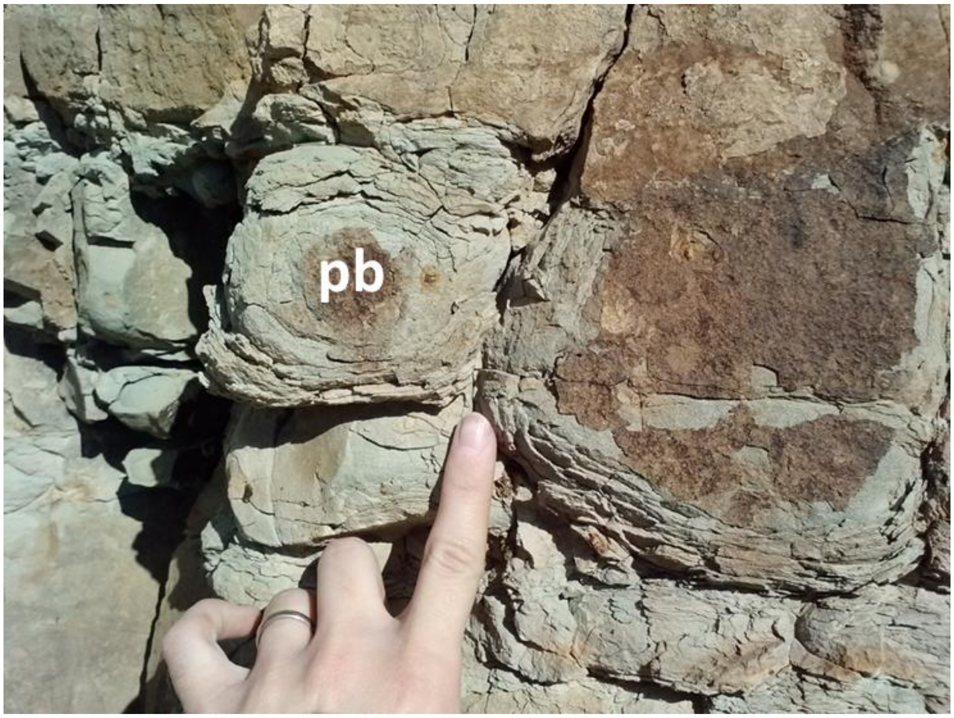

Figure 4.16 - Example of F9 - Soft sediment deformed sandstone; pb - pillow/ball structure.

siliciclastics) and oil shales (FA7). It is found predominantly at the basin margin, but thin deposits are observed near the basin center in core.

Interpretation: This facies is interpreted as lake margin carbonate deposition during times of higher salinity when preservation is enhanced. This is one of the most useful facies associations for interpreting lake level, as microbialites develop almost exclusively in shallow water (typical depth ranges for lacustrine microbialites are from 0-30 meters of water depth [Talbot and Allen, 1996]). Some microbialite beds that cap carbonate wackestone-grainstone facies of FA5 are interpreted as deepening upwards lake cycles. Similar packages are described in both the eastern Uinta and western Piceance Creek basins (Suriamin et al., 2011; Sarg et al., 2013; Swierenga, 2013).

Figure 4.17 – Example of F29 – Microbialite (field notebook for scale).

4.5 FA5 – Littoral to Sublittoral Carbonates

Facies association 5 is composed of F22 – Micritic dolomites (Fig. 4.18), F23 – Molluscan limestones (Fig. 4.19), F24 – Ostracod-bearing limestones and dolomites (Fig. 4.20), F25 – Intraclastic limestones and dolomites, F26 – Ooid-bearing limestones and dolomites (Figs. 4.18, 4.20, 4.22), and F27 – Pisoid-bearing limestones (Fig. 4.23). Similar facies are observed by Suriamin et al. (2011), Sarg et al., (2013) and Swierenga (n.d.). As mentioned previously, these facies are defined based on the dominant grain-type – i.e. other carbonate (or even siliciclastic) grains are often present. These facies form tabular beds with a thickness of centimeters to decimeters. They are found in association with virtually every other facies association, from channels to floodplain to oil shale, however the thickest beds are most prominent in the Hay Canyon outcrop near the basin margin.

Interpretation: The different facies of this association indicate a variety of energy conditions. The coated grains are predominantly interpreted to be found along the lake shoreline due to the continued motion necessary for coated grains (energy conditions found most often in a nearshore environment). Some of the mixed grain-type carbonates point to reworking sediments (mostly a mixture of ostracods and ooids); others point to areas of mixed carbonate-siliciclastic input (mostly a mixture of ostracods and silt-sand). Ostracods can be found throughout the lake deposits, and are the dominant carbonate grain found in association with the oil shales of FA7.

4.6 FA6 – Littoral to Sublittoral Siliciclastics

Facies association 6 is composed of F4 – Gradational planar laminated sandstone (Fig. 4.4), F7 – Ripple laminated sandstone (Fig. 4.5), and F14 – Green mudstone (Fig. 4.24). The green mudstone facies forms the dominant component of this facies association and ranges in thickness from meters to greater than 10 meters thick units. This mudstone is typically bioturbated with rust colored burrows typically less than a centimeter in diameter. The burrows are almost exclusively seen in transect (i.e. no vertical or branching burrows observed). In addition to the mudstone, thin (centimeters to decimeters thick) beds of fine-grained sandstone are rarely present. This facies association is generally found in association with marginal carbonates (FA4 or FA5) and channel deposits (FA1), but can be in association with deltaic deposits (FA3) and oil shale (FA7) as well. Tänavsuu-Milkeviciene and Sarg (2012) interpret a similar facies association.

Interpretation: The green color used to separate this facies from floodplain mudstones (F15 – Gray mudstone, F16 – Red mudstone, F17 – Variable mudstone) is interpreted as indicating a more reduced, subaqueous depositional environment than the floodplain mudstones.

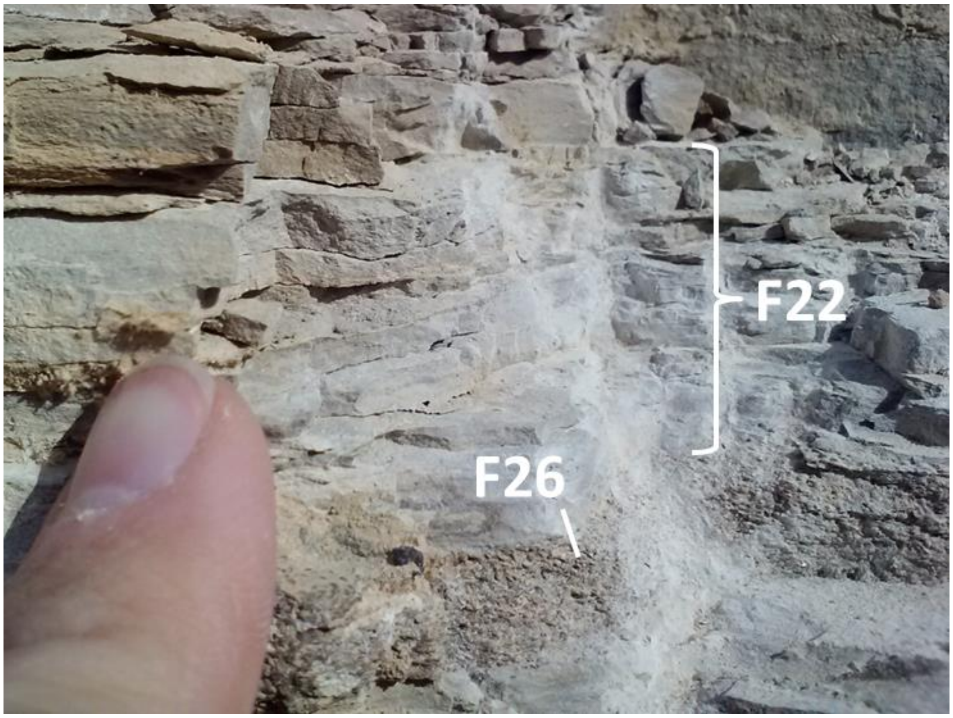

Figure 4.18 - Example of F22 - Micritic carbonate and F26 - Ooid packstone.

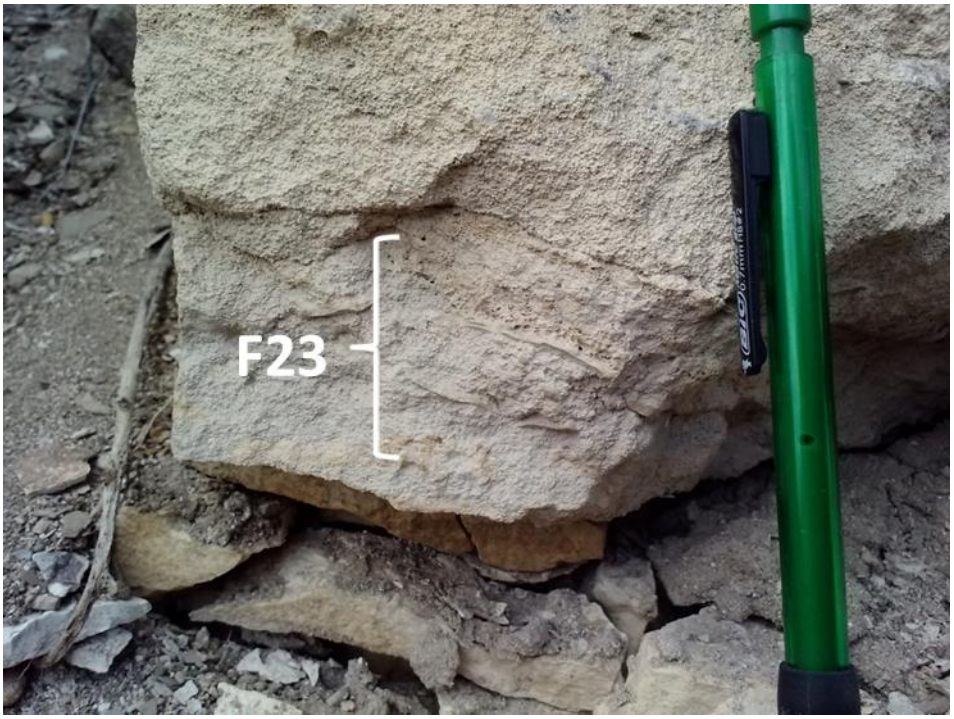

Figure 4.19 - Example of F23 – Ooid, bivalve wackestone (pencil for scale).

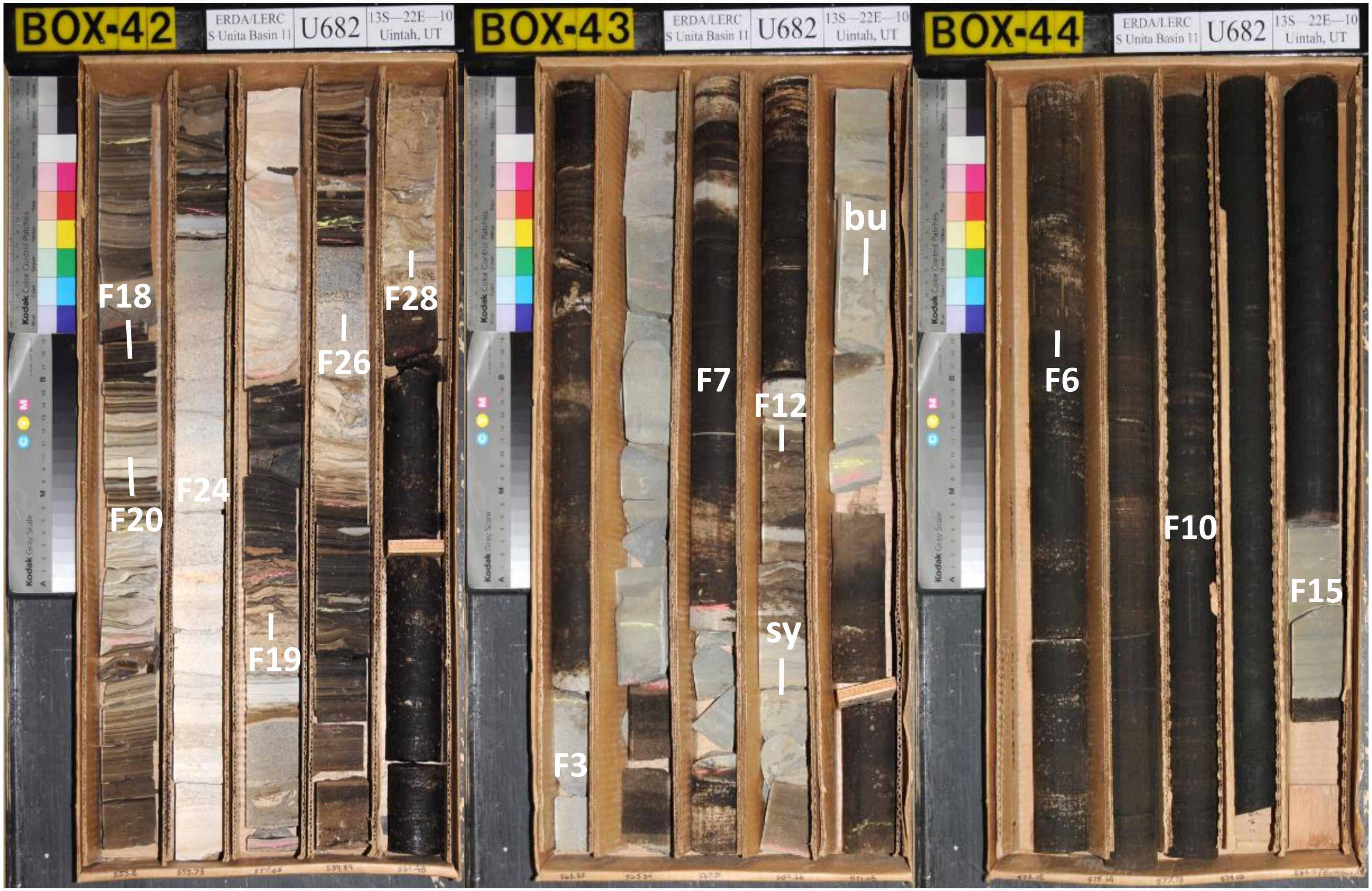

Figure 4.20 - 11 S Uinta Basin core showing examples of F3 – Stuctureless sandstone, F6 – Cross-stratified sandstone, F10 – Undifferentiated sandstone, F12 – Stratified/imbricated conglomerate, F15 – Gray mudstone, F18 – Black/brown mudstone, F19 – Brecciated black/brown mudstone, F20 – Light brown mudstone, F24 – Ostracod-bearing carbonate, F26 – Ooid-bearing carbonate, and F28 - Microbialite; sy – syneresis cracks, bu- burrows.

Figure 4.21 - Example of F26 – Ooid grainstone

Figure 4.22 - Example of F27 – Pisoid packstone/grainstone (pencil for scale).

The structure, composition, and arrangement of the beds are not indicative of deltaic deposition, however, but are more consistent with an interpretation of broad siliciclastic deposition near a fluvial source (prodelta?; compare with Tänavsuu-Milkeviciene and Sarg, 2012), or during a period of high precipitation and high runoff. Common association with marginal carbonates (FA4 and FA5) and channel deposits also support a littoral to sublittoral environment.

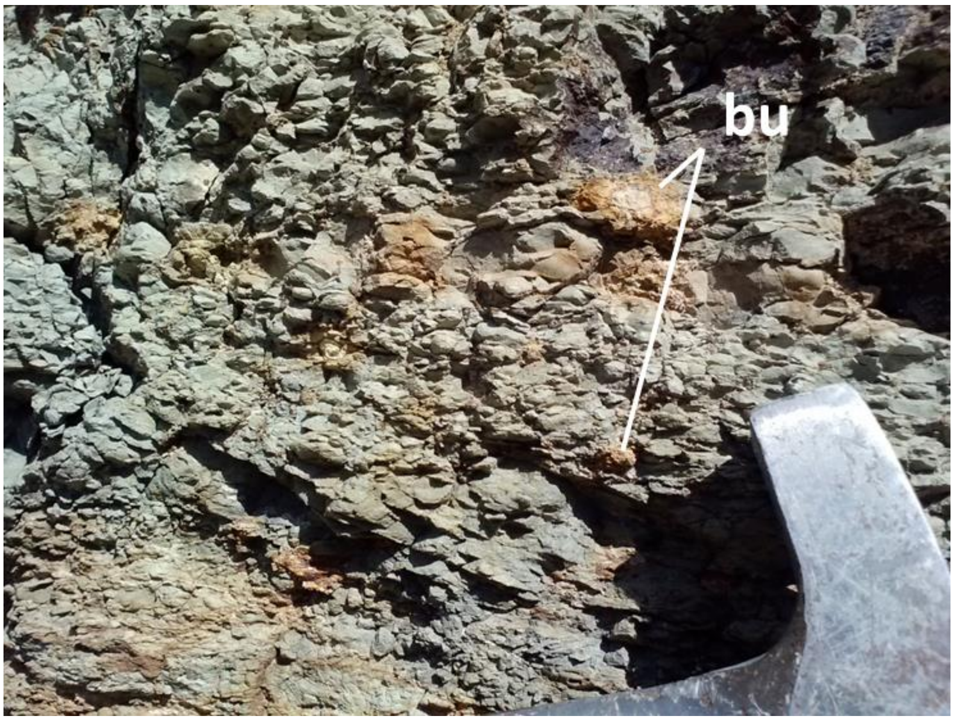

Figure 4.23 - Example of F14 - Green mudstone; bu - burrow; note the characteristic rust color of the burrows (rock hammer for scale).

4.7 FA7 – Oil Shale

Facies association 7 is composed of F18 – Black/brown mudstone (Figs. 4.20, 4.25, and 4.26), F19 – Brecciated black/brown mudstone (Fig. 4.20), and F20 – Light brown mudstone (Figs. 4.20, 4.25, and 4.26). These mudstones are finely laminated throughout and include thin beds of massive mudstone. Thin beds (centimeters to decimeters thick) are brecciated, with matrix ranging from mudstone to carbonate wackestone to grainstone. Occasional soft-sediment deformation occurs in the form of wavy to overturned beds. These facies are found dominantly towards the basin center, although they can be found at the margins. In the cores examined, they are usually in association with distal deltaic facies (FA3), although they can be found alongside almost any facies association (e.g. few very organic poor examples in Hay Canyon outcrop in association with littoral carbonate and fluvial channel facies). They become much more widespread upwards in the Green River Formation..

Interpretation: These facies represent the classic oil shales of the Green River Formation. Their organic-richness is indicated by color, density/weight, and Fisher Assay data where available (Johnson et al., 2010; Birgenheier and Vanden Berg, 2011). The few exceptions to this rule can be found in Hay Canyon where almost white examples can be found in outcrop. These examples are interpreted as lacustrine deposition of the same type of mudstone, but with more oxic lake conditions that are unfavorable for preserving the organic content. The increase in prevalence of this facies association moving up through the stratigraphy is interpreted as an increase in lake size/depth. Brecciated oil shale (F19) and slumped examples of black/brown and light brown oil shale are interpreted as gravitational deposits (Tänavsuu-Milkeviciene and Sarg, 2012).

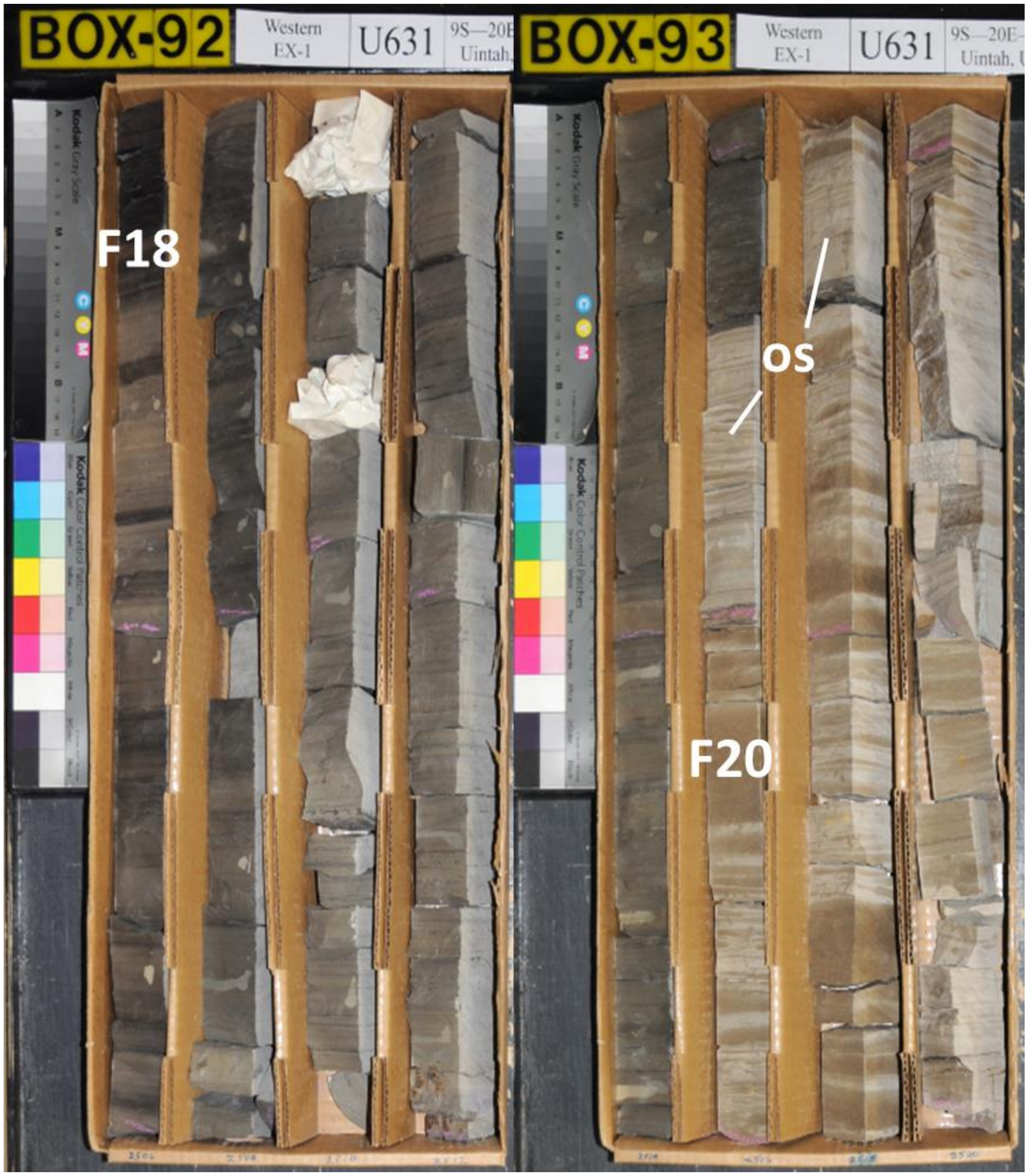

Figure 4.24 - Example of FA7 from EX-1 core showing typical finely-laminated deposits with variations in richness; F18 – Black/brown mudstone, F20 – Light brown mudstone; lightest material in F20 is ostracod-bearing in this location (examples marked "os").

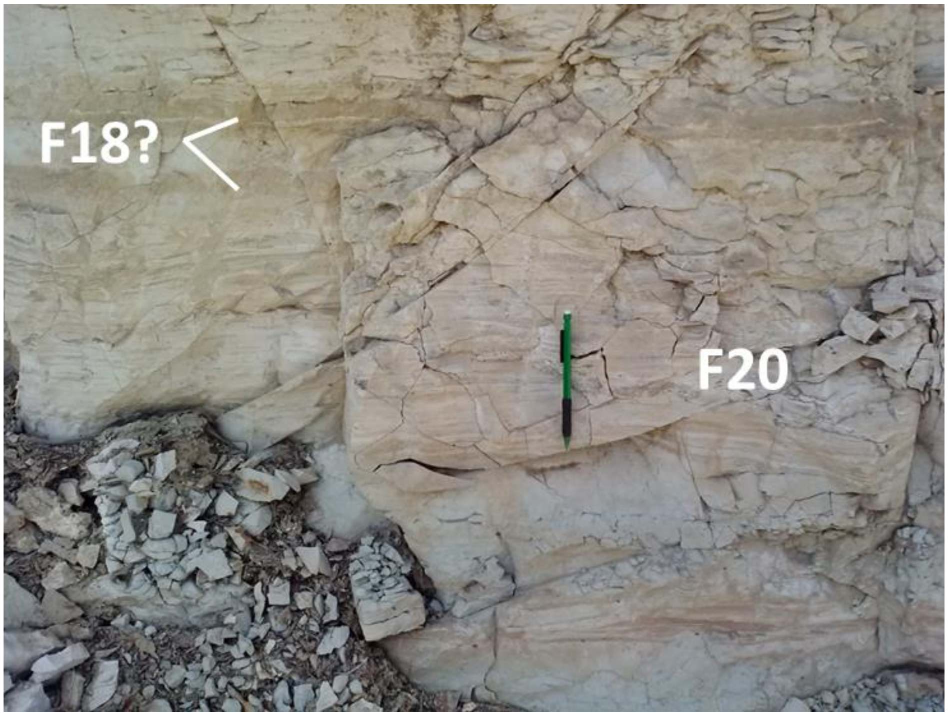

Figure 4.25 – Example of F20 – Light brown mudstone. One of only two examples of FA7 in Hay Canyon outcrop. This early pulse of FA7 is not organic rich, showing more of a gray-white color than brown. Subtle bands of slightly darker gray may be equivalent to F18 – Black/brown mudstone.

CHAPTER 5

CROSS SECTIONS AND MARKERS

Outcrop and core descriptions were matched with well logs from additional locations in the study area to construct two cross sections (Fig. 3.1). The C-C' cross section was chosen in a roughly north-south orientation (approximately equivalent to a dip section) and includes the Hay Canyon outcrop, both cores, and 8 additional wells. The D-D' line was chosen along a roughly east-west line (approximately equivalent to a strike section) and includes 6 wells. The cross sections have a total of four tie points with cross sections A-A' and B-B' from Hogan (2015), one tie point with Birgenheier and Vanden Berg (2011), and one tie point shared between the two cross sections of this study.

5.1 Cross Sections

Cross section C-C' contains the Hay Canyon outcrop, the 11 S Uinta Basin and EX-1 Utah cores, and 8 additional wells (Fig. 5.1). These wells contain an array of different log suites including gamma ray, spontaneous potential, resistivity, bulk density, and neutron porosity logs. The Hay Canyon outcrop contains a spectral gamma log using total counts per minute units. The 11 S Uinta Basin core has no logs, but the nearby 12-F-1 is considered a proxy for this core. This cross section shares the EX-1 Utah core/log suite and the NBU 920-14M3AS well/log suite with Hogan (2015), and the EX-1 Utah core/log suite with Birgenheier and Vanden Berg (2011). It shares the 1122-6O well/log suite with cross section D-D'.

Cross section D-D' contains 6 wells (Fig. 5.2). These wells all have similar log suites, with each well including some form of gamma ray, resistivity, bulk density, and neutron porosity log. This section shares the 16G-20-10-18 well/log suite and Skyline 16 core/log suite with Hogan (2015), and the 1122-6O well/log suite with cross section C-C'.

5.2 Markers

Following the methodology of Hogan (2015), various stratigraphic markers were chosen to be identified throughout the cross sections. The basis for most of these markers is the formation tops/markers provided by the Bill Barrett Corporation (BBC, an industry partner in the Green River Research Consortium). From the markers used by BBC, eight markers were chosen that were consistently identifiable across the southern margin of the basin. One additional marker, Marker 8, was chosen from the markers used by Hogan (2015), because of its very consistent log response between wells. Characteristic responses for each of the tops/markers can be seen in the type log for the study, the NBU 920-14M3AS well (Fig. 5.3). Detailed descriptions of the log characteristics of each marker are provided below. Note that while these markers are lithologically correlative (the logs throughout the study area are responding to the same feature or shift in lithology), they do not necessarily represent time correlative or sequence stratigraphic boundaries.

5.2.1 – Wasatch

The Wasatch marker (Fig. 5.4) is most easily identified by a sharp decrease in gamma followed by an interval (~30m) of lower gamma. This is accompanied by an interval of generally increased porosity. It is frequently, though not always, paired with a sharp increase in resistivity,

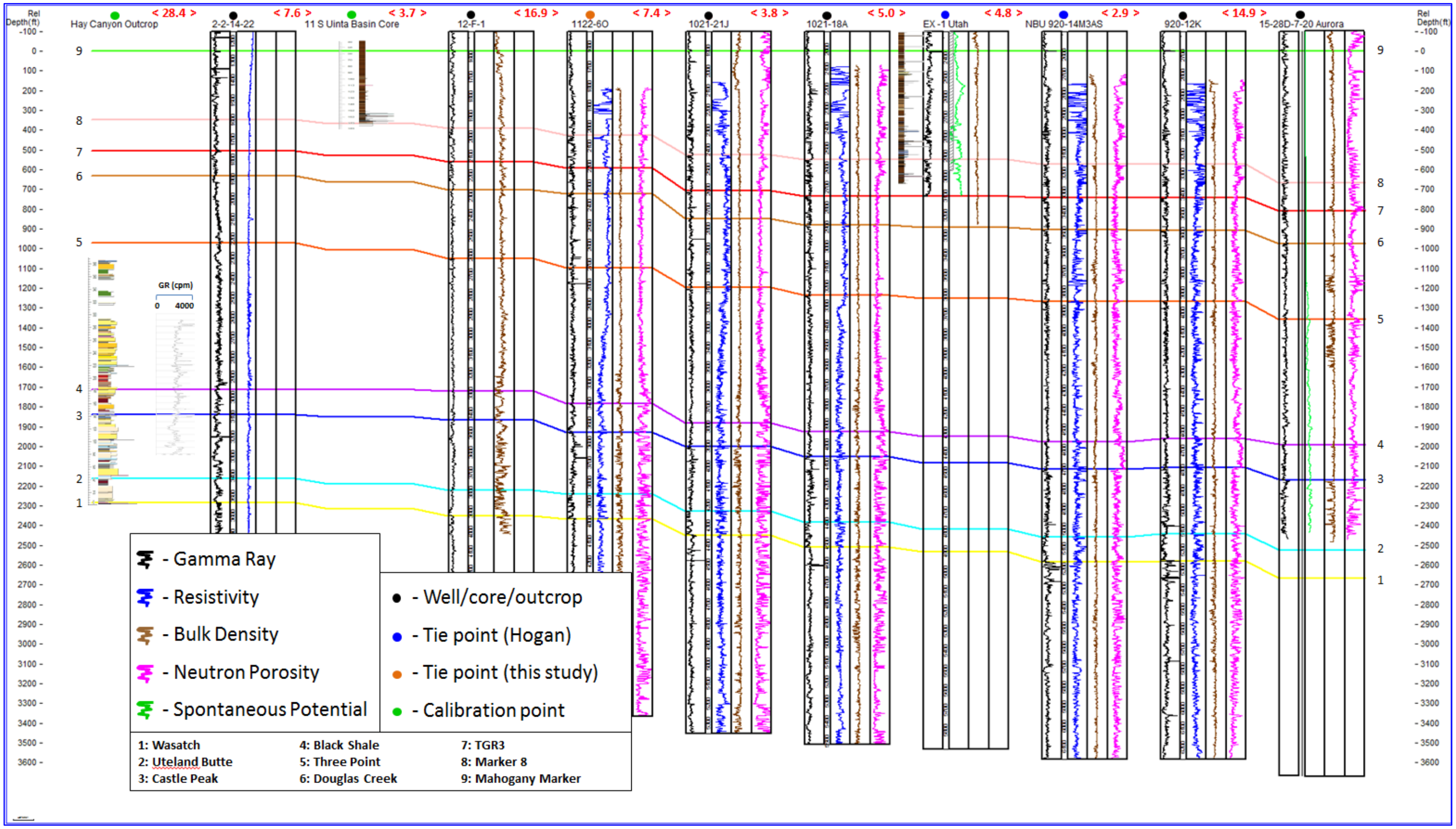

Figure 5.1 - Cross section C-C'.

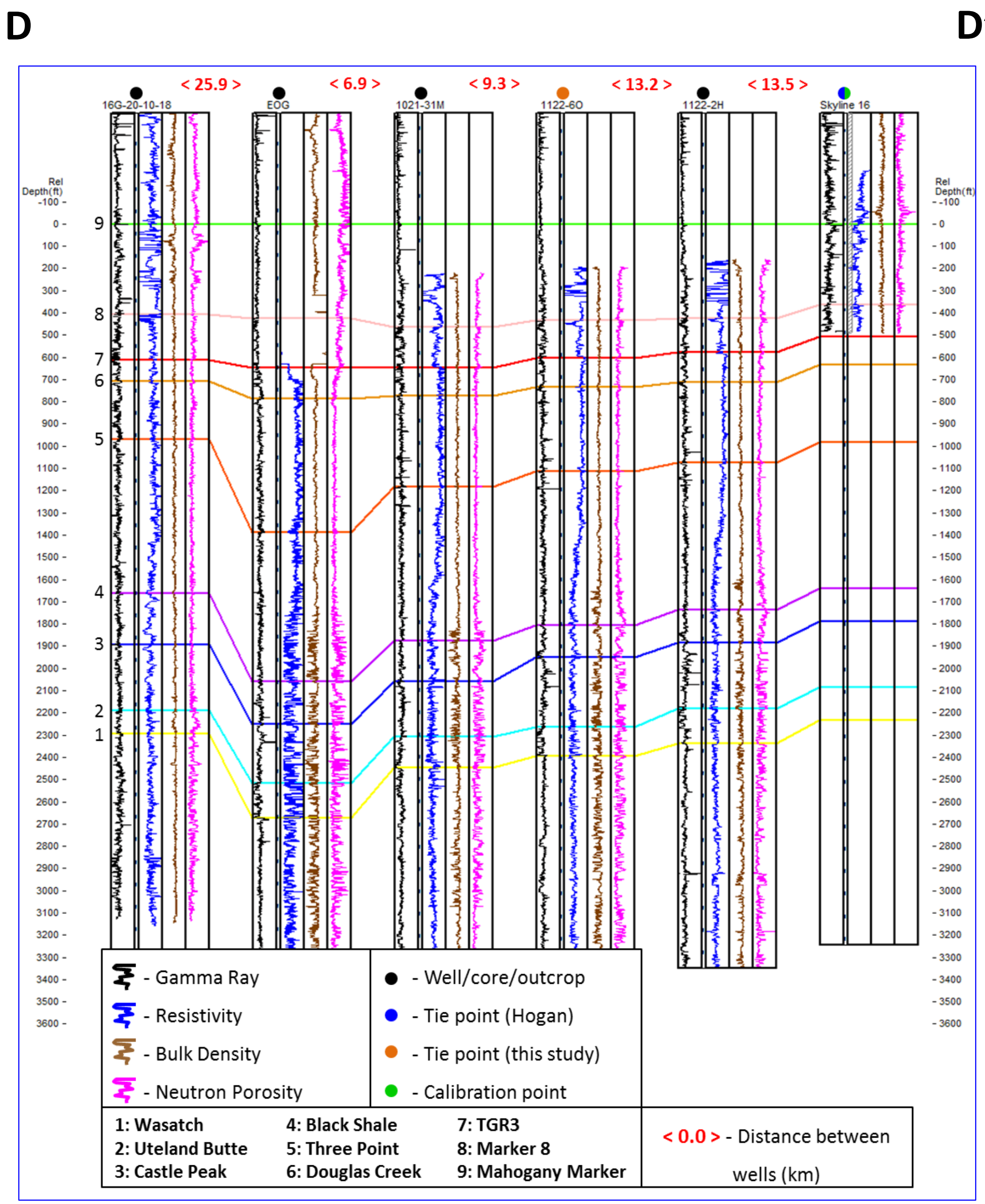

Figure 5.2 - Cross section D-D'.

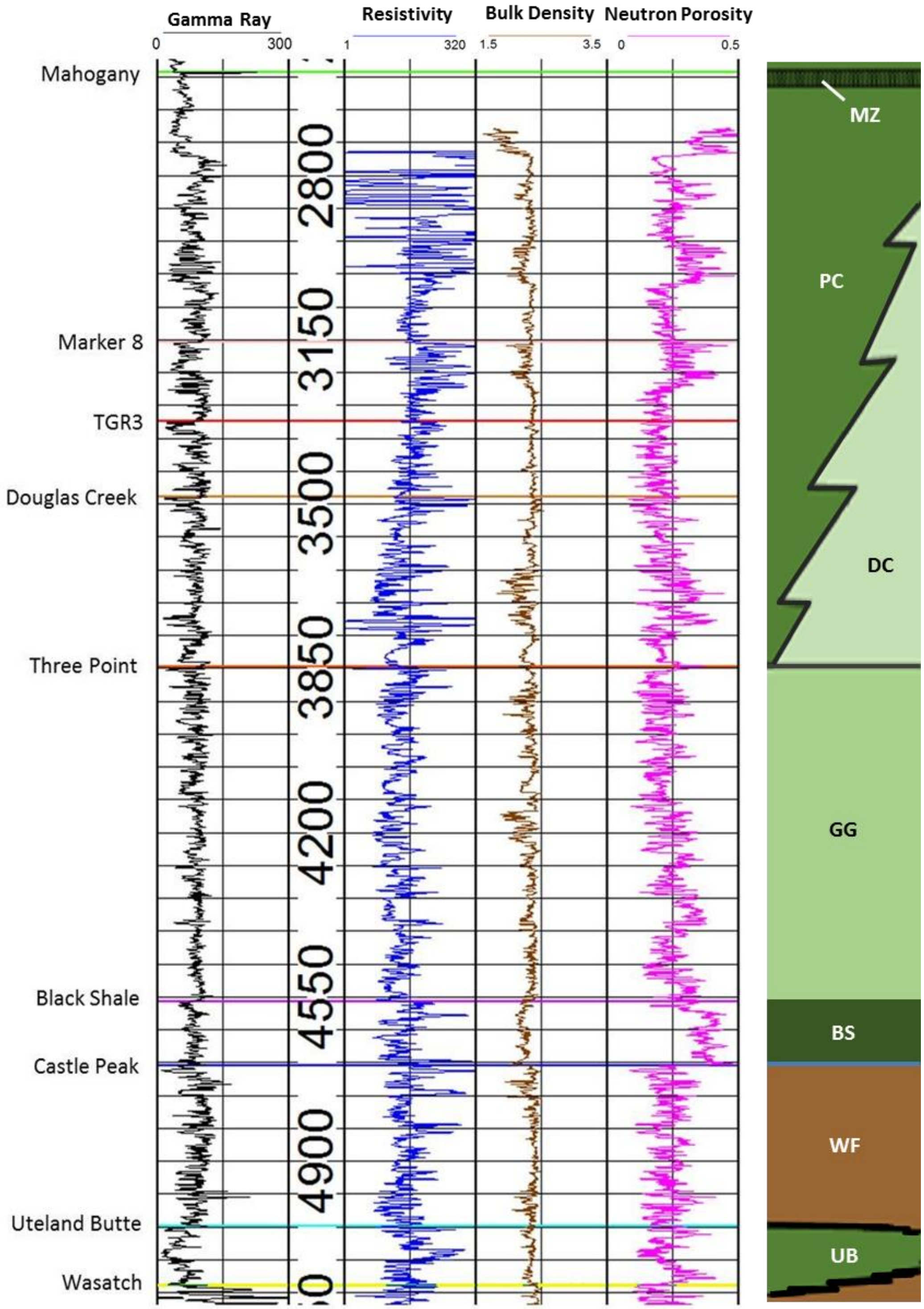

Figure 5.3 - Type log from well NBU 920-14M3AS. Abbreviations for stratigraphic column (right side) are as follows: UB – Uteland Butte, WF – Wasatch Formation (Colton Tongue), BS – Black Shale, GG – Garden Gulch, DC – Douglas Creek, PC – Parachute Creek, MZ – Mahogany Zone (see figure 2.4).

and a small (non-diagnostic) decrease in density. The sharp gamma decrease typically sits above sizeable interval of spikey, highly irregular gamma. This marker represents the boundary between the fluvially deposited sandstones of the Wasatch Formation, and the lake marginal carbonate and silt/shale deposits of the Uteland Butte (representing the first significant pulse of lacustrine sediments in the basin.

5.2.2 – Uteland Butte

The top Uteland Butte marker (Fig. 5.4) is easily identified throughout the basin by a sharp increase in gamma above the interval of low gamma that follows the Wasatch marker. This gamma spike is typically followed by a gradual increase in overall gamma. It is frequently paired with high peak in porosity and a sizeable low trough in resistivity. This marker represents the top of the Uteland Butte Member. The transition records the increased gamma associated with the return of feldspar-rich fluvial sands, and the retreat of the first lacustrine-rich phase of Uinta Basin stratigraphy.

5.2.3 – Castle Peak

The Castle Peak marker (Fig. 5.5) is best identified using the porosity log. This marker is located at a very sharp increase in porosity, with an interval of high porosity above. This is frequently mirrored by a sharp decrease in density. The gamma ray typically shifts to a period of increased gamma at the marker, and frequently (but not always) has a deep low just before the marker. This marker represents the top of the Castle Peak Member, an interval of interbedded carbonates and siliciclastics.

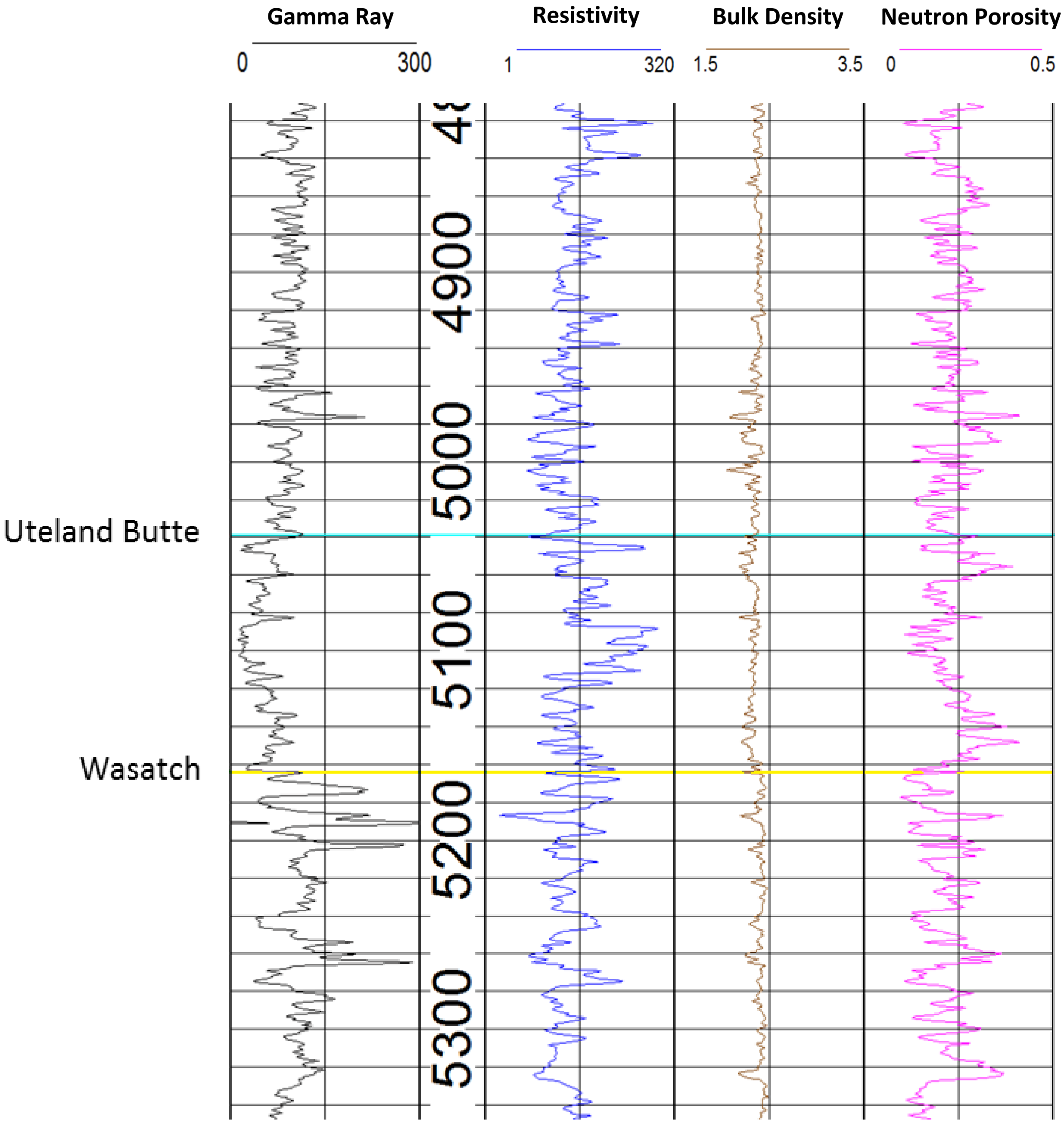

Figure 5.4 - Example of the Wasatch and Uteland Butte markers; from type log

5.2.4 – Black Shale

The Black Shale marker (Fig. 5.5) is identified by a consistent sharp increase in gamma with an interval of maintained high gamma afterwards. In most wells this marker also corresponds with a decrease in density and increase in porosity. In places, a sharp decrease in resistivity is observed, but this log is not diagnostic for the marker. The marker represents the top of the Black Shale bed, an interval of organic rich shale.

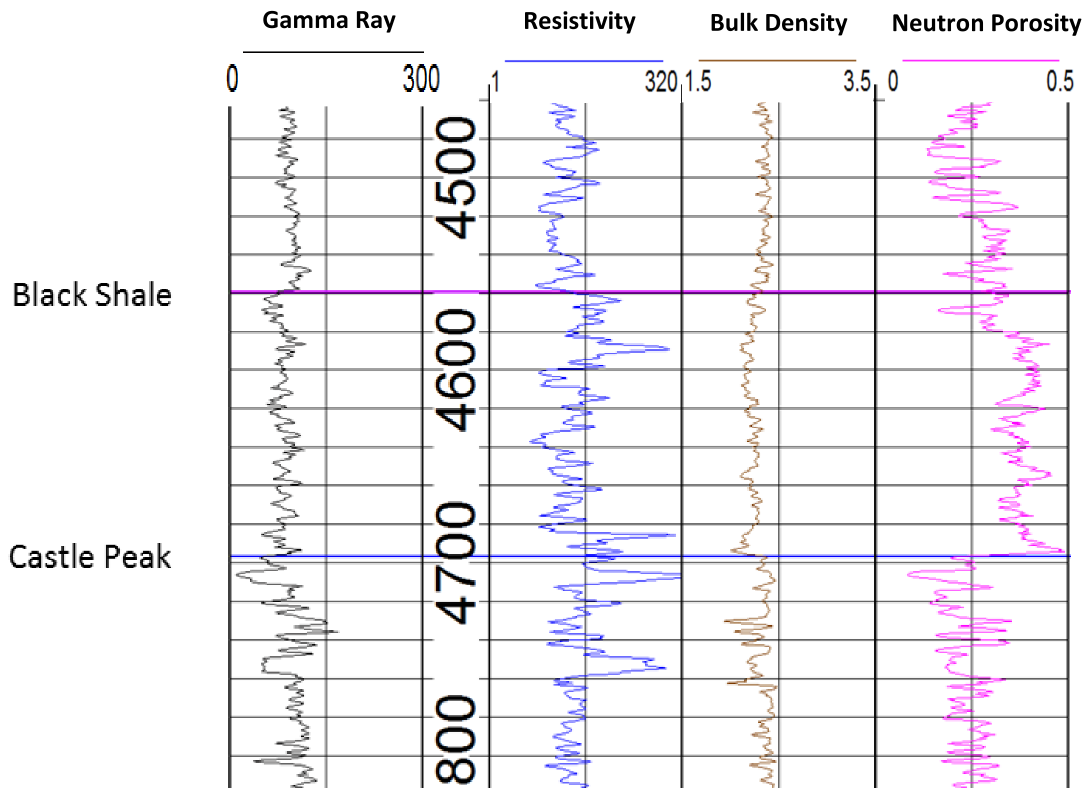

Figure 5.5 - Example of the Castle Peak and Black Shale markers; from type log

5.2.5 – Three Point

The Three Point marker (Fig. 5.6) is identified by a combination of the gamma and porosity logs. The porosity is most diagnostic with a strong high at the marker. This typically corresponds to an area just above a strong low in the gamma ray. The resistivity in some places shows a period of gradually increasing resistivity, reaching a sharp drop at the marker, and followed by a short interval of continued decreased porosity (not seen in all logs). This marker does not correspond to a particular lithostratigraphic contact, but is used informally in industry as a consistent marker. It is used in this study as the approximate boundary of the Garden Gulch and Douglas Creek/Parachute Creek members because in the basin center it marks the shift from dominantly lake-center mudstones (FA6) below to dominantly oil shale above. This change is less obvious near the basin margin because the Douglas Creek member is more similar to Garden Gulch member than the Parachute Creek member (see Fig. 6.6 for facies shift at Three Point marker from C to C').

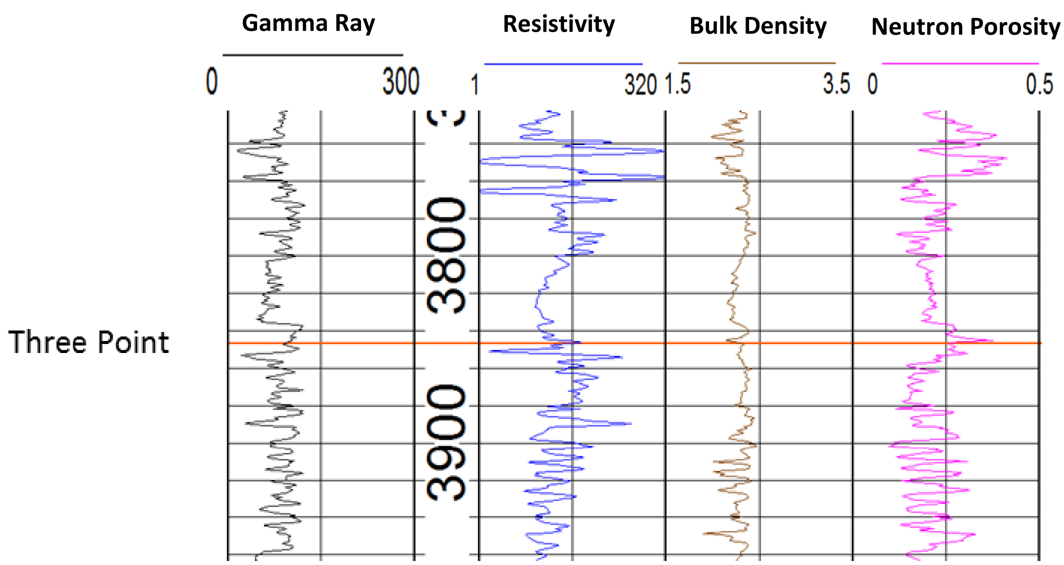

Figure 5.6 - Example of the Three Point marker; from type log

5.2.6 – Douglas Creek, TGR3, Marker 8

The Douglas Creek marker, TGR3 marker, and Marker 8 picks (Fig. 5.7) are some of the most consistent and easily identifiable in the section. They are each identified by sharp increases in gamma ray at each marker followed by intervals of generally blocky high gamma with an increasing number of low troughs upwards. This is paired with high peaks in porosity at the

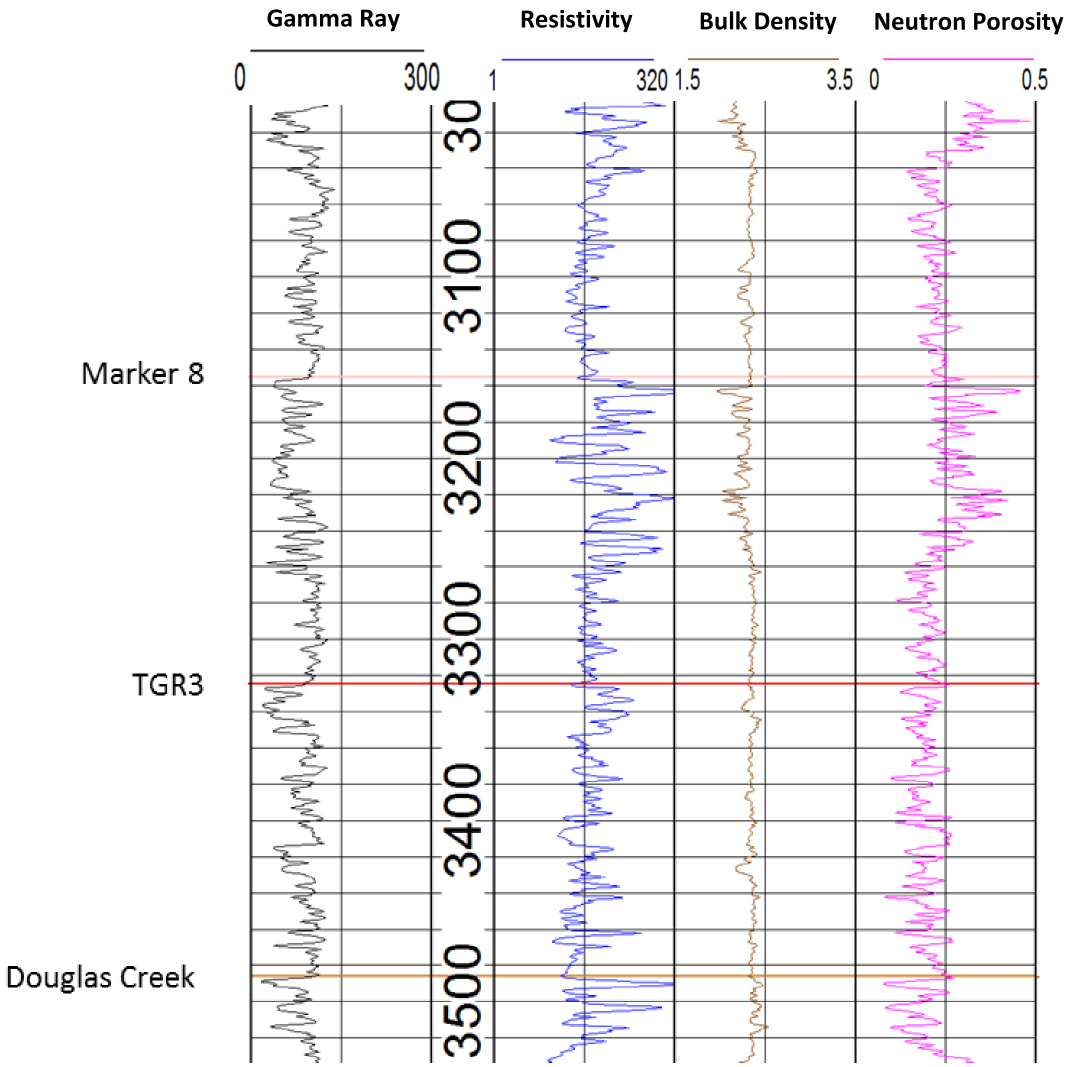

Figure 5.7 - Example of the Douglas Creek marker, TGR3 marker, and Marker 8; from type log

markers, followed by intervals lower porosity above. The Douglas Creek is not interpreted as the top of the Douglas Creek interval, but simply a useful, informal marker within the interval. The TGR3 marker is defined as the top of the R3 zone (Baker and Lucas, 1972). Marker 8 is an informal marker defined by Hogan (2015). These markers correspond to pulses of siliciclastic input interpreted as fluvial and deltaic facies for the Douglas Creek and TGR3 markers, respectively, and as a lean zone with increased silt and carbonate above Marker 8.

5.2.7 – Mahogany Marker

The Mahogany Marker (Fig. 5.8) is usually the most prominent marker in the section, identifiable as a very sharp peak in the gamma. It is frequently followed by an interval of significantly lower density and higher porosity, although many of the wells do not log anything but gamma this high in the section. While the gamma peak is in many wells one of the highest on the gamma ray curve in an interval of relatively low gamma, some of the wells (both proximal and distal) show no distinctive peak. The marker itself is one of the richest zones in the Green River oil shale (hence the high gamma and low density), but local fluctuations in carbonate content or organic richness may, in places, mask the gamma peak.

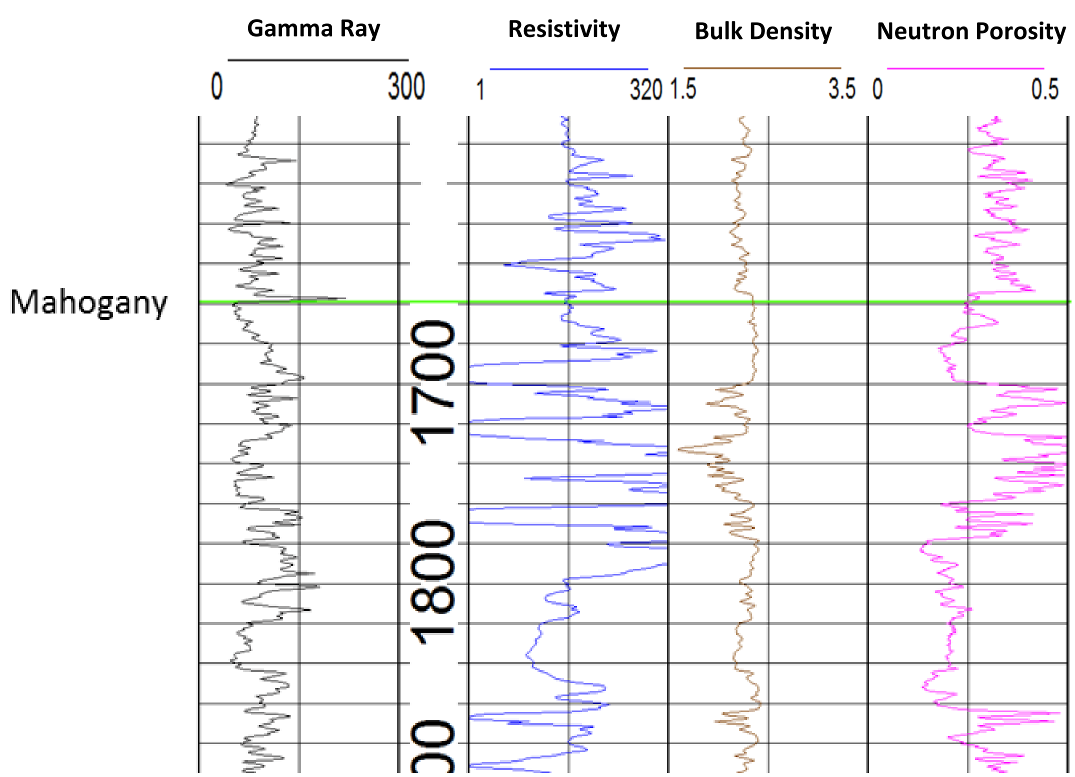

Figure 5.8 - Example of the Mahogany marker; from well 16G-20-10-18

CHAPTER 6

LOG CALIBRATION AND INTERPRETATION

The detailed core and outcrop descriptions made in this study were used to calibrate the additional well logs to the identified facies associations. A significant interval of the lower Douglas Creek Member is not represented by any of the core or outcrop, but as all of the missing interval is understood from other studies to contain the same facies associations as are present in the described intervals, an effective calibration is still possible.

In order to accomplish this calibration, the log characteristics of known facies associations were identified. The vertical relationships between associations were also noted. These characteristics were then identified in well logs that did not have core or outcrop associated with them. Care was taken to make sure vertical and horizontal facies association relationships were in accordance with the geologic relationships noted in core and outcrop descriptions, and with general geologic understanding of the basin.

For the Hay Canyon outcrop, the spectral gamma curves recorded in the field were used to calibrate facies associations. Ideally, multiple log types are used for calibration; but in spite of only having a single log type for Hay Canyon, the ability to calibrate this curve to outcrop (where lateral relationships and geometries are much more visible than in core) make this calibration point useful. The similarities between facies associations identified in spectral gamma and those identified in the more robust log suites from wells/cores show the benefit of this method.

It is necessary to note that these calibrations are based on gross characteristics of intervals, not specific log signatures. The resolution and accuracy of this type of comparison will not allow for a meaningful specific calibration. Despite this limitation, even a low resolution calibration based on detailed descriptions can meaningful enhance our understanding of basin deposition and development.

6.1 – Calibration of FA1 – Fluvial Channels

FA1 typically correlates to an irregular, overall moderate to high gamma ray curve, with frequent peaks (Figs. 6.1a and 6.1b). Given the frequent vertical amalgamation of these channel packages, this log character may continue vertically for tens of meters resulting in an almost blocky log response. In places, however, the gamma curve may show lower values (e.g. the upper portions of the Hay Canyon outcrop and Skyline 16 core), making these zones more difficult to distinguish from other facies associations. Resistivity seems to show no consistent correlation to the gamma in the lower Green River (Castle Peak interval), but in the more fluvially dominated intervals of the Garden Gulch and Douglas Creek members, low resistivity mirrors the overall high gamma of FA1 intervals. Irregularities in the Castle Peak are possibly related to factors such as cementation, diagenesis, fractures, etc.

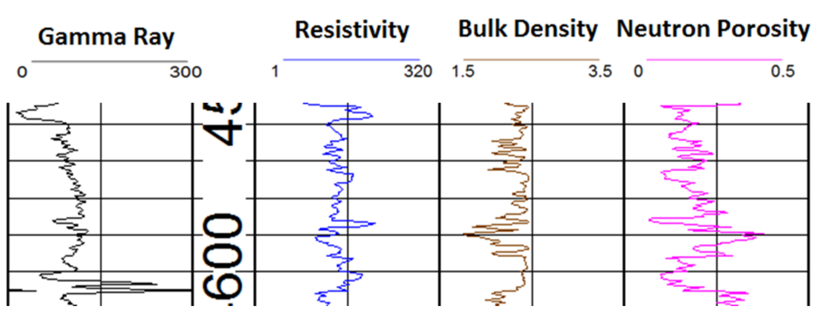

Figure 6.1a - Typical log response for FA1; from Well 1021-18A

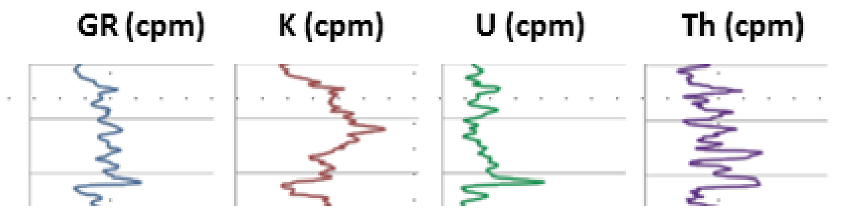

Figure 6.1b - Hay Canyon spectral gamma log response for FA1

6.2 – Calibration of FA2 – Floodplain Deposits and FA6 – Littoral to Sublittoral Siliciclastics

Due to the similarity of their composition, it was not possible to distinguish between the log calibrations for these two facies associations. These associations typically correlate to a very irregular, spikey, overall high gamma ray curve with spikey resistivity and spikey, often low porosity (Fig. 6.2a and 6.2b). This correlates to the overall high clay content and high density of the dominant mudstone facies.

6.3 – Calibration of FA3 – Deltaic Deposits

Deltaic deposits are primarily made up of the more distal interbedded turbidite deposits with a few thicker mouth bar sands at the most proximal end. This association therefore changes characteristics moving basinward through the section. Proximally the logs show a spikey gamma, resistivity, and porosity. Moving basinward, as the siliciclastics thin and begin to interfinger with the lacustrine mudstones, these peaks and troughs become more subdued and the overall interval thins (Fig. 6.3).

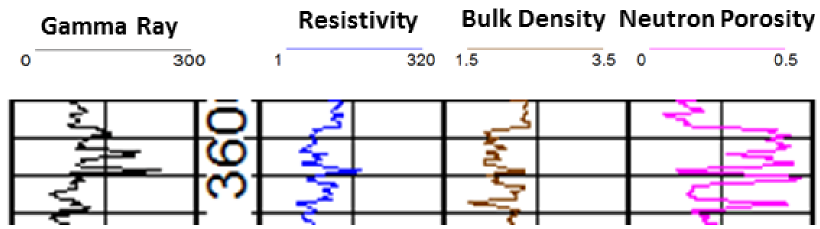

Figure 6.2a - Typical log response for FA2 and FA6; from Well 1122-6O

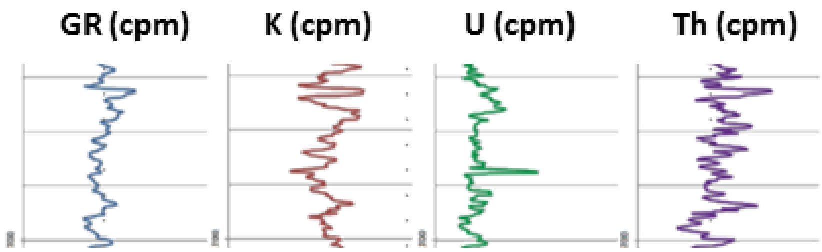

Figure 6.2b - Hay Canyon spectral gamma log response for FA2 and FA6

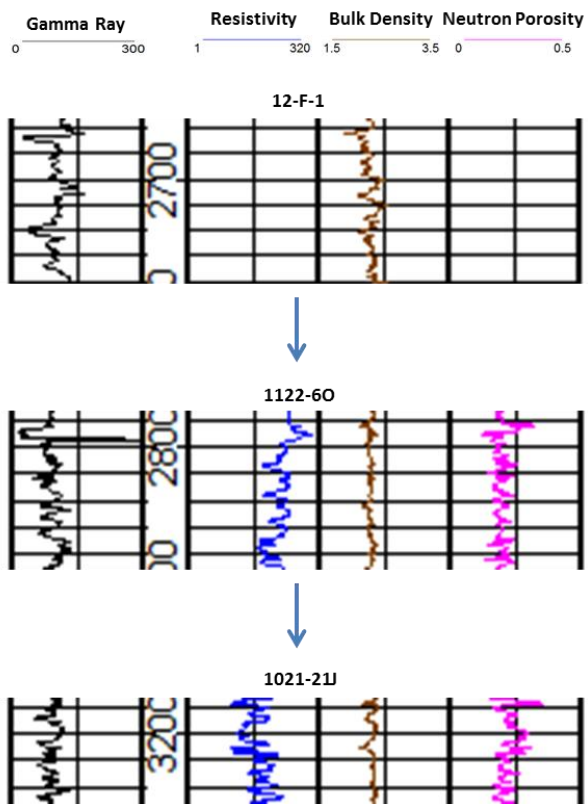

Figure 6.3 - Typical log response for FA3 moving from proximal to distal deposits; from Wells 12-F-1, 1122-6O, and 1021-21J

6.4 – Calibration of FA4 – Microbial Carbonates and FA5 – Littoral to Sublittoral Carbonates

These two facies associations cannot be distinguished from each other using log characteristics and so are lumped together in calibration. Carbonates typically show a characteristic low gamma deflection, frequently paired with high spikes in resistivity and density and low troughs in porosity (Fig. 6.4a and 6.4b).

6.5 – Calibration of FA7 – Oil Shale

This association is calibrated to an overall high gamma ray with some low troughs, paired with overall low density (Fig. 6.5). These log responses are traced back to the high organic and clay content of these deposits. They frequently have low resistivity as well, although this is not diagnostic. Porosity is highly variable, possible due to small interbeds of coarser material and/or variations in carbonate content.

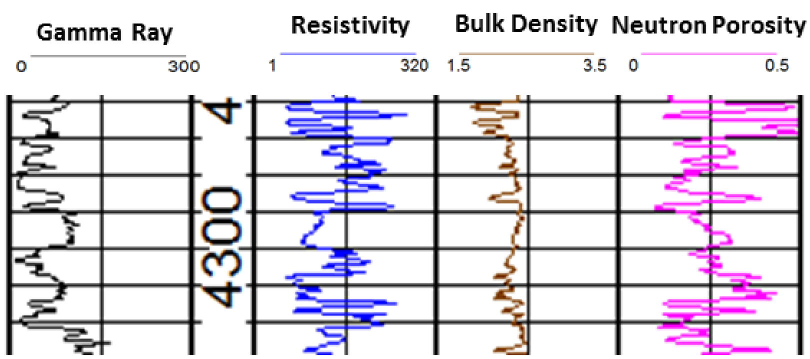

Figure 6.4a - Typical log response for FA4 and FA5; from Well 1021-21J

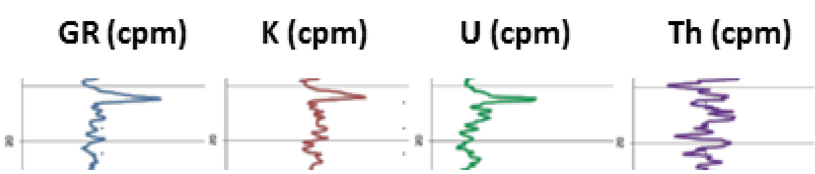

Figure 6.4b - Hay Canyon spectral gamma log response for FA4 and FA5

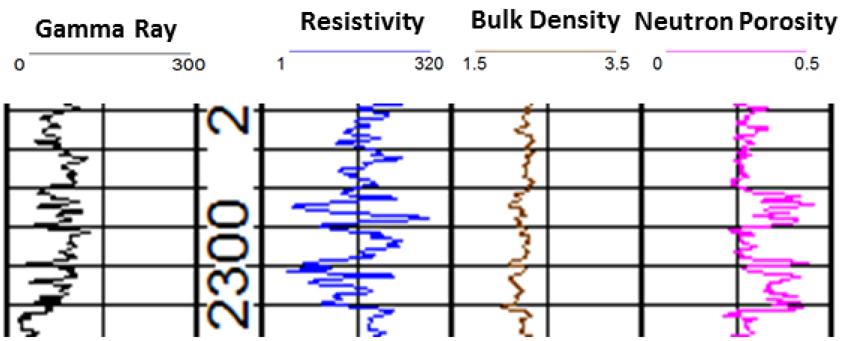

Figure 6.5 - Typical log response for FA7; from Well 1021-21J

6.6 – Interpretation of Cross Sections

Using the calibrations described above, both cross sections were interpreted for facies associations (Figs. 6.6 and 6.7).

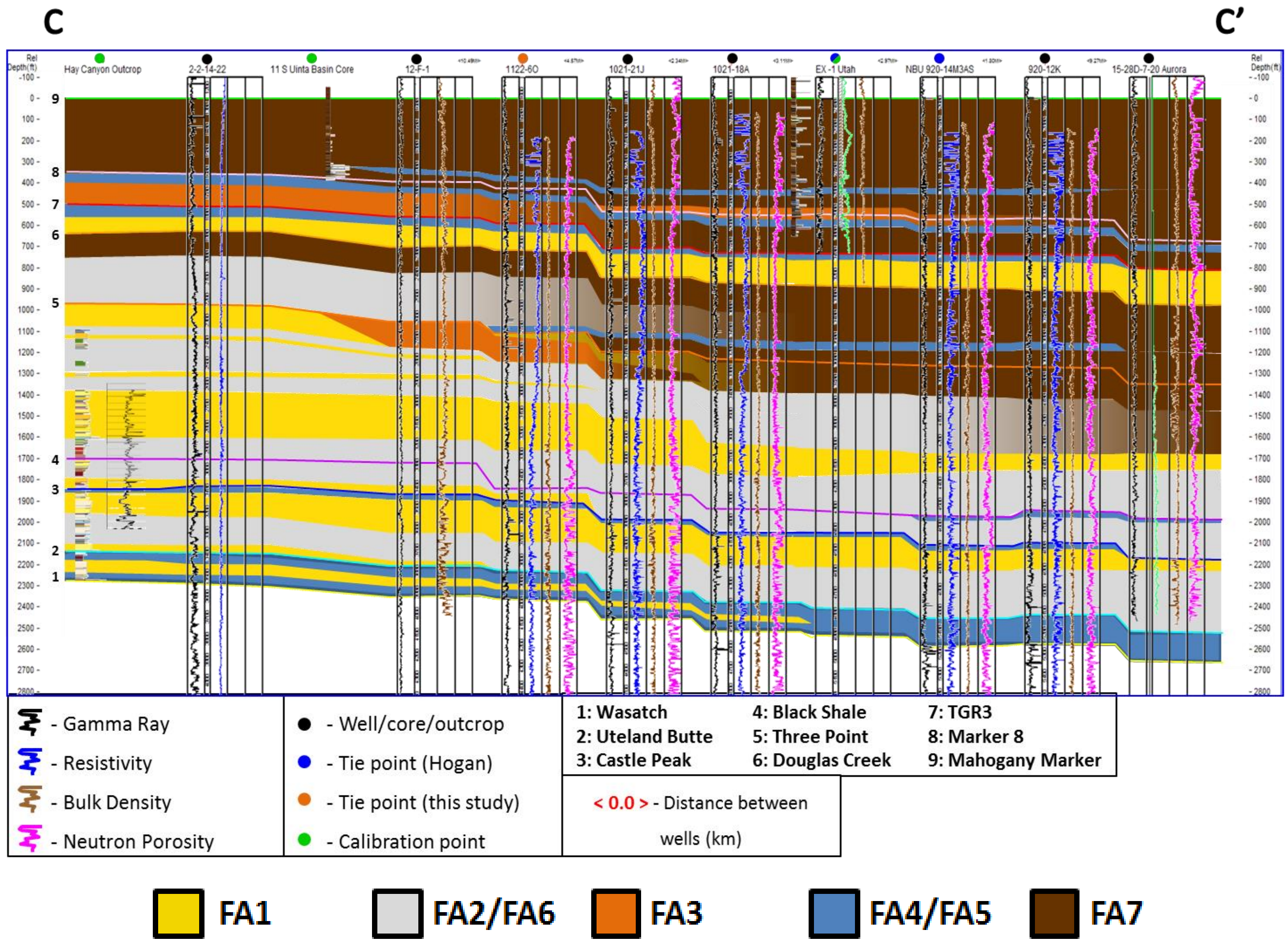

Figure 6.6 - Cross section C-C' interpreted according to the described log calibration

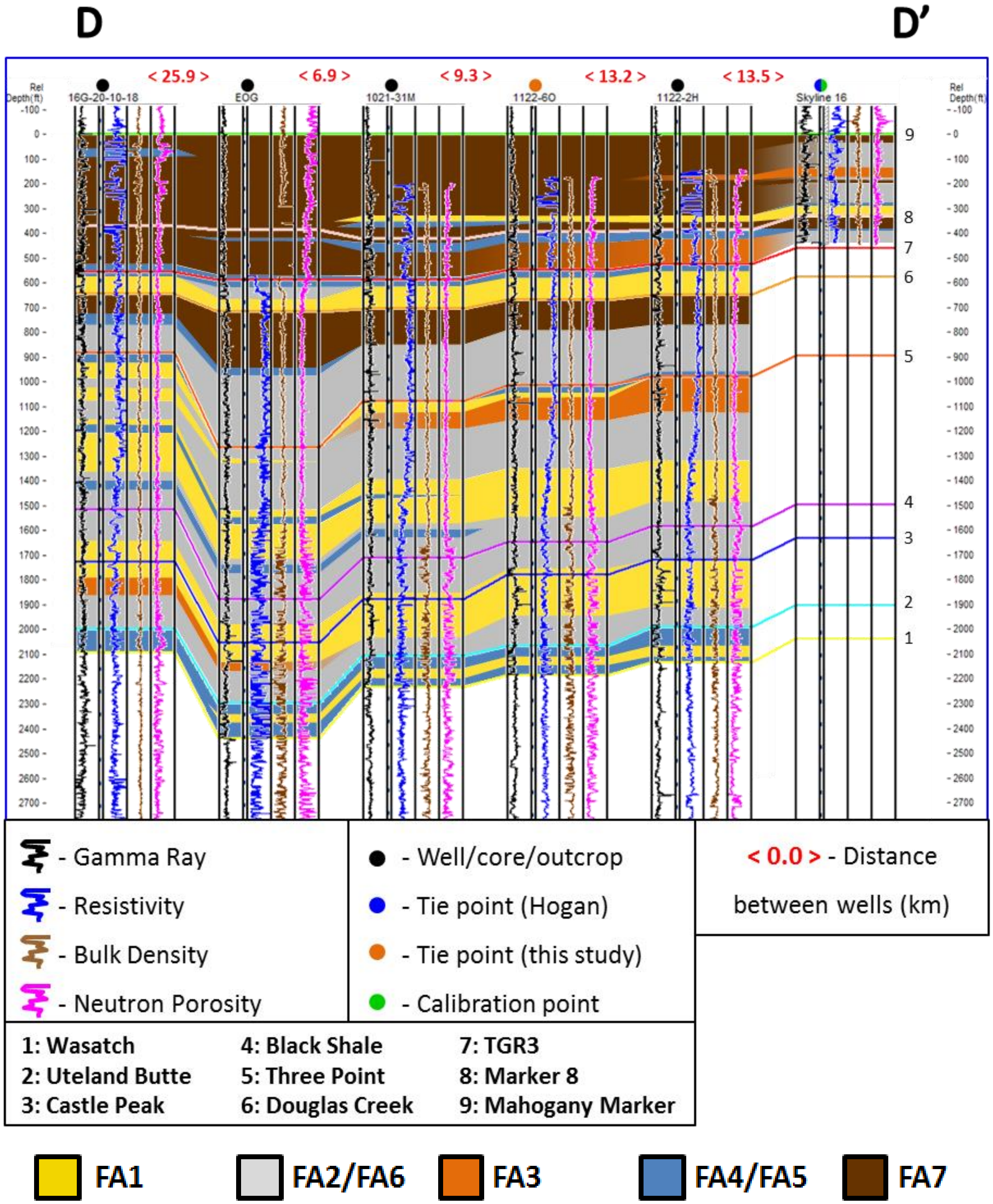

Figure 6.7 - Cross section D-D' interpreted according to the described log calibration

CHAPTER 7

DISCUSSION

Throughout the history of the Uinta basin, stratigraphic studies of the Green River Formation have dominantly focused on specific locations (see section "1.2 – Previous Work"), especially the outcrop belts in the south/southwest (e.g. Nine Mile Canyon and Hwy 191/Willow Creek Canyon) and east (e.g. Raven Ridge, Evacuation Creek, and Douglas Creek Arch). More recently, studies have also included the deeper basin center (Birgenheier and Vanden Berg, 2011) with its large number of well logs and cores due to resource production in the area. As each of these areas was examined, and especially when they are correlated with each other, two things are apparent: (1) some lithostratigraphic units are basin wide markers that can be correlated, even if nomenclature may differ, and (2) other lithostratigraphic units change significantly as they are traced across the basin.

This dichotomy revisits the decades-old discussion of lake level and lake type (Picard, 1955; Eugster and Surdam, 1973; Lundell and Surdam, 1975; Johnson, 1981; Smith et al., 2008; Tänavsuu-Milkeviciene and Sarg, 2012). Specifically, the facies distributions observed in this study point to an understanding that during some intervals in the development of Lake Uinta the lake level was both stable and deep enough that it deposited lithostratigraphic units that are correlative across the basin. This characteristic can be seen predominantly below the Three Point marker and above Marker 8. At other points, however, units are not correlative, and instead show marked change from margin to basin center, the characteristic seen from just below the Three Point up to Marker 8. These periods may represent periods of relatively rapid lake level change (i.e. change occurred quickly enough that no facies type was able to be preserved across the entire study area at that stratigraphic level) or are periods of intermediate lake level, where both marginal and profundal facies are preserved within the present day extent of the basin (very low or very high lake levels would have preserved mostly one dominant facies type [fluvial or profundal respectively] through the majority of the basin).

Additionally, this study shows two sediment sources: a southwestern source and an eastern source. The southwestern source is the main fluvial system that feeds into the basin (Dickinson et al., 2012). The eastern source has been previously identified by O'Hara (2013). The interpreted version of cross section D-D' (Fig. 6.7) shows more influence from the southwestern source below the Three Point Marker with little influence from this source above that marker (identified by the lack of fluvial and marginal facies associations above the Three Point marker in the westernmost wells of D-D'). The eastern source is seen through the entire section (identified by the packages of fluvial, deltaic, and marginal facies present in the easternmost wells of D-D'). However, the data used in this study and the scope of the study area are not sufficient to interpret any major changes in these two sediment sources. Cross section D-D' does not extend far enough to track the southwestern sediment source during the deepening and expansion of the lake observed above the Three Point marker. It is possible that the expanding lake causes the southwestern sediments to be deposited outside of the study area, without any diminishing of that source overall. The eastern end of cross section D-D' is located near the basin margin making the eastern sediment source identifiable even during the expanded lake deposition above the Three Point marker.

Because this study is integrated with Hogan (2015), it is important to compare the log calibrations of Hogan with the calibrations presented here. This comparison illustrates some differences in specific facies identified, but similarities in overall trends.

The major difference between this study and Hogan (2015) is the overall dominance of littoral to sublittoral mudstones interpreted by Hogan compared to the overall dominance of oil shale interpreted in this study. This is evident in three of the wells that are shared between the two studies: the EX-1 Utah well, the NBU 920-14M3AS well, and the 16G-20-10-18 well. The Skyline 16 well was directly described by Hogan, thus his facies calibrations were followed as closely as possible (slight adaptations were necessary due to different facies associations being used by the two studies). Note that Hogan only interprets above the Three Point marker, therefore comparisons only describe this interval (compare Figs. 7.1-7.2 with Fig. 6.6-6.7).

This study also interprets significantly less sandstone than is present in Hogan's interpretation. This is partly due to using different interpretations of the EX-1 Utah core. Hogan redrafted the description of Birgenheier and Vanden Berg (2011), whereas this study redescribed the core. In places, this study identifies individual interbedded sands and clays where Birgenheier and Vanden Berg describe thicker packages of sand. This difference in the vertical resolution of the descriptions has affected some of the fine-grained facies calibrations.

An additional factor is that this study differs from Hogan on the location of the stratigraphic markers in the EX-1Utah well, placing the Douglas Creek marker below the section, and the TGR3 marker, Marker 8, and Mahogany marker lower on the section than does Hogan. Based on log character alone, both placements (Hogan's and this study's) appear to be viable. Both placements also seem to be possible when correlating the wells of cross section B-B' of

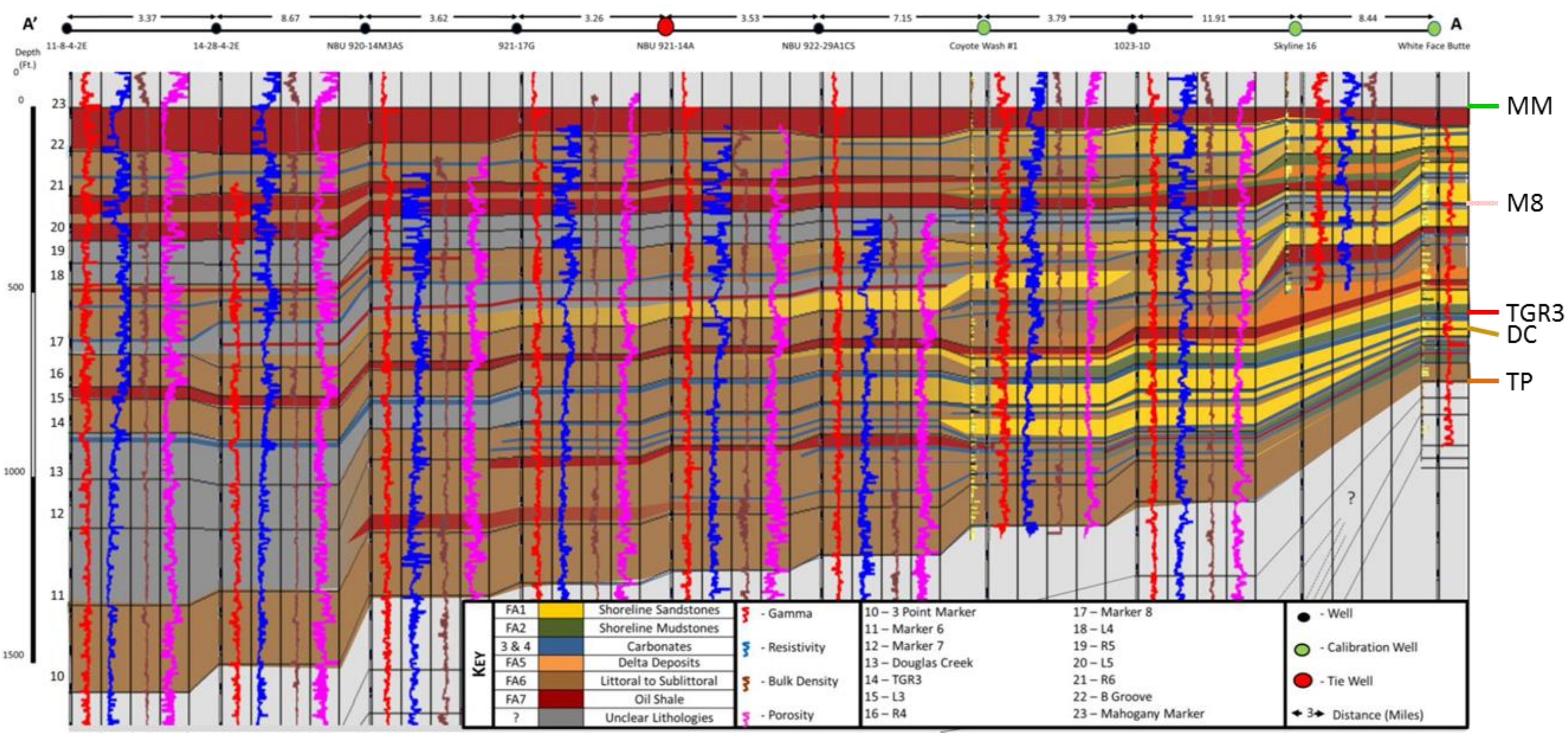

Figure 7.1 - Copy of Hogan's Fig. 5.15 showing interpretation of calibrated facies along cross-section B-B'; Wells NBU 920-14M3AS and Skyline 16 are tie points with this study. Abbreviations and colored lines added on the right identify the main markers used in this study: TP – Three Point, DC – Douglas Creek, TGR3 – TGR3, M8 – Marker 8, MM – Mahogany Marker.

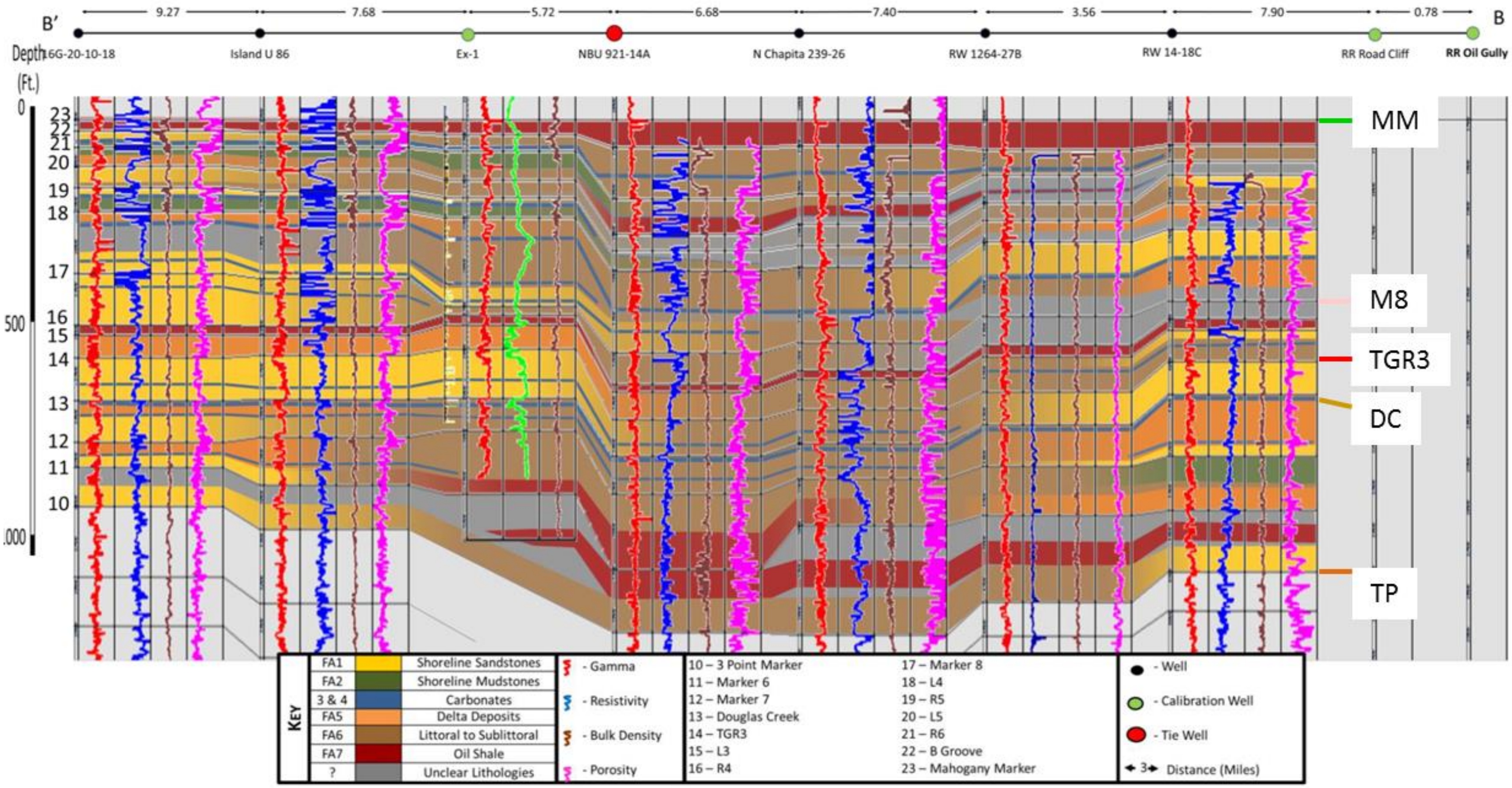

Figure 7.2 - Copy of Hogan's Fig. 5.16 showing interpretation of calibrated facies along cross-section B-B'. Wells 16G-20-10-18 and Ex-1 are tie points with this study. Abbreviations and colored lines added on the right identify the main markers used in this study: TP – Three Point, DC – Douglas Creek, TGR3 – TGR3, M8 – Marker 8, MM – Mahogany Marker.

Hogan (2015). However, when the additional wells from this study are added and correlated in cross section C-C’, only the lower placement of these markers appears to be viable (the higher placement would create an unexplained elevation of the markers and thinning of their respective intervals from the adjacent wells to the EX-1 Utah well).

While the additional data used by this study have allowed for a more fine-tuned calibration, the overall trends of both studies agree. Additional well logs and outcrop/core descriptions have simply added additional calibration points to improve the interpretation. Hogan’s interpretation of the EX-1 Utah well shows an influx of fluvial material topped by littoral to sublittoral siliciclastics and mudstones as well as oil shales with a few carbonate beds. Based on the redescription of the core and the lower placement of the markers, the current study places most of the core above the fluvial section, but interprets a similar upward transition to finer-grained oil shale with beds of carbonate. The fluvial influx interpreted in the adjoining wells of Hogan’s B-B’ cross-section correlates well with the other log signatures of this study’s C-C’ cross section. The 16G-20-10-18 well is the most divergent between the two studies, but again the overall pattern is the same, while the inferred grain sizes and facies differ. Hogan has interpreted shoreline/fluvial sandstones fining up into shoreline mudstones and deltaic facies with just a small amount of oil shales at the top. This study interprets shoreline mudstones, carbonates, and fluvial channels fining up more quickly into oil shales.

The NBU 920-14M3AS interpretation of Hogan is more similar to the interpretation in this study. Hogan interprets predominantly littoral to sublittoral siliciclastics with increasing upwards oil shale deposits and a few beds of carbonate. The current study interprets predominantly oil shale deposits with a few beds of carbonate. The main point of departure is a dominantly fluvial interval between the Douglas Creek and TGR3 markers; however, Hogan has an updip fluvial package at the same interval that he has interpreted as transitioning to littoral/sublittoral siliciclastics. Based on the consistent log signature from updip to basinward wells, this study interprets the fluvial facies as continuing farther into the basin.

In addition to comparisons between the log calibrations, comparisons can be made to the other findings of Hogan (2015). He found that the Castle Peak marker, interpreted as the top of the Castle Peak Reservoir (a term predominantly used in the southern part of the basin) was correlative to the Long Point Bed (a term used in the eastern basin and the Piceance Creek basin). This study adds weight to that finding by showing correlative markers that extend from the southern margin to the basin center (C-C') and from basin center to the eastern margin (D-D').

Hogan also interpreted the Skyline 16 core to be stratigraphically higher in the section than it had previously been interpreted to be. The D-D' cross section in this study lends support to this finding as well, showing strong correlation between log signatures of the neighboring well that indicates the Skyline 16 core only penetrates to just above the TGR3 marker.

CHAPTER 8

CONCLUSIONS

This study expands on the methodology of Hogan (2015) for calibrating well logs to the facies associations interpreted in the Green River Formation. Calibrating these wells to measured outcrop and core allows for greater accuracy in interpreting facies associations through the basin. Accuracy is dependent on the availability of well logs and calibrations points (outcrop and core).

8.1 – Further Work

This study focused on the southeastern section of the basin, and used most of the useful wells/cores in that region. However, in the process of identifying wells and cores to use for correlations, additional areas of study were noted moving westward and northward from basin center. A cross section in each of these directions would be very useful for tracking lake development and changes in sediment source (perhaps identifying the location of the southwestern fluvial source after the major lake level rise recorded in the Douglas Creek/Parachute Creek members).

Additionally, paleocurrent studies along the southern and eastern outcrop belts should be conducted to provide more precise constraints on the shifts in sediment direction. This information could be paired with provenance studies to determine whether the influx is from local drainage or a result of incorporating a southeastern fluvial system as lake level rose.

While this study shows that general calibrations can be made at the facies association scale, it does not incorporate any software in the process. The use of a neural network capable program to identify facies more systematically would presumably enhance the accuracy of these correlations. This software would be limited, however, by the variation in vintage and type of log suites available, especially for wells that have core available for description.

8.2 – Summary of Conclusions

(1) This study shows an increase in more profundal facies both moving basinward along the cross sections and upward in each individual outcrop, core, or well. This is interpreted as an increasing lake level as Lake Uinta initially floods the basin and then stabilizes.

(2) Petrophysical logs can be calibrated to rock types, but is inherently interpretive. It should only be attempted with multiple well logs (because no one log type is diagnostic for various facies), and a combination of gamma ray, density, and neutron porosity is preferred. However, given enough outcrop and/or core descriptions with which to compare, this type of calibration can be useful for understanding facies distribution and lake development.

(3) The D-D' cross section shows two sediments sources: a southwestern source and an eastern source. Influence from the southwestern source is observed below the Three Point marker; influence from the eastern source is seen throughout the section. The differences above and below the Three Point marker for the southwestern source may be a result of the expanding lake causes the southwestern sediments to be deposited outside of the study area. The eastern end of cross section D-D' is located near the basin margin making the eastern sediment source identifiable even during the expanded lake deposition above the Three Point marker.

(4) The cross sections from this study support the findings of Hogan (2015) that the base of the Skyline 16 core is higher than had been previously interpreted, and has a significant section of Green River stratigraphy below the base of core.

(5) The cross section from this study support the findings of Hogan (2015) that the top of the Castle Peak interval (represented by the Castle Peak marker in this study) in the south and west is correlative with the Long Point Bed in the east.

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APPENDIX A

SUPPLEMENTAL ELECTRONIC FILES

Supplemental files included in this thesis are composed of two cross sections (cross sections C-C' and D-D'; see Figs. 5.1 and 5.2). These cross sections are full resolution and can be used to better analyze the log suites. Cross section C-C' contains full resolution versions of each of the measured sections (Figs. 3.3a, 3.6, and 3.7).

Cross Section Files	Files containing full resolution versions of cross sections C-C' and D-D'.
Cross Section C-C'.pdf	PDF file of cross section C-C' containing all log suites used, markers identified, and full resolution versions of the measured sections from this study.
Cross Section D-D'.pdf	PDF file of cross section D-D' containing all log suites used and markers identified.