THESIS

SEQUENCE STRATIGRAPHIC DISTRIBUTION OF COAL-BEARING ROCKS FROM THE MESAVERDE GROUP IN THE EASTERNMOST ATLANTIC RIM OF THE WASHAKIE BASIN, WYOMING

Submitted by

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY JEFFREY M. DEREUME ENTITLED SEQUENCE STRATIGRAPHIC DISTRIBUTION OF COAL-BEARING ROCKS FROM THE MESAVERDE GROUP IN THE EASTERNMOST ATLANTIC RIM OF THE WASHAKIE BASIN, WYOMING BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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ABSTRACT OF THESIS

SEQUENCE STRATIGRAPHIC DISTRIBUTION OF COAL-BEARING ROCKS FROM THE MESAVERDE GROUP IN THE EASTERNMOST ATLANTIC RIM OF THE WASHAKIE BASIN, WYOMING

Coals occur in various levels of the siliciclastic Campanian upper Mesaverde Group in the Atlantic Rim area, Washakie Basin, south central Wyoming. This unit consists of continental, delta, and offshore facies showing several orders of internal cyclic architecture. At least five large-scale cycles form the upper part of the Mesaverde Group, internally arranged in stacks of up to five medium-scale cycles that are in turn subdivided into a maximum of five small-scale cycles. These cycles reflect million-year to Milankovitch-type sea-level fluctuations causing trans- and regression of varying magnitude, within an overall transgressive regime.

Coals developed preferentially in paralic and lower coastal plain environments in the Atlantic Rim in relative proximity to a nearby delta. The position closest to the shoreline was occupied by coal-rich mudstones reflecting siliciclastic input from the delta and the sea during floods. Both coals and coal-rich siliciclastic mudstones occur during all stages of a sea-level curve. While previous models suggested a preferential accumulation of coals during early transgressions, a peak in coal frequency characterizes early regressive sediments within the Mesaverde Group in the Atlantic Rim. This is believed to be the result of a heightened water table during early regressions promoting anoxic swamp and marsh environments, and frequent flooding of floodplains forming an ideal setting for accumulation of organic matter. The lateral continuity of Mesaverde coals is also positively influenced by development within paralic settings. Many of the most correlative coal seams in the Atlantic Rim occur within close stratigraphic proximity and/or lateral to marine deposits.

Integrating a sequence stratigraphic framework into the upper Mesaverde Group significantly enhances prediction patterns of coaly rocks by constraining their stratigraphic and lateral distributions. Clay- and silt-bearing organic-rich mudstones mark the transition from continental to marine facies, while pure coals only occur at a distance from the shoreline. The overall transgressive nature of the upper part of the Mesaverde Group reveals a highly diachronous facies distribution within the Washakie Basin. A significantly thicker coal-bearing interval characterizes the southern part, while successions further north show abundant mudstones, representing an overall earlier transition to marine conditions.

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This thesis is dedicated in loving memory to my father August John Dereume Jr., whose everlasting hard work and positive attitude has set the standard for which I strive to live my life.

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CHAPTER 1: INTRODUCTION

The Mesaverde Group of south-central Wyoming represents a succession of Upper Cretaceous strata that has recently become one of the most prominent new coalbed methane plays in the Rocky Mountain region (Cross, 1986; Lamarre and Ruhl, 2004; Livingston, 1982; Martinsen, 1993). Deposited landward of, and at the margins of the Western Interior Cretaceous Seaway, this succession contains transgressive-regressive cycles that are the product of tectonically and glacially-induced sea-level fluctuations (Glass, 1980; Livingston, 1982; Neuendorf, 1997). These changes have resulted in stratigraphic sequences that are proven to contain significant accumulations of methane-bearing coal source and reservoir rocks (Garcia-Gonzalez et al., 1996; Levey, 1985; Nummedal et al., 2002). The unconventional gas play covers 275 square miles of the 3,000 square mile Washakie Basin, targeting potential coals and carbonaceous shales of the Allen Ridge, Pine Ridge Sandstone, and Almond Formations of the Mesaverde Group. The stratigraphic accumulations of thermogenic and biogenic gas within this play have led to drilling and producing methane gas from fully saturated coals and carbonaceous shales of this area (Lamarre and Ruhl, 2004; Rice and Claypool, 1981; Tyler et al., 1992).

A detailed sedimentological model is needed in order to reassess and delineate marine versus nonmarine paleoconditions during Upper Cretaceous deposition of the Mesaverde Group. Numerous studies over the past few decades have returned ambiguous results, and a greater understanding is necessary to create predictive patterns for the formation and accumulation of coal-forming peat (Asquith, 1974; Ayers, 2002; Cobb and Cecil, 1993; Emery and Myers, 1996; Levey, 1985; Lewis, 1961; Livingston, 1982; McCord, 1984; Newman, 1981; Roehler, 1992; Roehler, 1990; Weimer, 1965; Weimer, 1966). Additionally, a sequence stratigraphic framework needs to be created in order to understand the stratigraphic occurrence and distribution of coaly rocks within transgressive-regressive cycles (Bohacs, 1997; Cross, 1988; Embry, 2002).

Current concepts envision that wide continental shelves which are successively flooded during initial transgression are ideal sites for accumulation and preservation of organic material (Cross, 1988; Ryer, 1983). However, on these coastal plains, channel avulsion will also influence formation and preservation of organic matter, so that the ultimate stratigraphic distribution of paralic to continental coals depends on both, allo- and autocyclic processes (Blaine, 1993; Bohacs, 1997; Cleveland et al., 2007; Livingston, 1982). This study, taking into account both factors, may therefore represent an ideal example for predicting the occurrence and extent of economically targeted carbonaceous rocks in other potential plays similar to the Mesaverde Group.

One of the main problems in exploiting coalbed methane plays is the influx of meteoric water, which in the case of the Allen Ridge, Pine Ridge Sandstone, and Almond Formations, is recharging via outcrops of the high Sierra Madres to the east. A large stratigraphic trap has formed by meteoric water holding thermogenic gas in place through downdip flow. The infiltrating freshwater likely promotes the production of biogenic gas, which is generated during decomposition of organic matter by anaerobic microorganisms (Rice and Claypool, 1981). Although meteoric recharge is contributing to the generation and emplacement of methane gas, the excess water must be produced in order to reduce average reservoir pressure and release the adsorbed methane (Schraufnagel, 1990). Autocyclic processes during deposition commonly lead to strata that are laterally discontinuous; however, connectivity between outcrop and subsurface has likely led to the infiltration and subsequent migration of meteoric freshwater. A greater understanding of potential and likely recharge pathways within Mesaverde formations can be attained by studying the continuity/discontinuity of outcropping coals, shales, and sands of the Washakie Basin.

In order to address the objectives of this project, the following hypotheses will be tested:

1. The most abundant coal accumulations within Upper Cretaceous strata of south central Wyoming are limited to times in basin evolution with wide shelf areas, namely the early and late transgressive systems tract.
2. Coal continuity within Upper Cretaceous strata of south-central Wyoming is a function of both allo- and autocyclic processes creating

isolated coaly intervals. Allocycles determine the position of coal in the stratigraphic framework, while autocyclic processes dissect and compartmentalize coal beds.

3. The marine sandstones of the Upper Cretaceous strata of south central Wyoming are porous and laterally continuous between outcrop and subsurface, therefore serving as a major potential recharging lithology for water influx into the producing zone.

The Mesaverde Group outcrops locally on the Rawlins-Sierra Madre uplift along the easternmost margin of the Washakie basin in south-central Wyoming (Fig. 1.1) (Roehler, 1990). The study area consists of two large outcrop sites (northern tower section, and southern JO Reservoir) along a north-south trending topographic ridge termed the Atlantic Rim, and three subsurface locations where cores AR Federal 1491 3-14, AR Federal 1591 13-15i, and AR Federal 1691 4-3 (roughly six miles apart) were drilled (Fig. 1.2). The two outcrop and three core locations are within the easternmost edge of the Washakie Basin[1].

[1] The tower section is found along the northern Atlantic Rim within Sections 10 and 11 of T.19N, R.89W. JO Reservoir is located in the central Atlantic Rim at Section 34 T.17N, R.90W. The three cores were taken east of the Atlantic Rim topographic ridge along a north-south trending transect. The southernmost AR Federal 1491 3-14 was drilled and cored within the NW 1/4 of the NE 1/4 of Section 14, T.14N, R.91W. The central AR Federal 1591 13-15i is located within the SE 1/4 of the NE 1/4 of Section 15, T.15N, R.91W. The northernmost AR Federal 1691 4-3 was taken at the NE 1/4 of the NW 1/4 of Section 3, T.16N, R.91W.

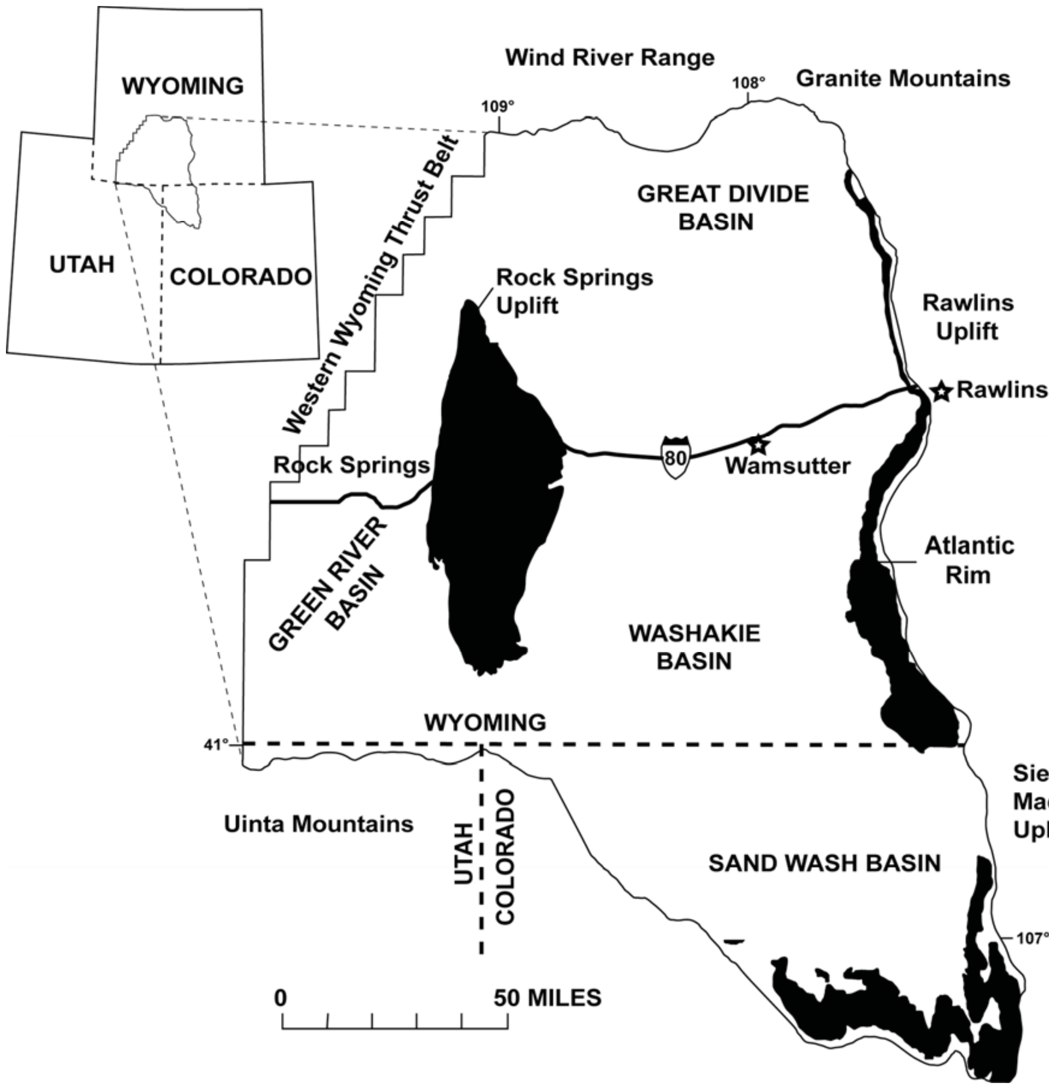


Figure 1.1. Location map showing the geographical areas and sub-basins of the Greater Green River Basin. Darkened areas indicate exposure of Upper Cretaceous (Mesaverde Group) strata. (Modified from Horn, 2001, and Roehler, 1990).

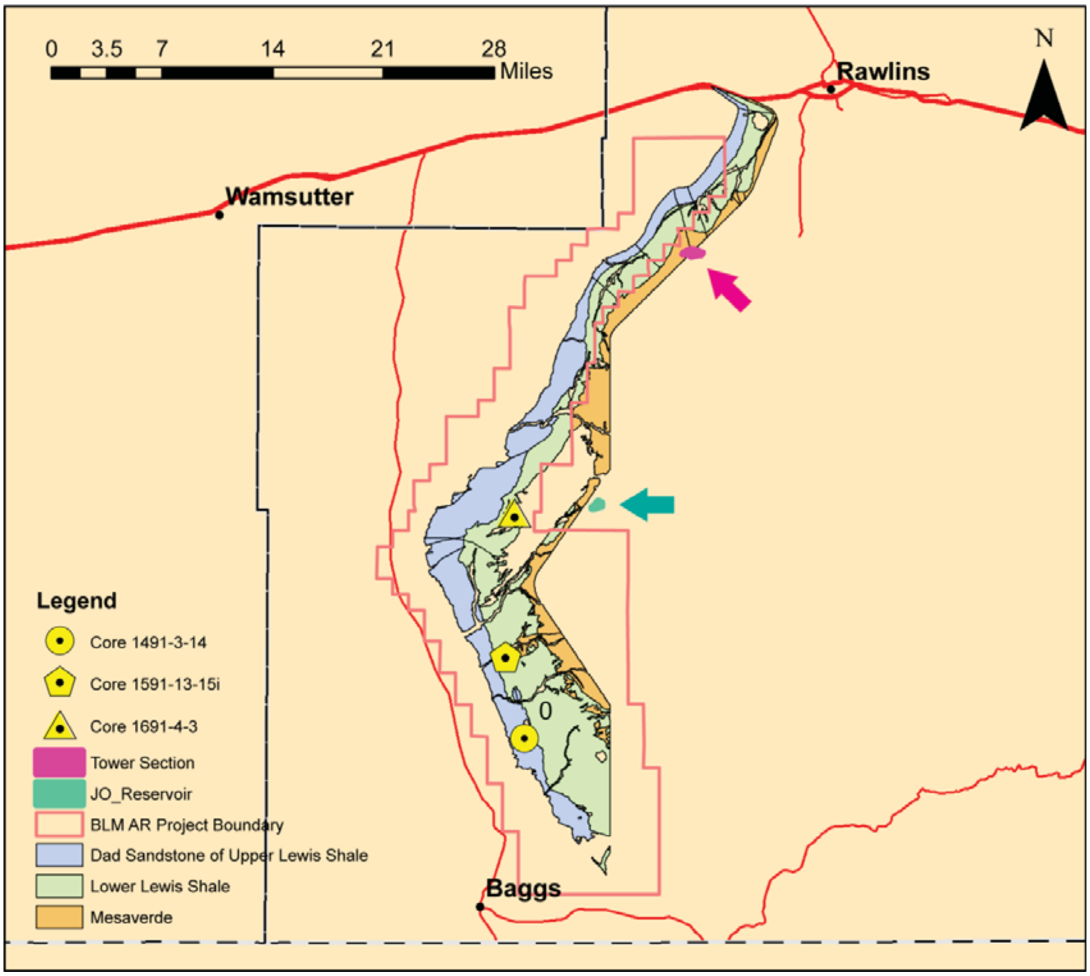


Figure 1.2. Core and measured stratigraphic section field locations found within the Atlantic Rim study area. (Data obtained from The Wyoming Geographic Information Science Center, and The Wyoming State Geological Survey).

CHAPTER 2: GEOLOGICAL SETTING

2.1 General aspects and tectonic evolution

The Greater Green River Basin is irregular in shape (refer to fig. 1.1), occupying 26,000 square miles in south-central Wyoming, with parts of the basin stretching into northeastern Utah, and northwestern Colorado (Roehler, 1990; Tyler et al., 1992). In its present stage, the basin is characterized by tectonically uplifted large-stand rims separated by broad shallow intramontane basins (Jacka, 1970; McCord, 1984; Tyler et al., 1992). Fragmented depressions/basins of the Greater Green River include the Green River Basin, the Great Divide Basin, the Washakie Basin (including the Atlantic Rim), and the Sand Wash Basin (Roehler, 1990). Positive topographic features confining these basins include the Western Wyoming Thrust Belt to the west, the Wind River Range to the north/northeast, the Rawlins and Sierra Madre Uplifts to the east, and the Uinta Mountains to the south (Fig. 2.1) (Castelblanco-Torres, 2003; McCord, 1984; Roehler, 1992).

With the breakup of Pangaea (175-55 Ma), compressional movement began along the western margin of North America as the Farallon tectonic plate was subducted beneath the North American tectonic plate, initiating volcanism, and leading to numerous orogenic events across much of western North America

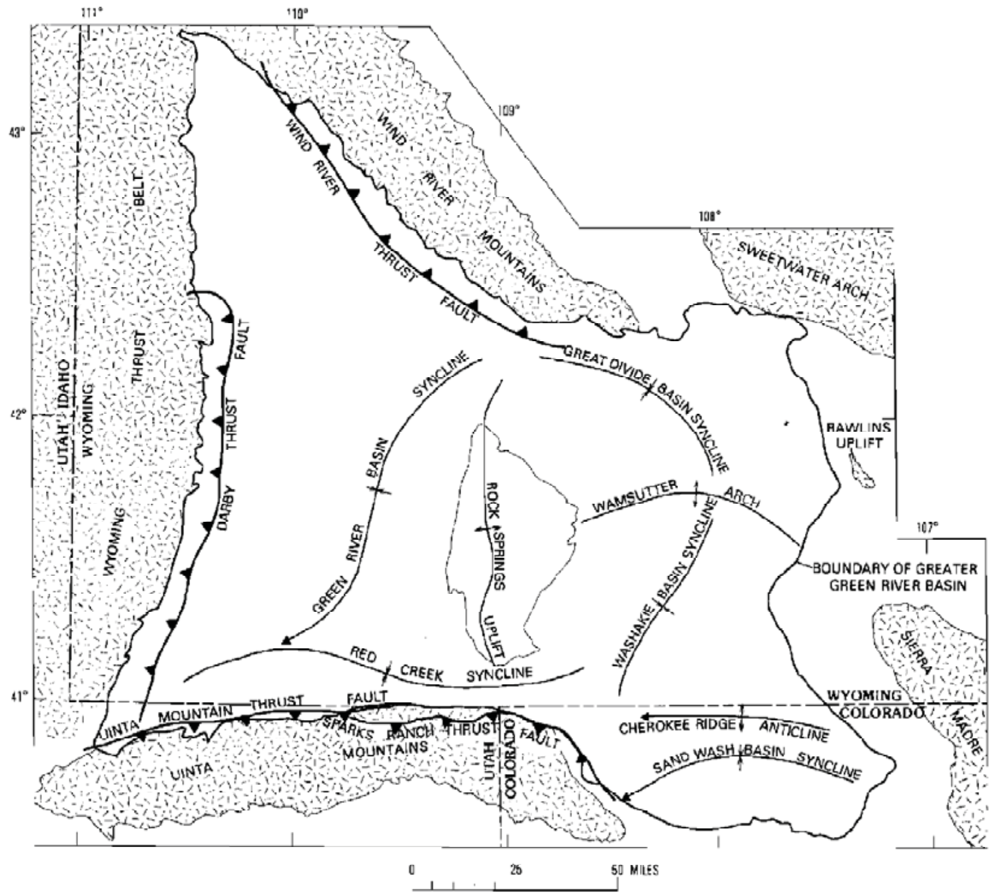


Figure 2.1. Key structural features documented within the Greater Green River Basin. (From Roehler, 1992).

and Canada (Cross, 1986; Kellogg et al., 2004). During the Late Jurassic (161.2-145.5 Ma), tectonic activity altered the area now occupied by the Greater Green River Basin shifting it from shallow-sea deposition on a continental shelf towards foreland basin deposition (Baars et al., 1988; Castelblanco-Torres, 2003; Cross, 1986). The newly formed foreland basin combined with high eustatic sea-level of the Cretaceous Period (145.5-65.5 Ma), allowed for warm water from the proto-Gulf of Mexico and cool water from the proto-Arctic Ocean to meet and flood the continental lowlands, forming the Western Interior Cretaceous Seaway (Fig 2.2) (Arthur and Dean, 1998; Blakey, 2009; Roehler, 1990). The Sevier orogeny (115-74.5 Ma) was initiated by compressional tectonism along North America's western margin, and resulted in the development of the Sevier fold and thrust belt across much of the western North America.

Figure 2.2. Late Cretaceous paleogeography of North America showing the approximate location of the Western Interior Cretaceous Seaway. Red star represents location of field study (From Blakey, 2009).

The strata of the Mesaverde Group (79.8-71.4 Ma) (Baars et al., 1988; Ogg et al., 2009) belong to a stage of basin development spanning both the Sevier and Laramide orogenies. The initiation of the Laramide orogeny (74.5-45 Ma) is marked by a decrease in subduction angle of the Farallon Plate, inferred from local rates of decreasing magmatism and increasing foreland subsidence (Baars et al., 1988; Cross, 1986; Saleeby, 2003). Decreased magmatism resulted from an eastward shift in lithospheric melting, while increased subsidence was caused by lithospheric loading and cooling. Towards the end of the Cretaceous and early Paleogene Periods, the previously established foreland basin was fragmented by basement-involved thrusting and folding in response to continued horizontal compressional forces from the west (Baars et al., 1988; Otteman and Snoke, 2005; Rodgers, 1987; Tyler et al., 1992). These forces drove localized uplifts, which created the present-day boundaries separating the four intramontane basins that make up the Greater Green River Basin (Bader, 2008; Castelblanco-Torres, 2003; Tyler et al., 1992). The end of the Laramide orogeny (45 Ma) was marked by the shearing off and subsequent foundering of the Farallon Plate, which reestablished regional magmatism, subsidence, and a normal subduction angle (Cross, 1986; Humphreys, 1995; Saleeby, 2003). Remnants of the Farallon Plate still exist as the Juan de Fuca and Cocos Plates, which are presently being subducted beneath the North American Plate along the western margin of North America.

2.2 Depositional environments

The Upper Cretaceous strata of the Greater Green River Basin is represented by stacked delta front transgressive sandstones and offshore muds, alternating with regressive pulses of estuarine, lagoonal, and fluvial deposits, including abundant coals (Caldwell, 1975; Nummedal et al., 2002). Within the

Upper Cretaceous strata, the Mesaverde Group was deposited as marine (towards the east) and nonmarine (towards the west) intervals controlled by fluctuating sea level (Entzminger, 1980; Lewis, 1961; Roehler, 1990). Deposition occurred in and along the western flank of the Western Interior Cretaceous Seaway, while the climate ranged from warm/temperate to subtropical with heavy annual rainfall (Kiteley, 1983; Weimer, 1965). The Sevier orogenic belt to the west combined with localized intra-basinal Laramide uplifts supplied sediments to the low-lying Greater Green River Basin-center(s) during the Late Cretaceous Period (McGookey et al., 1972; Tyler et al., 1992). Continental formations of the Mesaverde Group show westward thinning due to sediment bypass and erosion by high-energy fluvial systems during the Late Cretaceous Period, while an eastward fining trend reflects increasing distance from the sediment source, successively decreasing energy levels, and more mature sediment. Similarly, marine successions are thicker towards the east, exhibiting thousands of feet of marine mud, silt, and sand deposited within the paleoseaway (Barlow et al., 1993).

Given the time-span (8.4 Ma) represented by the Mesaverde Group, depositional environments were variable, ranging from freshwater coastal plain through transitional brackish-water, to shallow and deep offshore-marine (Asquith, 1974; Pyles and Slatt, 2000; Roehler, 1990). These environments shifted basin- and landward under the influence of sea-level fluctuations. Clastics were transported and deposited in and along continental settings, as well as being bypassed eastward into the Western Interior Cretaceous Seaway, creating thick packages of fluvial sediment that interfinger with offshore marine muds (Asquith, 1974; Barlow et al., 1993; Martinsen, 1993). Fueled by abundant sediment supply, shorelines prograded towards the southeast during regressions, and aggraded and retrograded towards the northwest during transgressions (Horn et al., 2001; McGookey et al., 1972; Newman, 1981; Roehler, 1990)

Along the eastern margin of the Washakie Basin (refer to fig. 1.1), the Steele Shale Formation underlying the Mesaverde Group represents offshore marine deposition of mud and silt. Lower formations of the Mesaverde Group including the Haystack Mountains, Allen Ridge, and Pine Ridge Sandstone Formations have sedimentary characteristics of continental deposition with minor marine influxes (Roehler, 1990). As described in the literature, the overlying Almond Formation is broken into 2-3 stratigraphic intervals defined by a basal freshwater coastal plain depositional environment, which is overlain by paralic and ultimately marine shoreline deposits (Livingston, 1982; Roehler, 1990). Following the deposition of the Almond, the Lewis Shale Formation occurred during the westward transgression of the Western Interior Cretaceous Seaway, and is characterized by offshore marine muds, with intervals of silt and fine-grained sands.

2.3 Stratigraphy and basin fill

The term Mesaverde Group has been used in various basins throughout Wyoming to classify a succession of Campanian (83.5-70.6 Ma) strata sharing common depositional characteristics. Although the nomenclature includes a variety of different formations, time spans, and depositional environments across the region, the main subdivisions are intervals of major transgressions and regressions (Barlow et al., 1993; Caldwell, 1975). A simplified stratigraphic column shows the Mesaverde Group and subdivisions in relation to surrounding formations within the Washakie Basin (Fig. 2.3).

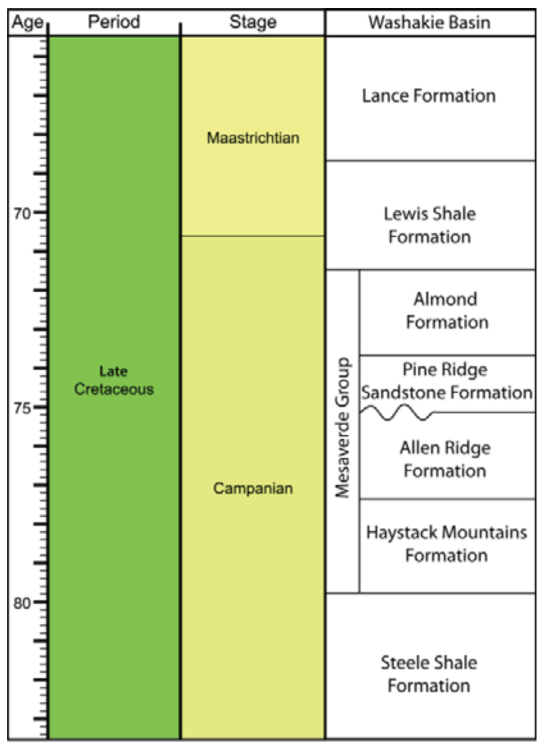


Figure 2.3. Simplified stratigraphic column of the Washakie Basin (Timescale data acquired from Ogg, 2009 and lithologic column modified from Baars *et al*., 1988).

The Mesaverde Group of the Washakie Basin is sandwiched between the underlying Steele Shale Formation and the overlying Lewis Shale Formation (refer to fig. 2.3). According to Roehler (1990), deposition of the Mesaverde Group occurred during two major marine transgressions and regressions, the result of tectonically and glacially-induced perturbations within the western margins of the Western Interior Cretaceous Seaway. Regardless of greenhouse conditions during the Cretaceous Period, ephemeral Antarctic ice sheets present between 100 and 33 Ma were likely significant enough to cause fluctuations of eustatic sea-level (Miller et al., 2005).

The earliest transgression-regression resulted in the deposition of the Steele Shale Formation and the lower part of the Mesaverde Group including the Haystack Mountains and Allen Ridge Formations. The Steele Shale Formation underlies the Mesaverde Group in the Atlantic Rim; however, farther to the east it occurs time-equivalent to the lower part of the Mesaverde Group (Roehler, 1990). Deposition of the Steele Shale Formation and the lower part of the Mesaverde Group are recorded over 6 million years, and shows immense stratigraphic thickness (Barlow et al., 1993) of up to 1,000's of feet for the Steele Shale Formation (Roehler, 1990), 1,000 feet for the Haystack Mountains Formation, and 1,900-2,600 for the Allen Ridge Formation.

A second episode of transgression-regression occurred from 75-65.5 Ma, resulting in the deposition of the upper part of the Mesaverde succession including the Pine Ridge Sandstone and Almond Formations. According to regional cross sections developed by Roehler (1990), to the east of the Atlantic

Rim, the Lewis Shale Formation is time-equivalent to the Almond Formation; however, west of the Atlantic Rim the Lewis Shale Formation overlies the Almond Formation, marking a major westward transgression of the Western Interior Cretaceous Seaway. Recorded over 3 million years, this second transgressive-regressive episode exhibits formation thicknesses thinner than those of the lower part of the Mesaverde Group, and abundant marine deposition (Barlow et al., 1993).

The base of the Pine Ridge Sandstone Formation marks a regressive maximum, expressed through an unconformity (Livingston, 1982; Roehler, 1990). Livingston (1982) noted the variable expression of this unconformity as well-documented in some localities, assumed in others, and nonexistent in a few sites. The Pine Ridge Sandstone Formation is similar to the other Mesaverde units representing variable thicknesses moving from west to east. Roehler (1990) recorded the Pine Ridge Sandstone Formation thickness between 50 and 250 feet near Rock Springs, with a significant thickening to several hundred feet towards the east, while core data from this project show a thickness of around 300 feet. The overlying Almond Formation also exhibits lateral variations in thickness. Roehler (1990) documented a thickness range between 300 and 800 feet, while core data from this project show a thickness of between 275 and 285 feet. The overlying Lewis Shale Formation is expressed as an immense package of up to 2,500 feet in thickness (Almon et al., 2005; Almon et al., 2001; Castelblanco-Torres, 2003; Roehler, 1990). The discrepancy in formation thicknesses is due to the broad regional scale of Roehler’s study, with larger stratigraphic packages of the Mesaverde Group being measured toward the west. Also, while this study integrates detailed sedimentological and stratigraphic data to identify formation tops, Roehler (1990), relied heavily on bio- and lithostratigraphy to highlight changes in the rock units.

CHAPTER 3: METHODOLOGY

The data used in this research was acquired from the stratigraphic description of three cores (refer to Fig. 1.2) and ten field-based measured sections (Fig. 3.1) followed by facies analysis, correlation, and facies modeling. Three cores (see Appendix I) AR Federal 1491 3-14, AR Federal 1591 13-15i, and AR Federal 1691 4-3 measuring 930.8', 624.1', and 742.0' respectively, were documented in detail during the spring and summer of 2009 with the aid of a 10x magnification hand lens and 10% HCl solution. These cores were analyzed with a focus on the upper part of the Mesaverde Group including the Allen Ridge, Pine Ridge Sandstone, and Almond Formations. Formation top depths from petrophysical well logs were assigned by Anadarko Petroleum Corporation (APC), and later adjusted in this study to accommodate missing core intervals that were lost during the drilling process. Cores AR Federal 1491 3-14 and AR Federal 1691 4-3 show the Allen Ridge, Pine Ridge Sandstone, and Almond Formation tops, while core AR Federal 1591 13-15i contains the Allen Ridge Formation top and only the lower part of the Pine Ridge Sandstone Formation. Criteria used while measuring and describing core include interval and bedding thickness, lithology, grain size, bioturbation index, sedimentary structures, ichnofossil identification, and nature of contacts.

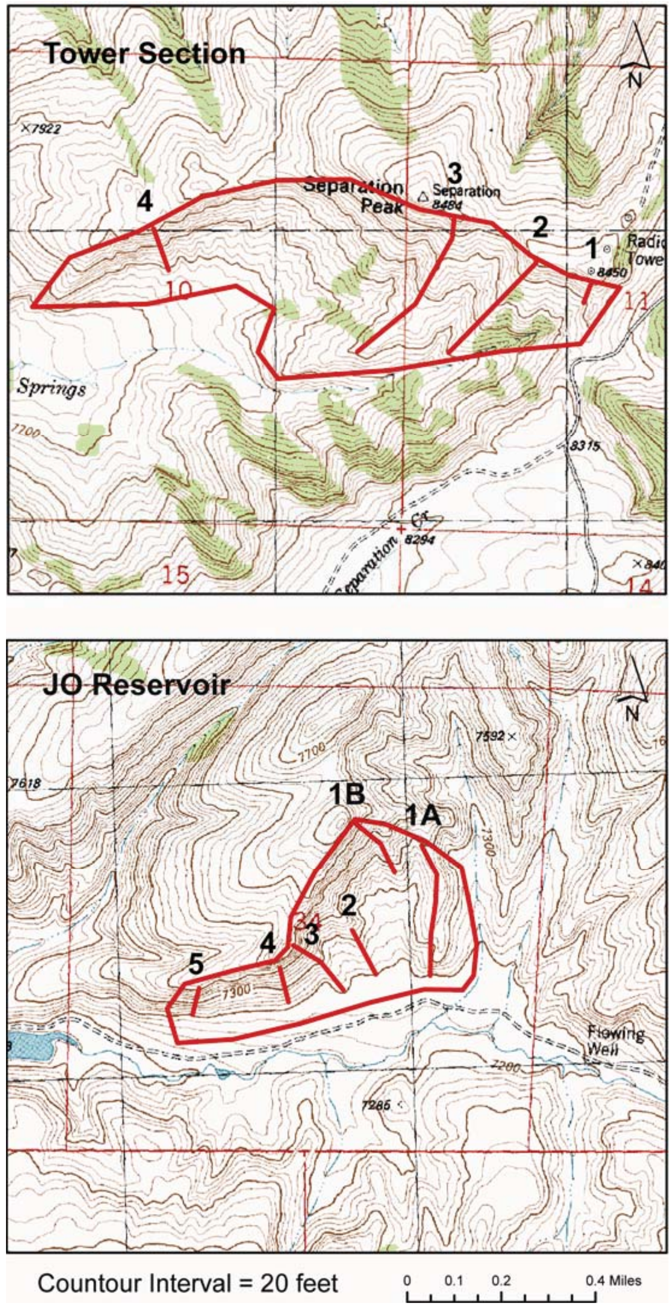


Figure 3.1. Carbon County locations of the Tower Section and JO Reservoir outcrop transects within the Atlantic Rim (refer to Fig. 1.2). Stratigraphic columns and study area boundaries are highlighted in red with the columns labeled in black. Approximate locations of Tower Section, Sections 10 and 11 of T.19N, R.89W; and JO Reservoir, Section 34 T.17N, R.90W (Data obtained from The Wyoming Geographic Information Science Center, http://www.uwyo.edu/wygisc/; and The Wyoming State Geological Survey, http://www.wsgs.uwyo.edu/).

Fieldwork was conducted during the spring and summer of 2009. Outcrop locations were chosen during a reconnaissance trip throughout the Atlantic Rim field area. Localities were selected based on the quality of exposure, proximity to core locations, and APC drilling efforts. Ten field-based measured sections (see Appendices II and III) were sampled and described in two areas (northern Tower Section and southern JO Reservoir) (refer to Fig. 1.2), a total of 2,256 feet. The Tower sections are numbered 1 through 4 and sections at the JO Reservoir location are numbered 1A through 5 moving from east to west. The criteria used while measuring and describing the outcrop sections are identical to those used during core documentation.

Facies, facies associations, and stacking patterns were assigned to the three core and ten outcrop descriptions during the fall and winter of 2009. The core and outcrop stratigraphic sections were digitized using PSICAT (http://psicat.org/), an online stratigraphic interval construction and analysis program. These sections were subsequently exported to Adobe Illustrator for further analysis and correlation.

Using the facies, facies associations, and stacking patterns assigned to the measured sections, flooding surfaces were identified based on their unique marine signatures. Marine flooding surfaces are practically isochronous surfaces separating younger from older strata that provide evidence for an abrupt increase in water depth (Abreu et al., 2009). These surfaces bound a cycle of deposition both above and below, and create the most effective and accurate correlation of genetically related strata within the Atlantic Rim. Field-based measured sections were correlated using photo mosaics of each outcrop locality to laterally trace distinguishable beds within each location.

CHAPTER 4: SEDIMENTOLOGY OF THE MESAVERDE GROUP

4.1 Introduction

The sedimentology of the Mesaverde Group of southern Wyoming was analyzed through three detailed drill core descriptions and ten field-based stratigraphic measured sections. From this analysis, thirteen lithofacies are identified, described, and listed in order of increasing grain size and distinct sedimentary structures. These thirteen facies are grouped into three facies associations. These depositional facies and facies associations are characteristic of distinct depositional environments.

4.2 Facies description and interpretation

4.2.1 Coal (Facies CO)

Description

The coals of the Mesaverde Group are black in color, and contain variable amounts of altered and compacted organic material (see Fig. 4.1). Beds range in thickness from less than one inch, to up to 3 feet, and rarely reach thicknesses of up to 10 feet. Both upper and lower contacts occur as sharp or gradational. Two abutting cleat[2] orientations within this facies are well defined in core, but they are

[2] A natural fracture in a coal seam resulting from coal dehydration, local and regional stresses, and unloading of overburden (Tyler et al., 1992).

sometimes difficult to view in outcrop. Occasionally there are silt and fine-grained sand lenses oriented horizontally within 6 inches of upper contacts which measure less than 1 inch, and can show internal current ripple lamination.

Interpretation

Deposited within a mire environment, the coals represent successively accumulating peat with little to no clastic influx (Bohacs, 1997; Galloway and Hobday, 1983). While upper horizons of accrued peat have high organic productivity, lower horizons become anoxic due to an elevated water table and overlying peat density. Smaller coalbed thicknesses suggest more frequent shedding of clastics into the peat-forming environments, resulting in the cessation of peat accumulation, while greater coalbed thicknesses represent a depositional environment more isolated from clastic incursions where peat can continue aggrading relatively unhindered (Cobb and Cecil, 1993). Upper contacts often represent interruptions in peat accumulation, having sharp contacts resulting from rapid sediment influx, and gradational contacts where clastic input occurred more gradually. Sand and silt lenses were likely incorporated into the coals during episodic clastic input, with sediment penetrating and settling in the uppermost intervals of accumulating peat (Galloway and Hobday, 1983).

4.2.2 Carbonaceous mudstone (Facies CM)

Description

This facies is a dark blackish-grey colored laminated mudstone (see Fig. 4.2), containing high amounts of organic material, with coal (facies CO) fragments and lenses throughout. The coal fragments are oriented parallel to bedding and measure less than 2 inches in diameter. Interval thicknesses vary from 4 inches up to 14 feet, and upper and lower contacts occur as sharp or gradational. Occasionally, millimeter-scale laminations of fine- to medium-grained sand are intercalated parallel to bedding, within 5 inches of the upper contact.

Interpretation

This facies represents a low-energy, highly-vegetated wetland-type depositional environment, which is reflected in the abundance of mud and partially preserved organic material. It was a relatively tranquil setting, dominated by the overbank deposition of muds and clays. The combination of accumulating mud and organic matter and a high water table resulted in subsurface anoxic conditions, leading to the partial preservation of organic material. Small carbonaceous mudstone thicknesses were created by sand influx into the wetland-type environment which interrupted mud aggradation, while large mudstone thicknesses resulted from successive overbank sedimentation. Gradual shifts from low- to high-energy deposition likely occurred where fine- to medium-grained sand was incorporated near the upper contact.

This episodic input of clastics suggests a shift in deposition characterized by a mud-dominated low-energy wetland environment which was inundated by a nearby high-energy silt- and sand-dominated fluvial environment.

4.2.3 Laminated silt to medium-grained sand-rich mudstone

(Facies LM)

Description

This mudstone is typically light bluish-grey in color and contains varying amounts of silt to medium-grained sand (see Fig. 4.3). Intervals of this facies range from 1 inch up to 20 feet, but are more commonly between 2 and 4 feet thick, having upper and lower contacts occurring as sharp or gradational. Bedding is defined by mud, silt, and occasionally sand that is preferentially accumulated, creating continuous and discontinuous horizontal laminae less than 1/4 inch thick. Organic material is infrequently preserved as millimeter to up to 1 inch diameter fragments. Individually the fragments have a horizontal orientation, while collectively they are preferentially accumulated parallel to bedding. Ichnofossils occur in places within this facies and include *Planolites* and *Zoophycos,* as well as the occasional presence of thin-walled mollusk shell fragments. The shell fragments are oriented concave-down and parallel to bedding. In outcrop these mudstones tend to be very fissile, and dry quickly when exposed to air.

Interpretation

This mudstone represents a low-energy depositional environment, which is reflected by the dominance of mud in this facies. The presence of silt to medium-grained sand laminae suggest that episodic silt- and sand-introducing moderate-energy events occurred during deposition. The medium-grained sands indicate limited erosion of sediment prior to deposition, suggesting a close geographic proximity between sediment source and depositional environment. The laminations which occur could also be the remnants of migrating floccule ripples (Schieber et al., 2007; Schieber and Yawar, 2009). Preserved organic material suggests that either conditions were tranquil and anoxic or that episodic sedimentation events created rapid burial, otherwise the non-resistant organic matter would have been decomposed and degraded by detritivores (detritus feeders) and ultimately not recorded in the rock record (Labandeira et al., 1997).

4.2.4 Silt-rich bioturbated mudstone (Facies BM)

Description

This mudstone consists of bioturbated mud (bioturbation index between 2 and 3 (Taylor and Goldring, 1993)) (see Fig. 4.4), that has a silt content between 10 and 30%, and lacks preserved and/or identifiable ichnofossils. Intervals of this facies are commonly between 3 inches and 3 feet in thickness, while upper and lower contacts occur as sharp or gradational. Bedding is difficult to define; however, the mud and silt can be preferentially accumulated creating irregular and discontinuous horizontal laminae, which occasionally show sediment loading where overlying silt has sunk into the mud.

Interpretation

This mudstone represents deposition within a fluctuating low- to moderate-energy environment, characterized by low-energy mud and clay deposition, interspersed with episodic moderate-energy silt sedimentation. Bioturbation was intense enough that it destroyed many of the trace fossils and original bedding structures. The resultant irregular, discontinuous, and horizontal mud and silt laminae are probably remnants of planar laminated bedding. The variable silt content reflects the recurrence of moderate-energy events interrupting low-energy mud and clay sedimentation. Deposition of this facies likely occurred in an offshore marine environment below fair-weather wave base, but above storm wave base where conditions for bottom dwelling organisms were favorable.

4.2.5 Ichnofossil-bearing mud/siltstone (IM)

Description

This facies consists of mud and siltstone, with abundant preserved ichnofossils (bioturbation index between 3 and 4 (Taylor and Goldring, 1993)) (see Fig. 4.5). *Chondrites, Phycodes, Teichichnus, Terebelina, and Zoophycos* are characterized by a variety of burrow structures that range from vertically to horizontally oriented. Bedding is unclear and indefinable throughout this facies; however, there is preferential accumulation of irregular and laterally discontinuous mud and silt laminae measuring up to 1/4 inch. Both upper and lower contacts typically appear gradational.

Interpretation

This facies was likely deposited in a low- to moderate-energy setting, which is indicated by low-energy sedimentation of mudstones with episodic silt influx likely occurring during moderate-energy events. Very little preserved bedding and irregular and discontinuous mud and silt laminae are the result of intense biological activity, while horizontal laminae suggest remnant planar bedding. A mixed association of suspension and deposit feeders is inferred from the large variety of trace fossils. The intense biological activity indicates that living conditions were favorable for bottom dwelling organisms, and only occasionally interrupted by higher energy depositional events. These characteristics reflect deposition within an offshore marine environment at or above storm-wave base, indicated by the periodic influx of higher energy silt.

4.2.6 Mottled mudstone (Facies MM)

Description

This mottled facies consists of bioturbated (bioturbation index between 4 and 5 (Taylor and Goldring, 1993)) muds (see Fig. 4.6), which are devoid of sedimentary structures and occur in intervals ranging from 2 to 20 feet in thickness. The mud breaks preferentially along clay-rich contacts, into millimeter- to centimeter-scale irregular lenses. These lenses contain silt, which appears to be preferentially accumulated horizontally, creating irregular and laterally discontinuous laminae. *Chondrites* occurs as vertical to subvertical, rounded and elongated trace fossils measuring less than 1/4 inch in diameter, which have a mud lining and fill.

Interpretation

These mottled muds represent relatively low-energy deposition in a distal offshore marine setting. The high percentage of mud and lack of sands suggest deposition occurred below or close to storm-wave base, while the presence of *Chondrites* is indicative of a fully marine depositional environment having very low oxygen levels (Bromley and Ekdale, 1984). The irregular mottled texture of this facies is likely a combination of compaction and intense bioturbation representing favorable living conditions at the sea floor. During the successive burial of saturated muds and clays, an overburden load is eventually reached and leads to sediments being compacted. This compaction results in a rapid escape of water and subsequent distortion of the original sediment fabric (H.H. Rieke and Chilingarian, 1974). The clay-rich contacts these muds break preferentially along, likely result from remnant bedding and/or bioturbation. The small range of grain sizes combined with consistency between burrow infill and surrounding sediment probably diminishes the visibility and identification of most trace fossils.

4.2.7 Convolute and horizontally-bedded very fine-grained sandstone (Facies CS)

Description

This facies is characterized by very fine-grained sandstones containing irregular intercalations of mud and silt (see Fig. 4.7), in intervals measuring less than 10 feet in thickness. Mud and silt content is variable ranging from as little as 10% to as much as 40%. Bedding of this facies appears horizontal to subhorizontal and is defined by millimeter- to centimeter-scale planar and/or ripple laminations. Within 3 feet of the upper contact, bedding becomes convolute and consists of millimeter- to centimeter-scale wavy, disorganized, and folded laminae (Lamberson and Bustin, 1993). The convolute bedding contains centimeter-scale faulting, and a localized amalgamation of mud, silt and sand creating a cloudy appearance. Centimeter-scale subangular to subrounded mud lithoclasts and millimeter- to centimeter-scale coal fragments and lenses are aligned horizontally and accumulated parallel to bedding. Occasionally there are vertically oriented *Skolithos* measuring less than 1 inch that have a clay lining, and a structureless fine- to medium-grained sand infill.

Interpretation

This facies was deposited under fluctuating low- and moderate- to high-energy conditions. Low-energy events are recorded in the mudstones, while medium- to high-energy deposition is reflected by the very fine-grained sand. Convolute bedding within this facies appears to have resulted primarily from post-depositional slumping, and small amounts of bioturbation. Slumping indicates down-slope vertical and lateral displacement of soft unconsolidated sediments, which likely caused the centimeter-scale faulting. The failure of these sediments probably initiated partial liquefaction due to increased pore pressure and reduced effective stress, resulting in a tightly packed mass of mud, silt, and sand responsible for the cloudy appearance (Kuenen, 1953). The depositional environment of this facies is likely a proximal crevasse splay, with the abundant slumping representing levee failure following moderate- to high-energy overbank flooding events (Lamberson et al., 1989).

4.2.8 Very fine- to medium-grained massive sandstone with rip-up clasts (Facies MS)

Description

This facies consists of very fine- to medium-grained massive sandstones (see Fig. 4.8) without any discernable internal grain size trends. Unit thicknesses range from 10 inches up to 29 feet, almost always having sharp basal, and gradational upper contacts. These sandstones contain mudstone and siltstone lithoclasts that are elongate in shape, up to 4 inches long, and show preferential accumulation parallel to bedding. These clasts are generally subangular to angular, and many of them show millimeter-scale laminations of intercalated clay, silt, and sandstone. The lithoclasts in places contain horizontal and/or vertical roundish bioturbations of an inch or less in diameter, generally filled with medium-grained sandstone. Despite the silt- and mudstone clasts, the structureless sandstones also occasionally contain millimeter-scale coal fragments that are horizontally oriented and accumulated parallel to bedding. Rarely, up to 6 inch thick layers of mudstone (facies LM) are intercalated into the massive sandstones.

Interpretation

The very fine to medium sandstone grains in this facies reflects a moderately high-energy depositional environment. As grain size trends are lacking within individual beds, deposition must have occurred during fairly constant high-energy conditions. The lack of any visible sedimentary structures is either a cause of rapid deposition, and/or reflects the absence of small-scale grain-size variations that would form well recognizable internal laminations. However, the horizontally oriented mud clasts reveal that if an internal lamination is present, it is likely planar bedding. These sandstones may therefore reflect deposition under upper flow regime conditions, or the clay clasts had been incorporated through rapid deposition from a high-density suspension flow (Postma, 1988). The large amounts of clay clasts show that the deposition of the massive sandstones is connected with the sedimentary environment of the mudstones; the clay clasts are subangular to angular, thereby revealing very limited transport and rapid deposition phases. In very protected places the mudstone beds partially survived erosion and are preserved as irregular mudstone intercalations within the massive sand. The coal fragments occasionally present in this facies reflect the incorporation of minor amounts of organic material during deposition. However, the relatively high-energy flow depositing the massive sandstones may have prevented the incorporation of larger wood debris, which when fresh float and are not easily incorporated into near-bottom rapid sedimentation events.

4.2.9 Planar laminated silt and very fine- to fine-grained sandstone (Facies PS)

Description

This facies consists of a very fine- to fine-grained planar laminated sandstone containing silt (see Fig. 4.9), which is preferentially accumulated parallel to bedding. Internal laminations range from millimeter-scale up to 1/2 inch in thickness and are more visible where silt is deposited. Intervals of this facies vary from 1 inch up to 4 feet, and have sharp or gradational upper and lower contacts. Organic material is preserved as elongated fragments up to 1 inch in length, oriented parallel to bedding, and occurs predominately in silt-rich intervals. This facies occasionally contains unlined *Skolithos* which measure up to 6 inches in length and up to 1/2 inch in diameter.

Interpretation

This facies represents a high-energy, likely shallow-marine depositional environment, reflected by the abundance of very fine- to fine-grained sandy substrate and upper flow regime planar laminations. The subtle shifts in grain-sizes suggest relatively consistent high-energy conditions. Preserved organic material within this environment is likely a product of rapid sedimentation. A lack of abundant bioturbation indicates that either energy levels were typically too high to promote suitable living conditions for the majority of organisms, or that upper sediment layers were constantly reworked so that little bioturbation was preserved.

4.2.10 Fine-grained Skolithos-bearing sandstone *(Facies SK)*

Description

This facies consists of fine-grained sandstones, containing vertically to sub-vertically oriented *Skolithos* (see Fig.4.10). The *Skolithos* measure up to 6 inches in length and 1/4 inch in diameter, and are expressed as cylindrical to sub-cylindrical, straight to slightly-curved, smooth-walled, clay-lined shafts containing a homogenous fine-grained sand fill. Intervals of this facies commonly range in thickness from 2 to 5 feet, and occasionally occur in larger packages up to 10 feet, having sharp or gradational upper and lower contacts. Individual sandstone beds show remnant planar and/or ripple laminations and are bounded/separated by irregular mud and silt laminae up to 1/4 inch thick.

Interpretation

Skolithos are generally associated with shallow-water marine and brackish-water depositional environments. Planar and ripple laminations represent slight fluctuations in flow regime, although the original bedding was ultimately disrupted by bioturbation. The fine-grained sands of this facies suggest that the sediment has been extensively eroded prior to deposition. Mud and silt laminae separating the sand intervals indicate that there were episodic energy fluctuations responsible for the intercalated mud and silt.

4.2.11 Very fine- to fine-grained wave rippled sandstone (Facies WV)

Description

This facies is a very fine- to fine-grained, well-sorted sandstone, containing wave-ripple cross-bedding (see Fig. 4.11) reflected by symmetrical crest and trough structures, and further defined by internal off-shoot structures (de Raaf et al., 1977). Intervals of this facies range in thickness from 8 inches up to 5 feet, and have upper and lower contacts that are sharp or gradational. Bedding appears to be laterally continuous, with a lack of bioturbation. Small-scale variations in subangular to rounded grains form internal laminations up to 1/8 inch thick. Occasionally, organic material is preserved as millimeter-scale fragments, which are preferentially accumulated parallel to bedding.

Interpretation

The dominance of sand grains, combined with the wave ripples suggests deposition occurred within a high-energy near-shore marine sedimentary environment. Symmetrical wave ripple structures indicate bidirectional currents prevailed during deposition. The sediment was moderately eroded, which is represented by the well-sorted, subangular to rounded grains. The occasional incorporation of organic material within this facies supports the idea of episodic rapid sedimentation events, necessary for preserving the less-resistant organic fragments.

4.2.12 Fine-grained current rippled sandstone (Facies RS)

Description

This facies consists of sandstones containing current ripples (see Fig. 4.12) that form individual beds up to 3 inches thick. Stacked intervals of this facies range in thickness from 6 inches up to 10 feet, and both upper and lower contacts occur as sharp or gradational. Occasionally intervals will show climbing ripple structures. Infrequently, mud and silt rip-up clasts up to 1/2 inch in diameter, as well as millimeter-scale coal fragments are preferentially accumulated parallel to bedding. This facies typically contains an overall lack of bioturbation; however, vertically oriented *Skolithos* may occur, having a mud fill, and measuring up to 4 inches in length, with diameters up to 1/4 inch. Occasionally paleo-roots located near the top of beds in outcrop are represented by vertically oriented (up to 8 inches vertical and millimeter- to centimeter-scale diameters), bifurcating, mud- and iron-lined traces.

Interpretation

The presence of current ripples in sand indicates deposition from lower flow regime unidirectional currents having moderate-energy. Grain sizes and roundness reflect extensive erosion of sediment prior to deposition, and the limited occurrence of coal and rip-up clasts indicates that either the less resistant fragments were completely broken down, or that there was limited input of mud, silt, and organic material into the system. Climbing ripples within this facies suggest variability in the rates of sedimentation, and resulted in response to increased sediment loads, which caused the ripples to form and migrate over an overall aggrading bed. *Skolithos* support deposition within a moderate-energy, shallow water, marine or brackish environment, dominated by sandy substrate with infrequent episodic mud sedimentation that is only preserved in the burrows. Root systems on the other hand suggest that the upper contact of this facies occasionally forms a discontinuity surface characterized by subaerial exposure and a lack of deposition. This facies is likely a product of deposition within a moderate-energy fluvial environment.

4.2.13 Medium-grained cross-bedded sandstone (Facies CB)

Description

This facies consists of straight to sigmoidal cross-bedded sandstones (see Fig.4.13), which are asymmetrical in cross section. The medium grains within are well-sorted subangular to rounded sands. Beds of this facies measure up to 12 inches in thickness and are commonly arranged in intervals measuring from 4 feet up to 20 feet in thickness. Upper contacts are almost always sharp, while lower contacts are typically sharp erosional scours truncating laminae and incorporating lithoclasts of underlying beds. These subangular to angular lithoclasts commonly measure up to 1 inch in diameter and are oriented parallel to bedding. Although this facies typically lacks bioturbation, vertically oriented

Skolithos measuring up to 8 inches in length with diameters of up to 1/4 inch, occasionally occur, and almost always have a clay lining and a homogenous medium- to coarse-grained sand fill. Occasionally outcrops contain orange-red iron concretions with diameters up to 10 inches that are arranged parallel to bedding and preferentially accumulated along single bedding horizons.

Interpretation

This facies represents a moderate- to high-energy fluvial environment reflected in the presence of lower flow regime bedforms and the abundance of medium-grained sand sedimentation. The asymmetry of bedding structures combined with basal scour surfaces suggest sediment transport and deposition occurred by way of unidirectional currents strong enough to erode underlying sediments. Although the grains of this facies are well-sorted, the variation in roundness suggests there was limited erosion of sediment prior to deposition. The degree of bioturbation within this facies indicates that either the moderate- to high-energy environment was not preferred by living organisms, or that the upper sediment layer was being continuously reworked as to not preserve most trace fossils.

4.3 Facies associations

The facies of the Mesaverde Group in the Atlantic Rim area of Wyoming can be grouped into 3 facies associations I to III based on their vertical and lateral facies relationships. Facies association I consists of a total of seven facies which are coal (facies CO), carbonaceous mudstone (facies CM), laminated mudstone (facies LM), convolute and horizontally bedded sandstone (facies CS), very fine- to medium-grained massive sandstone with rip-up clasts (facies MS), current rippled sandstone (facies RS), and cross-bedded sandstone (facies CB). Five of these facies also occur in facies association II, while facies CB and MS are exclusive to facies association I. Facies association II shows coal (facies CO), carbonaceous mudstone (facies CM), laminated mudstone (facies LM), convolute and horizontally bedded sandstone (facies CS), current rippled sandstone (facies RS), and planar laminated silt and sand (facies PS), with none of these facies being limited to this association. Facies association III consists of bioturbated mudstone (facies BM), ichnofossil-bearing mudstone (facies IM), mottled mudstone (facies MM), planar laminated silt and sand (facies PS), *Skolithos*-bearing sandstone (facies SK), and wave rippled sandstone (facies WV), with all but facies PS occurring exclusively in this association.

Figure 4.1. Coal (facies CO).

Figure 4.2. Carbonaceous mudstone (facies CM).

Figure 4.3. Laminated silt- to medium-grained sand-rich mudstone (facies LM).

Figure 4.4. Silt-rich bioturbated mudstone (facies BM).

Figure 4.5. Ichnofossil-bearing mud/siltstone (facies IM).

Figure 4.6. Mottled mudstone (facies MM).

Figure 4.7. Convolute and horizontally-bedded very fine-grained sandstone (facies CS).

Figure 4.8. Very fine- to medium-grained massive sandstone with rip-up clasts (facies MS).

Figure 4.9. Planar laminated silt and very fine- to fine grained sandstone (facies PS).

Figure 4.10. Fine-grained *Skolithos*-bearing sandstone (facies SK).

Figure 4.11. Very fine- to fine-grained wave rippled sandstone (facies WV).

Figure 4.12. Fine-grained current rippled sandstone (facies RS).

Figure 4.13. Medium-grained cross-bedded sandstone (facies CB).

CHAPTER 5: STACKING PATTERNS AND DEPOSITIONAL MODEL

5.1 Overall facies organization

The Mesaverde Group shows pronounced vertical and lateral facies trends throughout the study area in both core and outcrop transects. The entire succession is characterized by a distinct deepening trend reflected in successively more marine sediments towards the top (see Appendices I through V). The transect depicted by the three cores also shows a pronounced shallowing trend towards the south of the study area with more continental deposits in that direction throughout the measured stratigraphic interval. Smaller-scale trends exist that subdivide the succession into well defined several hundred to only few feet thick packages, based on their recurring nature interpreted as cycles (cf. de Raaf et al., 1965). The most prominent of these cycles are between 75 and 275 feet thick and referred to as large-scale cycles. The large-scale cycles are internally organized into several medium-scale cycles (10-80 feet in thickness) that are in turn broken up into small-scale (5-55 feet in thickness). The recognition of large-, medium-, and small-scale cycles are based on vertical facies successions. The large- and medium-scale cycles are delimited at the base by facies association III sharply overlying facies association

I and II sediments, while the small-scale cycles result from combinations of facies associations I, II, and III.

The Mesaverde Group in the study area consists of six of the large-scale cycles herein termed the Allen Ridge 1 and 2 (AR1 and 2), Pine Ridge 1 and 2 (P1 and 2), and Almond 1 and 2 (A1 and 2) stratigraphic intervals. These packages are well defined in the northern part of the study area with facies association III sediments sharply overlying facies association I and II strata. Towards the south, however, the facies association III sediments become successively thinner and eventually pinch out so that a subdivision into the above mentioned six large-scale stratigraphic packages becomes increasingly difficult.

The large-scale cycles show an overall symmetrical internal architecture with facies association III sediments at the base that are increasingly substituted by facies association I and II sediments towards the center. In their upper part, successively more facies association III sediments are intercalated. The thickness of individual facies packages varies from cycle to cycle, and also within each cycle laterally, with facies association III sediments becoming thinner towards the south of the study area. Some of the large-scale cycles are not well developed, in places missing the basal facies association III portion resulting in the amalgamation of cycles into a succession consisting of only facies association I and II sediments. While some of the facies association III sediments diminish to the south along the core transect, it is still possible to correlate four of the six large-scale cycles laterally relatively well from core to core.

The six large-scale cycles consist of several medium-scale cycles that are characterized by a facies association III succession that is in turn overlain by facies associations I and II sediments. Up to five of these medium-scale cycles can be arranged into one large-scale cycle. Towards the south of the study area, however, less and less medium-scale cycles are recognizable. This is caused by (1) the pinching out of beds consisting of facies association III sediments that form the base of the medium-scale cycles. This results in the amalgamation of several medium-scale cycles, or (2) the medium-scale cycles are difficult to identify because facies association III sediments are missing due to erosion. The thickness of each of the facies associations forming the medium-scale cycles varies dramatically and ranges from cycle to cycle and laterally from as little as a few feet to as much as 140 feet.

The depositional succession of the upper part of the Mesaverde Group can be further subdivided based on small-scale cycles that result from combinations of facies associations I, II, and III. Up to five of the small-scale cycles can form one of the medium-scale cycles. The thickness of each cycle and the facies that form it are highly variable. Throughout facies associations I and II, the cycles both coarsen and fine upward, but are neither laterally traceable in outcrop nor correlatable between cores (see Appendices IV and V). However, the cycles formed by facies association III deposits coarsen upward and are laterally traceable (see Appendix IV). The small-scale cycles within facies association III sediments consist of a sharp base overlain by mud and silt with silt and sand on top. Within the lower part of the Almond Formation, the silt and sand facies become more pronounced towards the south of the study area. Most of the small-scale cycles within facies association III deposits are easily correlated across the transect depicted by the three cores (see Appendix IV), while some become less identifiable towards the south of the study area where facies association III sediments are less well developed.

Because many of the large-, medium-, and small-scale cycles are more clearly defined in the northern part of the study area, an estimate of cycle numbers should be attained using stratigraphic columns from this area. Cycle numbers are laterally variable within the upper part of the Mesaverde Group, especially towards the south of the study area where many of the cycles are amalgamated and may or may not show distinct stacking trends of facies associations I, II, and III. By using the maximum amount of well-defined large-scale cycles from the laterally correlative sections in the northern part of the study area, an estimate of cycle numbers can be developed throughout the core transect. Therefore, the total number of large-scale cycles in the upper part of the Mesaverde Group is estimated to be six, two in the Allen Ridge Formation, two in the Pine Ridge Sandstone Formation, and two in the Almond Formation. Because only the uppermost part of the Allen Ridge Formation has been observed in this study, it should be noted that additional depositional cycles and stratigraphic surfaces may occur within the lower part of the Allen Ridge.

Both coal and carbonaceous mudstone facies show distinct trends regarding their stratigraphic and geographic distribution within cycles of all orders. Stratigraphic trends suggest that the greatest accumulation of coal occurs in the upper part of the Pine Ridge Sandstone Formation (Fig 5.1), while

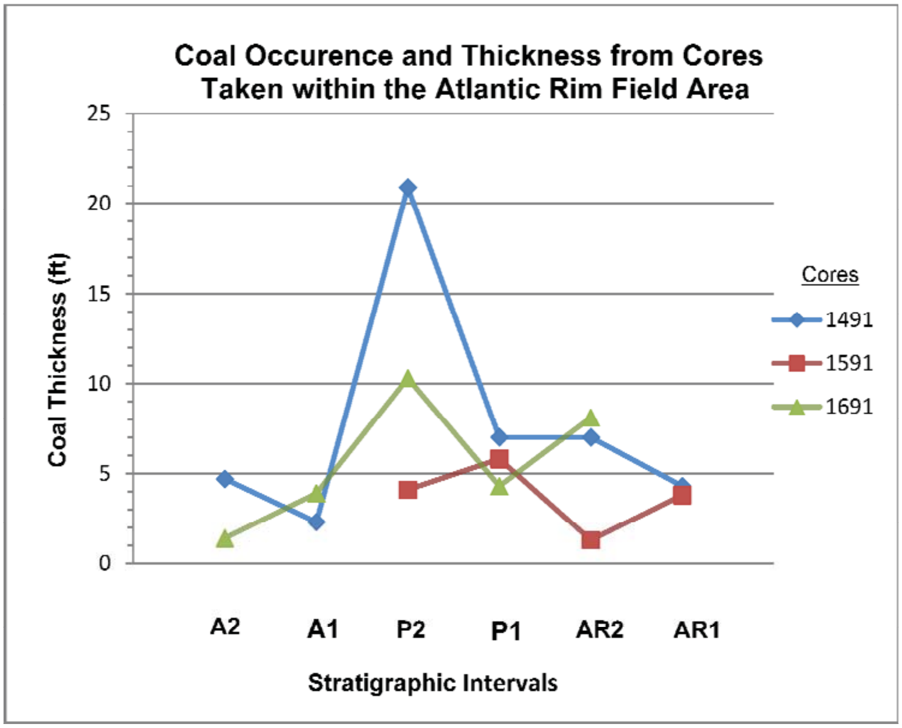


Figure 5.1. Coal occurrence and thickness measured from cores taken within the Atlantic Rim field area of the Washakie Basin. A2-upper part of Almond Fm., A1-lower part of Almond Fm., P2-upper part of Pine Ridge Sandstone Fm., P1-lower part of Pine Ridge Sandstone Fm., AR2-upper part of Allen Ridge Fm., AR1-lower part of Allen Ridge Fm.

the largest cumulative thickness of carbonaceous mudstone is encountered in the lower part of the Pine Ridge Sandstone Formation (Fig. 5.2). Geographic trends show that the thickest coal accumulations occur towards the south of the study area, while carbonaceous mudstones are most dominant towards the north. Some coal beds within the center and upper parts of the Pine Ridge

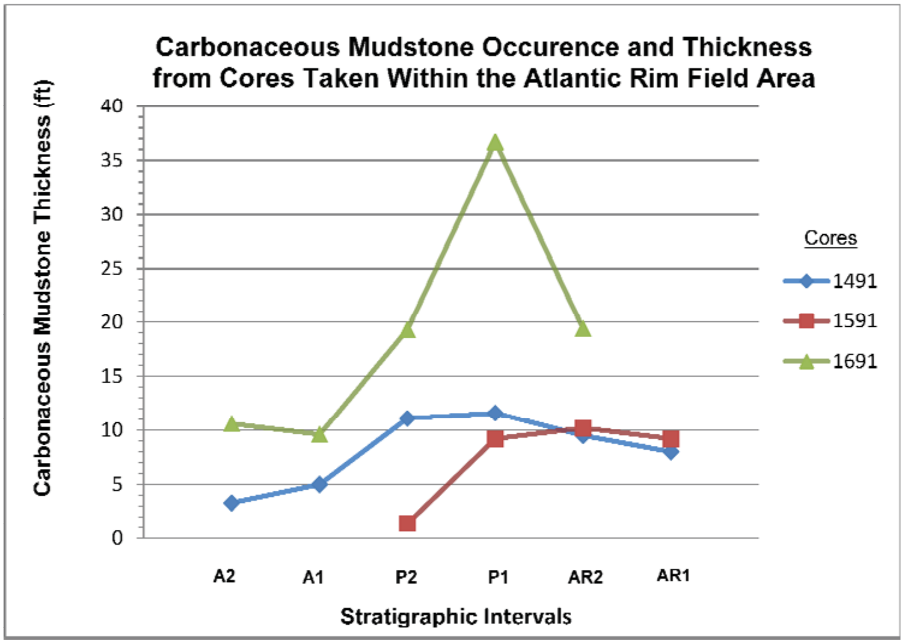


Figure 5.2. Carbonaceous mudstone occurrence and thickness measured from cores taken within the Atlantic Rim field area of the Washakie Basin.

Sandstone and upper part of the Almond Formations are laterally continuous across the transect depicted by the three cores, but the majority of coals observed in the Atlantic Rim sections are laterally discontinuous and appear to thin and eventually pinch out. There are appreciable accumulations of coal within the subsurface of the Atlantic Rim; however, the outcrop transects show very little to no measured coal intervals.

5.2 Depositional model

The Upper Cretaceous Mesaverde Group succession in the study area shows a subdivision into three broad facies belts (Fig. 5.3), the continental facies association I, the intermediate facies association II at the interface of land and sea influenced by both continental and marine environments, and the fully marine facies association III. The continental environment was characterized by both

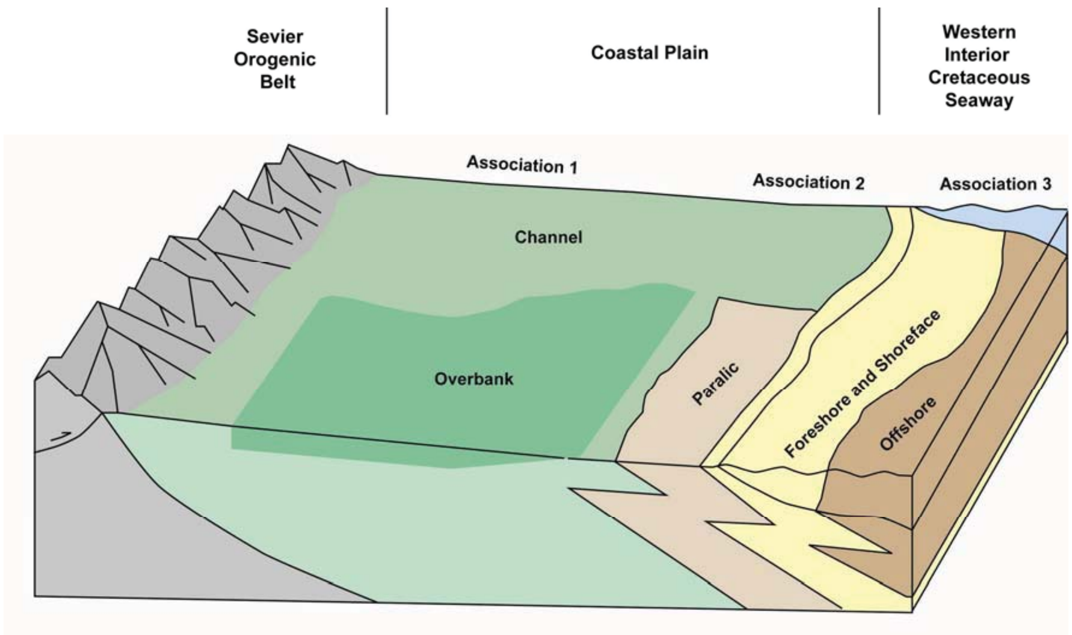


Figure 5.3. Distribution of sedimentary coastal/foreland environments interpreted from the Mesaverde Group, and observed from the Atlantic Rim in the easternmost Washakie Basin, Wyoming (Modified from Roehler, 1990).

high- and low-energy deposition which is reflected in sand-, silt-, and mudstones with coals, respectively. The convolute and horizontally bedded-, current rippled-, and cross-bedded sandstones of facies association I represent sedimentation of dunes, ripples, and sand sheets within a fluvial channel system showing varying energy deposition of upper and lower regime flow conditions (Ashley, 1990). The channel morphology is still apparent from the limited lateral continuity of facies association I coarse sediments in outcrops that form well-defined lenses in the field (cf. Bridge and Tye, 2000). The lense-like nature of these channels as well as the repeated avulsion of individual channels with erosion into adjacent overbank sediments is ultimately responsible for their strongly varying stacking patterns in cores and the lack of correlation possibilities of these channel sands from one core to the next or across large-scale outcrops.

Lateral to the fluvial settings of the coastal environment were interdistributary wetland-type depositional environments characterized by coal, carbonaceous- and laminated mudstones. These facies represent the aggradation of mud and organics with limited input of silt- and sand-sized sediment (McCabe, 1984). In subsurface and outcrop, the overbank sediments occur stacked with fluvial sandstones indicating the occurrence of channel avulsion and/or sand splays into what was likely a low topographic floodplain area. The influence of shifting fluvial systems on the overbank sediments is apparent from the variable coarsening and fining upward facies successions of the facies association I deposits (Bridge and Tye, 2000). These shifting systems also result in a relative lack of correlation of small-scale continental mudstone intervals not only between subsurface and outcrop, but also from one stratigraphic column to the next in both core and outcrop transects. The internal architecture of these facies also reflects proximity to the sediment source. Laminated- and some carbonaceous mudstones show traces of clastic influx and occasional flow indicators such as current ripples, suggesting deposition occurred proximal to the fluvial system. Coals however, show little to no clastics and must have been deposited distal to and/or isolated from the sediment source and subsequent clastic influx (McCabe, 1984).

Facies association II sediments reflect lower coastal plain, paralic, and nearshore marine sedimentary environments. This depositional setting was characterized by frequently fluctuating energy levels that resulted in the episodic deposition of high-energy sand- and siltstones, which occur tightly intercalated with coals, carbonaceous- and laminated mudstones in both core and outcrops. The facies successions represent a transition between strictly continental and strictly marine sedimentation. The convolute and horizontally bedded-, current rippled-, and planar sandstones of facies association II reflect sedimentation under varying energy levels of both upper and lower flow regimes. These sands alternate with and cut into low-energy mudstones. The mudstones contain very little silt and sand and have sharp upper and lower contacts suggesting they were relatively isolated and that shifts in sedimentation were abrupt within this environment. Intercalations of continental sand- and mudstones and marine sandstones are the result of sand transport and episodic sediment influx from variable directions (Schwartz, 1982). This environment consisted of deposition within nearshore fresh- to brackish water marshes, swamps, and bays that received sediment input from channel avulsion and crevasse splays of distributary streams flowing from the coastal plain, and from both eolian processes and marine ingressions which breached the paleoshoreline, resulting in thin intercalations of marine silt and sand into back barrier coals, carbonaceous- and laminated mudstones (Bridges, 1976; Horne and Ferm, 1978).

The foreshore and shoreface environment defined in the upper part of the Mesaverde Group was characterized by high-energy deposition of sand and silt. The planar laminated-, *Skolithos*-bearing-, and wave rippled sandstones show distinctive upper and lower flow regime bedforms, suggestive of a nearshore marine sedimentary environment (Johnson and Baldwin, 1986). Facies successions representing nearshore environments are often loosely referred to as deltaic. However, provided good three dimensional control of facies- and stacking patterns using a broad distribution of core and/or well logs, ancient shorelines are able to be classified as truly deltaic (Bhattacharya, 1992). The abundance of facies association I and II sands in the center of the core transect suggests that during periods of increased base level this same area would likely have been the location of a deltaic system. The northern and southern cores of the transect represent a coastline environment directly adjacent to the delta and show successively stacked facies association III sands that likely originated from the nearby delta and were transported laterally by waves and currents. The high input of sediment is apparent from the coarsening upward successions that have facies association III sands in their upper part, and represent the filling of accommodation space and/or shallowing of this depositional environment

(Heward, 1981). Internally these sands are well-sorted and contain very little mud indicating significant transport of sediment from the source prior to deposition along the paleoshoreline. The foreshore and shoreface environment was narrow yet laterally extensive along the western margins of the Western Interior Cretaceous Seaway, which is evident from the lateral continuity of the facies association III coarse sediments which form ideal marker horizons for correlation across the core transect.

The offshore environment was characterized by low-energy deposition that is reflected in the successions of marine mudstones within the Upper Cretaceous Mesaverde Group stratigraphic interval. The bioturbated-, ichnofossil-bearing-, and mottled mudstones represent sedimentation of mainly muds and clays with very few flow indicators suggesting that sedimentation occurred within a relatively tranquil deep-marine setting beyond the influence of fair-weather ocean waves. Offshore deposition occurred in both proximal and distal settings relative to the paleoshoreline, which is represented by the variable amounts of silt and sand incorporated within the mudstones, and the associated degree of bioturbation. Proximally deposited muds received episodic input of silt- and sand-sized sediment, brought in from high-energy nearshore areas (Davis and Byers, 1989), and low bioturbation. In contrast, more distal muds deposited landward of the continental shelf experienced less terrigenous sediment influx and higher levels of bioturbation as the environment became increasingly more tranquil. Deposition of the facies association III mudstones took place over a broad area covered by the paleoseaway, which is apparent from the strong lateral continuity of these deposits across the core transect of the Atlantic Rim.

CHAPTER 6: DISCUSSION

6.1 Correlation strategy

Deposition of the Mesaverde Group sediments was strongly influenced by base level changes which formed depositional cycles of different magnitudes that are nicely preserved in the rock record. The large-scale cycles prove ideal for correlation because the depositional trends that created them acted on a regional to over-regional scale and are therefore used in this study to tie subsurface and outcrop locations of the Atlantic Rim. The following discussion will focus on only the large-scale cycles within the upper part of the Mesaverde Group, which have durations of about 1 million years and form third-order cycles of deposition (0.5-3 million years) as defined by Emery (1996).

The upper part of the Mesaverde Group in the study area consists of six large-scale cycles, each of them between 75 and 275 feet, bounded by distinct marine flooding surfaces separating packages of both marine and continental strata (see Appendices I and IV). Larger cycle thicknesses are the result of high sediment accumulation and/or variable rates of compaction. These large-scale cycles are well defined in the upper part of the succession especially in the north of the study area. However, towards the south and especially within the lower portion of the succession, the marine flooding surfaces are not well defined or pinch out within an entirely continental succession. So even though these six cycles may not always be well defined throughout the study area, they do represent a viable subdivision of the succession and an accurate definition of time lines in the Mesaverde interval. The newly proposed stratigraphic subdivision, though, will be more difficult to apply south of the study area as marine intercalations are expected to become less and less pronounced, thereby preventing a chronostratigraphic subdivision of the succession. The same general concept holds true for the higher order cycles that dissect the large-scale cycles within the study area.

The correlation of marine flooding surfaces used in this study to link cores, was also applied to tie the outcrop sections with the cores. However, strong weathering of outcrops often prevented the recognition of distinctive sedimentary structures and trace fossils that are crucial to recognize marine facies. Nevertheless, the dominance of continental facies throughout the outcrop areas argues for this succession to be equivalent of the upper (P2) or lower (P1) part of the Pine Ridge Sandstone Formation. The fact that these outcrops are located north of the cores where the marine influence tends to increase also supports this interpretation. As mudstones are observed on top of the measured sections at the JO Reservoir and Tower Section, this also implies that at least the Almond Formation has a lateral mudstone equivalent here assigned to the Lewis Shale Formation. The Lewis Shale is therefore highly diachronous in the study area and shows an onset several millions of years earlier in the north than in the south.

Previous authors (Lewis, 1961; Livingston, 1982; Newman, 1981; Roehler, 1990) have defined the Almond Formation as having a lower-continental and an upper-marine interval. In contrast, the detailed facies analysis in this study shows that the lower part of the Almond Formation is dominated by mostly marine sediments which are overlain by upper Almond continental to marginally marine deposits. The previous studies were located at or west of the Atlantic Rim, except for research by Livingston (1982) which also focused on the Kindt Basin, Wild Horse Draw, and Coral Canyon located 20-30 miles north- and southeast of Rawlins, Wyoming (refer to fig. 1.1). While it seems reasonable that the lower part of the Almond Formation could become increasingly continental moving towards the west within the Washakie and Greater Green River Basin(s) based on paleogeographic reconstructions (refer to fig. 2.2), it seems unlikely that any measured sections west of the Atlantic Rim could record marine deposition within the upper part of the Almond Formation. If the upper part of the Almond Formation is continental within the Atlantic Rim study area, then the same stratigraphic interval should become increasingly more continental to the north and west of the Washakie Basin. It is possible that previous studies focusing on the Almond Formation have misinterpreted the facies present in this stratigraphic succession and/or altogether lacked detailed facies observations which have undermined their interpretations. This discrepancy suggests that a study refocused on regional variation of the upper and lower parts of the Almond Formation is necessary and should incorporate recent facies models and newly formed correlation strategies.

6.2 Sequence stratigraphic framework

The sequence stratigraphic analysis of the Atlantic Rim subsurface dataset is based on the facies trends observed in the large- medium- and small-scale cycles indentified within the upper part of the Mesaverde Group. While the small- and medium-scale cycles represent parasequences, the large-scale cycles form laterally correlative depositional sequences. Using the transgressive-regressive (T-R) sequence developed by Embry and Johannessen (1992), the sequence stratigraphic analysis of the subsurface dataset allows for a closer observation of how depositional trends observed within the Atlantic Rim were influenced by base level[3] rise and fall during the Late Cretaceous Period, and for correlations previously defined by flooding/transgressive surfaces to be refined using maximum flooding (MFS) and maximum regressive (MRS) surfaces which have greater basinal-scale isochroniety (Embry, 2002) (Fig. 6.1).

Sequences within the Mesaverde Group are defined by sequence boundaries/maximum regressive surfaces defined at the base of the first facies association III intercalation, marking a major shift from continental towards marine deposition within a succession of mostly facies associations I and II deposits. A total of four sequence boundaries have been delineated within the Atlantic Rim sections and bound three complete cycles of base level rise and fall (see Appendix IV). Additionally, there are two incomplete cycles of base level fluctuation occurring in the upper parts of the Allen Ridge and Almond

[3] Base level in a stratigraphic sense is an abstract surface representing equilibrium between areas of erosion and deposition. Base level changes are fluctuations in the distance between base level and a fixed datum at or near the center of the earth, and are controlled by tectonics and/or changes in eustatic sea-level (Cross, 1991; Embry, 2002).

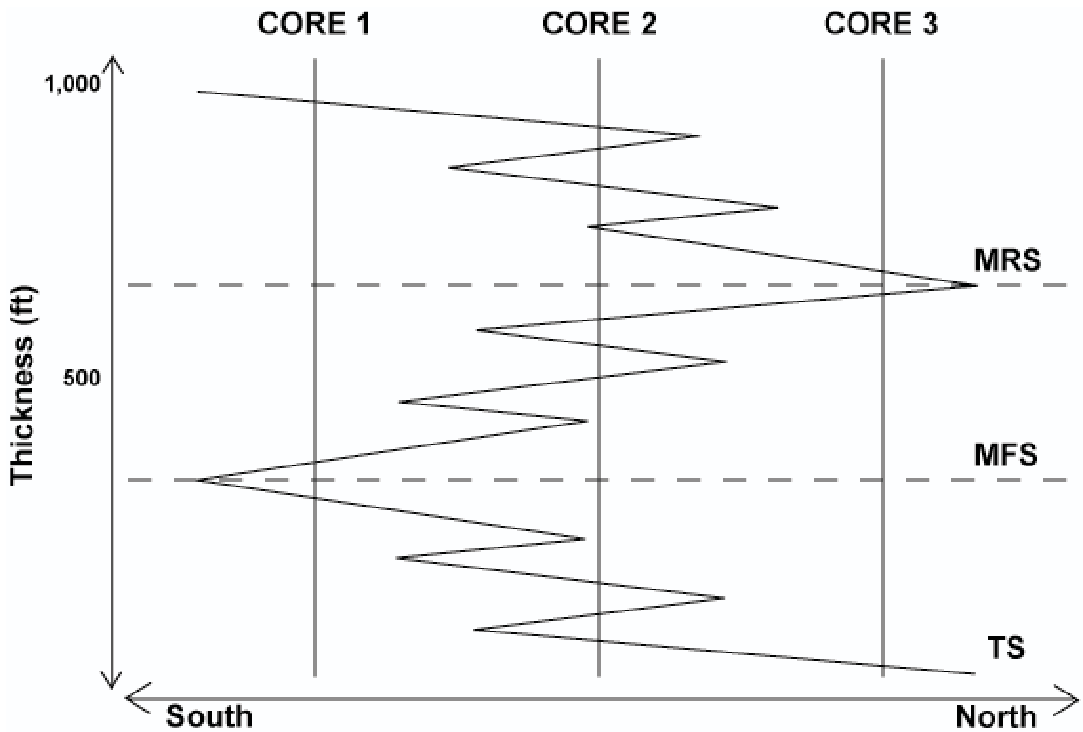


Figure 6.1. Schematic showing the isochroniety of the maximum flooding (MFS) and maximum regressive (MRS) surfaces across three stratigraphic columns as opposed to the slightly more diachronous transgressive surface (TS).

Formations. It is still possible to define sequence boundaries towards the south of the study area where facies association III sediments are less well developed, by identifying broad shifts in facies- and stacking trends which reflect the nearby fluctuation in base level. These depositional trends within the facies association I and II packages are often characterized by successively decreasing amounts of coal.

The depositional sequences are divided into two systems tracts by the MFS, a surface representing the most landward extent of shoreline migration and basinal facies that separates the transgressive systems tract (TST) below from the regressive systems tract (RST) above (Catuneanu, 2006; Embry, 2002). This surface is placed at the upper contact of the most distally deposited facies association III sediments, and where facies association III deposits are missing, the MFS is interpreted from broad variations in facies- and stacking trends, which often consist of increasing accumulations of coal above this surface (see Appendix IV). Three maximum flooding surfaces have been defined in the Atlantic Rim sections that divide the three complete aforementioned cycles into their respective intervals of increasing or decreasing accommodation space (Embry, 1993; Embry and Johannessen, 1992). There is also one additional MFS that occurs within the incomplete cycle in the upper part of the Allen Ridge Formation.

The thickness of the TST intervals increases upward within the Mesaverde Group, which reflects the overall deepening trend of the entire succession. The transgressive systems tracts reveal increases in accommodation space and episodic landward shifts of the three facies belts, which are apparent from the increasing amount of facies association III deposits towards the top of the succession. Facies association I, II, and III sediments are not exclusive to either of the two systems tracts, although the TST is commonly characterized by coarsening upward successions of facies association III mud-, silt-, and sandstones, as well as intervals of intercalated beds of facies association I and II deposits containing appreciable coal and carbonaceous mudstones.

The regressive systems tracts record falling base level and subsequent decreases in accommodation space within the basin, which are reflected in the abundance of stacked facies association I and II sediments occurring within this systems tract. Although the upper part of the Mesaverde Group succession is interpreted as deepening, the regressive systems tracts record successive shallowing and basinward shifts of the three facies belts within the overall deepening upward trend. The RST contains facies successions often characterized by unpredictable stacking patterns and grain size trends consisting of coarsening- and fining-upward intervals of facies associations I and II with an abundance of coal and carbonaceous mudstones, and significantly less facies associations III sediments than the TST.

The T-R sequence developed by Embry and Johannessen (1992) is the only sequence that has objectively recognizable stratigraphic surfaces (Embry, 2002). This method is particularly useful within the upper part of the Mesaverde Group stratigraphic interval, because previously defined methods of sequence stratigraphy (Galloway, 1989; Posamentier et al., 1988; Posamentier and Vail, 1988) rely on hard-to-recognize subaerial unconformities that represent the start of both base level rise and fall, which could not be readily identified within Atlantic Rim sections. The accurate delineation of the MRS and MFS in this study are strongly supported through detailed facies analysis (refer to Chapter 4), and proved to be the only objectively identifiable stratigraphic surfaces within the sections of the Atlantic Rim.

6.3 Sequence stratigraphic distribution of coal-bearing rocks

The sequence stratigraphic framework previously defined for the Atlantic Rim subsurface dataset (refer to Chapter 6.2) has been implemented to better understand the sequence stratigraphic distribution of coal- and carbonaceous mud-bearing rocks within the Mesaverde Group in south central Wyoming. This sequence stratigraphic analysis reveals that the greatest accumulation of coal is limited to the early regressive systems tract (Fig 6.2), while the largest cumulative thickness of carbonaceous mudstones occurs within the late regressive systems tract, as well as having a significant presence in the early

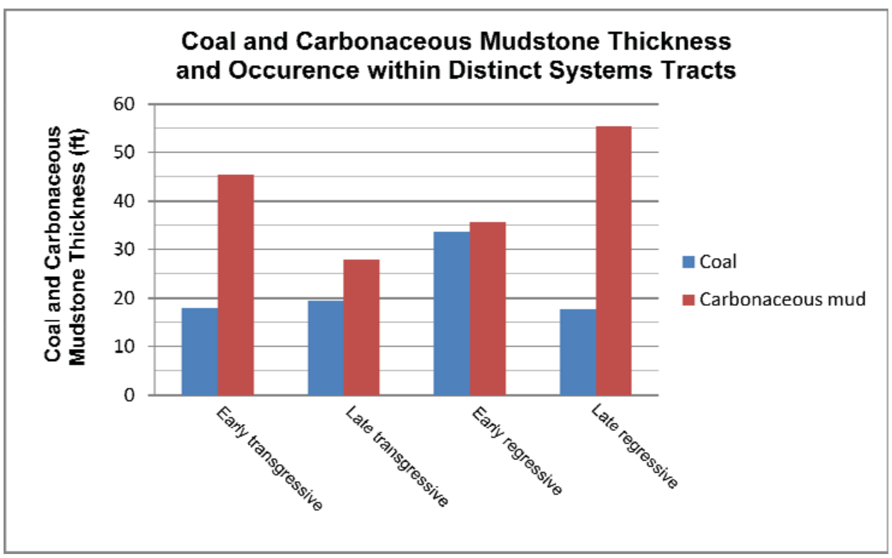


Figure 6.2. The delineation and thickness of coal and carbonaceous mudstone within distinct systems tracts, from cores taken from the Atlantic Rim field area of the Washakie Basin.

transgressive systems tract. Recent models focused on predicting the occurrence, distribution, and quality of coal-bearing strata (Catuneanu, 2006; Coe et al., 2003) conclude that the thickest and most extensive coal seams are associated with maximum flooding surfaces, hence marking the base of the highstand systems tract, equivalent to the early regressive systems tract of the T-R sequence defined by Embry and Johannessen (1992) (Fig. 6.3). The early regressive systems tract represents a basinward shift of facies belts from the fully marine facies association III towards intercalations of facies associations I, II, and III.

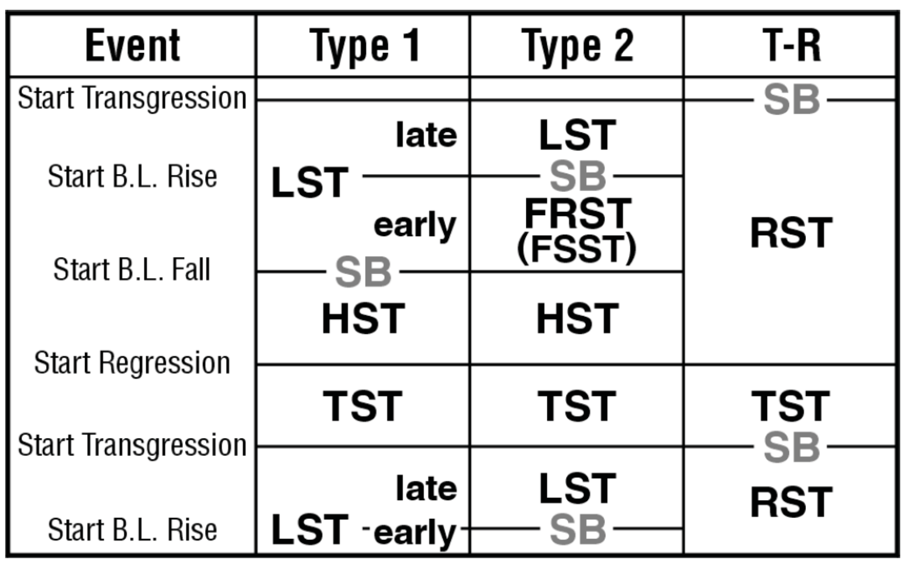


Figure 6.3. A comparison of systems tracts and the surfaces which define them. LST-lowstand systems tract, TST- transgressive systems tract, HST-highstand systems tract, FRST-forced regressive systems tract, FSST-falling sea level systems tract, RST-regressive systems tract, SB-sequence boundary (From Embry, 2002).

Using the T-R sequence to define the sequence stratigraphic position of coaly rocks highlights the question of how the formation and preservation of the Mesaverde Group organic-rich deposits were influenced by base level rise and fall. Coals are limited to formation and preservation within continental and paralic settings, and the facies successions of the Atlantic Rim show that many of the facies association I and II coals occur intercalated or lateral to intervals of facies association III sediments. It is likely that an elevated water table resulting from episodic marine flooding events prominent within the early regressive systems tract promoted swamps, flooding of floodplains, and channel avulsion within coastal environments landward of the paleoshoreline (Hamilton and Tadros, 1994). The heightened water table also caused anoxic conditions necessary to decrease the likelihood of peat oxidation within marsh-like environments, while the avulsion of channels and shedding of clastics enabled the burial of peat and subsequent preservation as coal. The sequence stratigraphic analysis of coals in the Atlantic Rim suggests that while local distribution, thickness, continuity, and geometry were controlled by autocyclic processes including channel migration, channel diversion, and bar migration, the regional stratigraphic distribution was a function of widespread allocyclic processes such as uplift, subsidence, climatic variation, and eustatic change in sea level (Flores, 1993).

With episodic base level fluctuations and subsequent flooding of the coastal plain, many but not all of the Mesaverde Group coal intervals are located in close stratigraphic relation and/or lateral to facies association III sediments, suggesting deposition often occurred in paralic settings. Facies association III deposits are more frequent towards the northern part of the study area, while coal abundance increases towards the south of the study area. This suggests that successive marine flooding in the northern part of the study area often shut off coal-forming peat production here, while peat was able to continue accumulating relatively unhindered within the paralic environments towards the south of the study area. The increased marine influence towards the north likely introduced clastics into many of the coal-forming environments, which resulted in the large accumulations of carbonaceous mudstones occurring here. Previous studies have also concluded that coals forming in paralic environments are more laterally continuous than those originating in coastal plain environments (Bohacs, 1997; Flores, 1993). Many of the most laterally continuous coals of the Atlantic Rim occur in the center and upper parts of the Pine Ridge Sandstone and upper part of the Almond Formations. Although these coals are not exclusive to the transgressive or regressive systems tracts, they do have a close stratigraphic relation to intercalations of facies association III sediments. This suggests that the formation of laterally continuous coal seams is indeed positively influenced by the aggradation of peat within a paralic depositional environment. Conversely, coals that are stratigraphically isolated from facies association III intervals within the Mesaverde sections likely originated in coastal plain environments and will be more laterally discontinuous and have greater clastic signatures than those of paralic settings.

CHAPTER 7: CONCLUSIONS

The Allen Ridge, Pine Ridge Sandstone, and Almond Formations of the Mesaverde Group consist of recurring intervals of sand-, silt-, and mudstones with coals. These formations show thirteen facies: coal, carbonaceous mudstone, laminated silt to medium-grained sand-rich mudstone, silt-rich bioturbated mudstone, ichnofossil-bearing mud/siltstone, mottled mudstone, convolute- and horizontally-bedded very fine-grained sandstone, very fine- to medium-grained massive sandstone with rip-up clasts, planar laminated silt and very fine- to fine-grained sandstone, fine-grained *Skolithos*-bearing sandstone, very fine- to fine-grained wave rippled sandstone, fine-grained current rippled sandstone, and medium-grained cross-bedded sandstone. These facies are grouped to form three facies associations I-III based on vertical and lateral facies relationships.

The three facies belts forming the upper part of the Mesaverde Group in the Atlantic Rim include the continental facies association I, the intermediate facies association II influenced by both continental and marine environments, and the marine facies association III. The continental environment was characterized by high- and low-energy deposition within fluvial and overbank settings reflected in sand-, silt-, and mudstones with coals. The intermediate environment consisted of frequently fluctuating energy levels within lower coastal plain, paralic, and nearshore marine sedimentary environments represented by high-energy sand- and siltstones that occur tightly intercalated with coals, carbonaceous- and laminated mudstones. The marine environment was subdivided into foreshore/shoreface and offshore locations, which is apparent from the intervals of high-energy sands and varying degrees of bioturbated mudstones. These facies belts and their associated environments shifted landward and basinward as a response to base level changes resulting in a complex, but well-defined cyclic architecture within the upper part of the Mesaverde Group. The cyclic architecture reveals a distinct deepening trend represented by successively more pronounced marine deposits towards the top.

The Mesaverde Group is subdivided into six large-scale cycles here termed the Allen Ridge 1 and 2, Pine Ridge 1 and 2, and Almond 1 and 2 stratigraphic intervals. Each of these cycles consists of a marine interval having a sharp basal contact with, and overlain by continental to mixed continental marine sediments, which in their upper part become intercalated with successively more marine deposits. This combination of facies associations I, II, and III is regarded as one large-scale cycle, 6 of which create the upper part of the Mesaverde Group in south central Wyoming. These large-scale cycles are internally organized into stacks of up to 5 medium-scale cycles that are in turn formed by up to 5 small-scale cycles.

A correlation of the large-scale cycles within the Atlantic Rim sections reveals that the dominant continental facies forming the Mesaverde outcrops at the JO Reservoir and Tower Section locations are correlative with the upper or lower part of the Pine Ridge Sandstone Formation (interval P2 or P1). The mudstones overlying these outcrops are interpreted as the Lewis Shale Formation which was deposited time-equivalent and is correlative with at least the Almond Formation farther to the west. The Almond Formation in the Atlantic Rim is characterized as largely marine and is defined by a thick lower marine interval that is overlain by a pronounced continental succession. The marine sandstones defined within at least the Almond Formation are correlative with the Lewis Shale Formation in outcrop, and are therefore not continuous between subsurface and outcrop.

The upper part of the Mesaverde Group consists of 5 transgressive (TST) and 4 regressive (RST) systems tracts that reflect 3 complete and 2 incomplete cycles of base level rise and fall. The respective systems tracts are defined by 4 maximum regressive (MRS) and 4 maximum flooding (MFS) surfaces. The MRS is placed at the basal contact of the marine interval marking a major shift from continental towards marine deposition. The MFS occurs at the upper contact of the most distally deposited marine sediments and represents the most landward extent of shoreline migration.

Stratigraphic trends in the Atlantic Rim show that the greatest accumulation of coal occurs in the upper part of the Pine Ridge Sandstone Formation, while geographic trends suggest that coals are most dominant towards the south of the study area. The local distribution, thickness, continuity, and geometry of the Late Cretaceous coals were controlled by autocyclic processes, while regional stratigraphic distribution is a function of allocyclic processes. Although coals do occur during various stages of base level fluctuation, the greatest occurrence of coal is limited to the early regressive systems tracts. Some of the coal seams in the upper part of the Mesaverde Group can be correlated relatively well across the core transect, but none of these are able to be traced laterally between subsurface and outcrop locations of the Atlantic Rim. Many of the laterally continuous coals occurring within the center and upper parts of the Pine Ridge Sandstone and upper part of the Almond Formations were formed in close stratigraphic proximity and/or lateral to marine intervals, suggesting that laterally continuous coals are indeed positively influenced by formation within paralic environments.

BIBLIOGRAPHY

Abreu, V., J. E. Neal, K. M. Bohacs, and J. L. Kalbas, eds., 2009, Sequence stratigraphy of siliciclastic systems-The ExxonMobil Methodology: Atlas of exercises: Houston, SEPM.

Almon, W. R., W. C. Dawson, F. G. Ethridge, E. Rietsch, S. J. Sutton, and B. Castelblanco-Torres, 2005, Sedimentology and petrophysical character of Cretaceous marine shale sequences in foreland basins-potential seismic response issues: Evaluating fault and cap rock seals: AAPG Hedberg Series, v. 2, 215-235 p.

Almon, W. R., W. C. Dawson, S. J. Sutton, F. G. Ethridge, and B. Castelblanco, 2001, Sequence stratigraphy, petrophysical variation, and sealing capacity in deepwater shales, Upper Cretaceous Lewis Shale, south-central Wyoming: Wyoming Gelogical Association Guidebook, p. 163-171.

Arthur, M. A., and W. E. Dean, 1998, SEPM Concepts in Sedimentology and Paleontology No. 6: Stratigraphy and paleoenvironments of the Cretaceous Western Interior Seaway, USA v. 6: Tulsa, SEPM Society for Sedimentary Geology.

Ashley, G. M., 1990, Classification of large-scale subaqueous bedforms: a new look at an old problem: Journal of Sedimentary Petrology, v. 60.

Asquith, D. O., 1974, Sedimentary models, cycles, and deltas, Upper Cretaceous, Wyoming: American Association of Petroleum Geologists Bulletin, v. 58, p. 2274-2283.

Ayers, W. B., 2002, Coalbed gas systems, resources, and production and a review of contrasting cases from the San Juan and Powder River basins: American Association of Petroleum Geologists Bulletin, v. 86, p. 1853-1890.

Baars, D. L., B. L. Bartleson, C. E. Chapin, B. F. Curtis, R. H. D. Voto, J. R. Everett, R. C. Johnson, C. M. Molenaar, F. Peterson, C. J. Schenk, J. D. Love, I. S. Merin, P. R. Rose, R. T. Ryder, N. B. Waechter, and L. A. Woodward, 1988, Basins of the Rocky Mountain region, *in* L. L. Sloss, ed., Sedimentary cover- North American Craton: U.S., v. D-2: Boulder, Colorado, Geological Society of America, p. 109-220.

Bader, J. W., 2008, Structural and tectonic evolution of the Cherokee Ridge arch, south-central Wyoming: Implications for recurring strike-slip along the Cheyenne Belt suture zone: Rocky Mountain Geology, v. 43, p. 23-40.

Barlow, J. A. J., M. J. Doelger, D. M. Mullen, and I. Barlow & Haun, 1993, KU-3 Mesaverde Group, *in* C. A. Hjellming, ed., Atlas of major Rocky Mountain gas reservoirs: Socorro, NM, Authority of state of New Mexico.

Bhattacharya, J. P., 1992, Deltas, *in* R. G. Walker, and N. P. James, eds., Facies models: response to sea level change, Geological Association of Canada p. 157-177.
Blaine, C. C., 1993, Allogenic and autogenic controls on sedimentation in the central Sumatra Basin as an analogue for Pennsylvanian coal-bearing strata in the Appalachian Basin: Geological Society of America, v. 286, p. 3-22.
Blakey, R., 2009, North American paleogeography, Flagstaff, Arizona, Northern Arizona University.
Bohacs, K., 1997, Sequence stratigraphic distribution of coaly rocks; fundamental controls and paralic examples: American Association of Petroleum Geologists Bulletin, v. 81, p. 1612-1639.
Bridge, J. S., and R. S. Tye, 2000, Interpreting the dimensions of ancient fluvial channel bars, channels, and channel belts from wireline-logs and cores: American Association of Petroleum Geologists Bulletin, v. 84, p. 1205-1228.
Bridges, P. H., 1976, Lower Silurian transgressive barrier islands, southwest Wales: Sedimentology, v. 23, p. 362-374.
Bromley, R. G., and A. A. Ekdale, 1984, Chondrites: a trace fossil indicator of anoxia in sediments: Science, v. 224, p. 872-874.
Caldwell, W. G. E., 1975, The Cretaceous system in the western interior of North America: The geological association of Canada annual meeting and symposium, p. 666.
Castelblanco-Torres, B., 2003, Distribution of sealing capacity with a sequence stratigraphic framework- Upper Cretaceous Lewis Shale, south-central Wyoming, Colorado State University, Fort Collins, 212 p.
Catuneanu, O., 2006, Principles of sequence stratigraphy: Oxford, Elsevier, 375 p.
Cleveland, D. M., S. C. Atchley, and L. C. Nordt, 2007, Continental sequence stratigraphy of the Upper Triassic (Norian-Rhaetian) Chinle strata, northern New Mexico, U.S.A.: Allocyclic and autocyclic origins of paleosol-bearing alluvial successions: Journal of Sedimentary Research, v. 77, p. 909-924.
Cobb, J. C., and C. B. Cecil, 1993, Modern and ancient coal-forming environments: Special paper 286: Boulder, CO, The Geological Society of America, 198 p.
Coe, A. L., D. W. J. Bosence, K. D. Church, S. S. Flint, J. A. Howell, and R. C. Wilson, 2003, The sedimentary record of sea-level change: New York, NY, Cambridge University Press, 288 p.
Cross, T., 1991, High resolution stratigraphic correlation from the perspective of base level cycles and sediment accomodation, *in* J. Dolson, ed., Unconformity related hydrocarbon exploration and accumulation in clastic and carbonate settings: short course notes, Rocky Mountain Association of Geologists, p. 28-41.

Cross, T. A., 1986, Tectonic controls of foreland basin subsidence and Laramide style deformation, Western United States: Special Publication of the International Association of Sedimentologists, v. 8, p. 15-39.

Cross, T. A., 1988, Controls on coal distribution in transgressive-regressive cycles, Upper Cretaceous, western interior, U.S.A: SEPM special publication, v. 42, p. 371-380.

Davis, H. R., and C. W. Byers, 1989, Shelf sandstones in the Mowry shale: evidence for deposition during Cretaceous sea level falls: Journal of Sedimentary Petrology, v. 59, p. 548-560.

de Raaf, J. F. M., R. J. Boersma, and A. v. Gelder, 1977, Wave generated structures and sequences from a shallow marine succession, Lower Carboniferous, County Cork, Ireland: Sedimentology, v. 24, p. 451-483.

de Raaf, J. F. M., H. G. Reading, and R. G. Walker, 1965, Cyclic sedimentation in the Lower Westphalian of North Devon, England: Sedimentology, v. 4, p. 1-52.

Embry, A. F., 1993, Transgressive-regressive (T-R) sequence analysis of the Jurassic succession of the Sverdrup Basin, Canadian Artic Archipelago: Earth Science, v. 30, p. 301-320.

Embry, A. F., 2002, Transgressive-regressive (T-R) sequence stratigraphy: 22nd Annual Gulf Coast Section SEPM Foundation Bob F. Perkins Research Conference, p. 151-172.

Embry, A. F., and E. P. Johannessen, 1992, The falling stage systems tract: recognition and importance in sequence stratigraphic analysis, *in* D. Hunt, and R. L. Gawthorpe, eds., Sedimentary Response to Forced Regression, vol. 172. Geol. Soc. London Speci. Publ, p. 1–17.

Emery, D., and K. J. Myers, eds., 1996, Sequence stratigraphy: Oxford, Blackwell Science.

Entzminger, D. J., 1980, The Upper Cretaceous stratigraphy in the Big Hole Mountains, Idaho, *in* S. Hollis, ed., Wyoming Geological Association Guidebook, Stratigraphy of Wyoming, v. 1: Jackson Hole, Mtn States Litho, Casper, p. 163-172.

Flores, R. M., 1993, Coal-bed and related depositional environments in methane gas-producing sequences, *in* L. B.E., and R. D.D., eds., Hydrocarbons from coal: Studies in geology, v. 34, American Association of Petroleum Geologists, p. 13-37.

Galloway, W. E., 1989, Genetic stratigraphic sequences in basin analysis I: architecture and genesis of flooding surface bounded depositional units: American Association of Petroleum Geologists Bulletin, v. 73, p. 125-142.

Galloway, W. E., and D. K. Hobday, 1983, Terrigenous clastic depositional systems: applications to petroleum, coal, and uranium exploration: New York, Springer-Verlag, 423 p.

Garcia-Gonzalez, M., R. C. Surdam, and M. L. Lee, 1997, Generation and expulsion of petroleum and gas from Almond Formation coal, Greater Green River Basin, Wyoming: American Association of Petroleum Geologists Bulletin, v. 81, p. 62-81.

Glass, G. B., ed., 1980, Guidebook to the coal geology of the Powder River Coal Basin, Wyoming: Cheyenne, Wyoming, The Geological Survey of Wyoming.

Hamilton, D. S., and N. Z. Tadros, 1994, Utility of coal seams as genetic stratigraphic sequence boundaries in non-marine basins: an example from the Gunnedah Basin, Australia: American Association of Petroleum Geologists Bulletin, v. 78, p. 267-286.

Heward, A. P., 1981, A review of wave-dominated clastic shoreline deposits: Earth-Science Reviews, v. 17, p. 223-276.

Horn, B. W., T. A. Cross, J. A. Hornbeck, M. Vielma, and M. zavala, 2001, Stratigraphic controls on reservoir strata; a comparison of fluvial and tidal reservoirs in the Almond Formation, Coal Gulch, Wamsutter, Echo Springs and Table Rock Fields, Washakie Basin, Wyoming: Guidebook-Wyoming Geological Association, v. 52, p. 149-161.

Horne, J. C., and J. C. Ferm, 1978, Carboniferous depositional environments: eastern Kentucky and southern West Virginia: Department of Geology, University of South Carolina, 151 p.

Humphreys, E. D., 1995, Post-laramide removal of the Farallon slab, western United States: Geology v. 23, p. 987-990.

Jacka, A. D., 1970, Sediment economics of upper Cretaceous sandstones Rocky Mountain Region, *in* R. L. Enyert, ed., Wyoming Geological Association Guidebook, Wyoming Sandstones Symposium, v. 1: Casper, Mtn. States Litho, Casper, p. 187-219.

Johnson, H. D., and C. T. Baldwin, 1986, Shallow siliclastic seas, *in* H. G. Reading, ed., Sedimentary environments and facies Oxford, Blackwell Scientiffic Publications, p. 229-282.

Kellogg, K. S., B. Bryant, and J. C. R. Jr., 2004, The Colorado Front Range-Anatomy of a Laramide uplift, *in* E. P. Nelson, and E. A. Erslev, eds., Field trips in the southern Rocky Mountain, USA: Geological Society of America Field Guide 5, Geological Society of America.

Kiteley, L. W., 1983, Paleogeography and eustatic-tectonic model of late Campanian (Cretaceous) sedimentation, southwestern Wyoming and northwestern Colorado Rocky Mountain Section of Society of Economic Paleontologists and Mineralogists, Paleogeography symposium, p. 273-303.

Kuenen, P. H., 1953, Significant features of graded bedding: American Association of Petroleum Geologists Bulletin, v. 37, p. 1044-1066.

Labandeira, C. C., T. L. Phillips, and R. A. Norton, 1997, Oribatid mites and the decomposition of plant tissues in Paleozoic coal-swamp forests: Palaios, v. 12, p. 319-353.

Lamarre, R. A., and S. K. Ruhl, 2004, Atlantic Rim coalbed methane play; the newest successful CBM play in the Rockies: American Association of Petroleum Geologists Rocky Mountain Section (with Colorado Oil & Gas Association). .

Lamberson, M. N., and R. M. Bustin, 1993, Coalbed methane characteristics of Gates Formation coals, northeastern British Columbia: effect of maceral composition: American Association of Petroleum Geologists Bulletin, v. 77, p. 2062-2072.

Lamberson, M. N., R. M. Bustin, W. Kalkreuth, and K. C. Pratt, 1989, Lithotype characteristics and variation in selected coal seams of the Gates Formation, northeastern British Columbia: Geological Fieldwork, p. 461-468.

Levey, R. A., 1985, Depositional model for understanding geometry of Cretaceous coal: Major coal seams, Rock Springs Formation, Green River Basin, Wyoming: American Association of Petroleum Geologists Bulletin, v. 69, p. 1359-1380.

Lewis, J. L., 1961, The stratigraphy and depositional history of the Almond Formation in the Great Divide Basin, Sweetwater County, Wyoming, *in* G. J. Wiloth, ed., Symposium on Late Cretaceous rocks, Wyoming and adjacent areas: Wyoming Geological Association Guidebook, 16th Annual Field Conference, Casper, WY, p. 87-95.

Livingston, L. A., 1982, Stratigraphy and coal development potential of upper Mesaverde Group, Carbon County, Wyoming: Bulletin - Utah Geological and Mineral Survey, v. 118, p. 50-61.

Martinsen, O. J., 1993, Mesaverde Group (Upper Cretaceous), southeastern Wyoming; allostratigraphy versus sequence stratigraphy in a tectonically active area: American Association of Petroleum Geologists Bulletin, v. 77, p. 1351-1373.

McCabe, P. J., 1984, Depositional environments of coal and coal-bearing strata, *in* R. A. Rahmani, and R. M. Flores, eds., Sedimentology of coal and coal-bearing sequences: International Association of Sedimentologists, Special Publication 7, p. 13-42.

McCord, J. P., 1984, Geologic overview, coal, and coalbed methane resources of the Greater Green River coal region- Wyoming and Colorado: American Association of Petroleum Geologists Bulletin, v. 17, p. 271-293

McGookey, D., J. Haun, L. Hale, H. G. Goodell, D. McCubbin, R. Weimer, and G. Wulf, 1972, Cretaceous system, *in* W. W. Mallory, ed., Geologic Atlas of the Rocky Mountain Region Denver, A.B. Hirschfeld Press, p. 190-228.

Miller, K. G., M. A. Kominz, J. V. Browning, J. D. Wright, G. S. Mountain, M. E. Katz, P. J. Sugarman, B. S. Cramer, N. Christie-Blick, and S. F. Pekar, 2005, The Phanerozoic record of global sea-level change: Science, v. 310, p. 1293-1298.

Neuendorf, K. K. E., 1997, Glossary of geology, *in* K. K. E. Neuendorf, J. James P. Mehl, and J. A. Jackson, eds., Glossary of Geology Alexandria, VA, American Geological Institute, p. 1-779.

Newman, H., 1981, Greater Green River Basin stratigraphy as it relates to natural gas potential: Proceedings of the 1981 SPE/DOE symposium on low permeability gas reservoirs, p. 193.

Nummedal, D., P. Yin, and R. J. Steel, 2002, Sequence stratigraphy of coal-bearing strata in the Washakie and Sand Wash Basins, Wyoming and Colorado-derived from Outcrops, Laramie, University of Wyoming, p. 1-23.

Ogg, J., A. Lugowski, and F. Gradstein, 2009, TimeScale creator database and visualization; version 4.2.1(downloaded from www.tscreator.org; March, 2010).

Otteman, A. S., and A. W. Snoke, 2005, Structural analysis of a Laramide, basement-involved, foreland fault zone, Rawlins uplift, south-central Wyoming: Rocky Mountain Geology, v. 40, p. 65-89.

Posamentier, H. W., M. Jervey, and P. R. Vail, 1988, Eustatic controls on clastic deposition I- sequence and systems tract models, *in* C. W. e. al., ed., Sea level changes: an integrated approach: SEPM Spec. Pub. 42, p. 109-124.

Posamentier, H. W., and P. R. Vail, 1988, Eustatic controls on clastic deposition II- sequence and systems tract models, *in* C. W. e. al., ed., Sea level changes: an integrated approach: SEPM Spec. Pub. 42, p. 125-154.

Postma, G., 1988, Large floating clasts in turbidites; a mechanism for their emplacement: Sedimentary Geology, v. 58, p. 47-61.

Pyles, D. R., and R. M. Slatt, 2000, A high frequency sequence stratigraphic framework for shallow through deep-water deposits of the Lewis Shale and Fox Hills Sandstone, Great Divide and Washakie Basins, Wyoming: Deep-water reservoirs of the world Gulf Coast Section Society of Economic Paleontologists and Mineralogists Foundation, 20th annual Bob F. Perkins Res, v. 20, p. 836-857.

Rice, D. D., and G. E. Claypool, 1981, Generation, accumulation, and gas potential of biogenic gas: The American Association of Petroleum Geologists, p. 5-25.

Rieke, H. H. I., and G. V. Chilingarian, 1974, Interrelationships among density, porosity, remaining moisture content, pressure and depth, Developments in sedimentology: Amsterdam, Elseveir, p. 31.

Rodgers, J., 1987, Chains of basement uplifts within cratons marginal to orogenic belts: American Journal of Science, v. 287, p. 661-692.

Roehler, H., 1992, Introduction to Greater Green River Basin geology, physiography, and history of investigations: U.S Geological Survey professional paper, v. Report # P 1506-A, p. A1-A14.

Roehler, H. W., 1990, Stratigraphy of the Mesaverde Group in the central and eastern Greater Green River Basin, Wyoming, Colorado, and Utah: U.S Geological Survey professional paper, v. 1508, p. 1-52.

Ryer, T. A., 1983, Transgressive-regressive cycles and the occurrence of coal in some Upper Cretaceous strata of Utah: Geology, v. 11, p. 207-210.

Saleeby, J., 2003, Segmentation of the Laramide Slab-evidence from the southern Sierra Nevada region: GSA Bulletin, v. 115, p. 655-668.

Schieber, J., J. Southard, and K. Thaisen, 2007, Accretion of mudstone beds from migrating floccule ripples: Science, v. 318, p. 1760-1762.

Schieber, J., and Z. Yawar, 2009, A new twist on mud deposition- mud ripples in experiment and rock record: SEPM special publication, v. 7, p. 1-18.

Schraufnagel, R., 1990, Coalbed methane production: American Association of Petroleum Geologists Bulletin, p. 341-359.

Schwartz, R. K., 1982, Bedforms and stratification characteristics of some modern small-scale washover sand bodies: Sedimentology, v. 29, p. 835-850.

Taylor, A. M., and R. Goldring, 1993, Description and analysis of bioturbation and ichnofabric: Journal of the Geological Society, v. 150, p. 141-148.

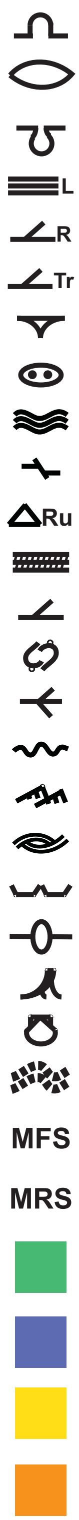
Tyler, R., W. R. Kaiser, and A. R. Scott, 1992, Evaluation of the coalbed methane potential in the Greater Green River, Piceance, Powder River, and Raton Basins, Rocky Mountain Foreland, Western United States: Controls critical to coalbed methane producibility, Austin, Texas, Bureau of Economic Geology, p. 385-414.

Weimer, R., 1965, Stratigraphy and petroleum occurrences, Almond and Lewis Formations (Upper Cretaceous), Wamsutter Arch, Wyoming: Sedimentation of late Cretaceous and Tertiary outcrops, Rock Springs uplift, p. 65-80.

Weimer, R. J., 1966, Time-stratigraphic analysis and petroleum accumulations, Patrick Draw Field, Sweetwater County, Wyoming: Bulletin of the American Association of Petroleum Geologists, v. 50, p. 2150-2175.

APPENDIX I

Legend applies to all figures within the following appendices.



- Convulute bedding
- Lenticular
- Load structure
- Parallel bedding
- Climbing ripples
- Trough crossbedding
- Brachiopod fossile
- Concretion
- Wavy bedding
- Offset bedding
- Rip up clast
- Planar crossbedding
- Crossbedding
- Slumping/contored bedding
- Hering bone
- Wave ripples
- Current ripples
- HCS
- Syneresis cracks
- Burrows
- Rooting
- Fossil bivalve
- Trace fossils
- Maximum flooding surface
- Maximum regressive surface
- Continental
- Marine
- Transgressive systems tract (TST)
- Regressive systems tract (RST)

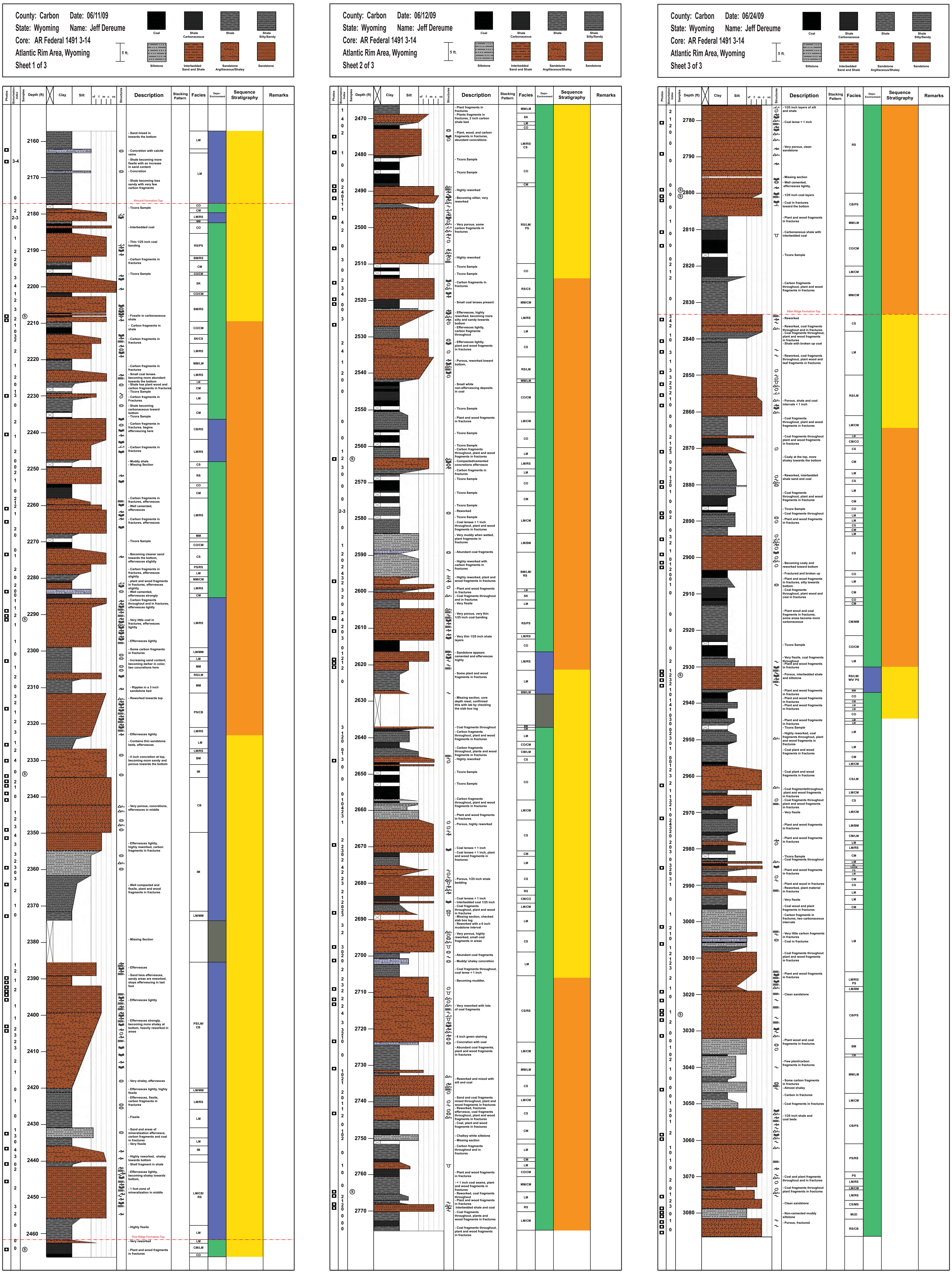


Figure 1. Stratigraphic description of core AR Federal 1491 3-14.

Figure 2. Stratigraphic description of core AR Federal 1591 13-15i.

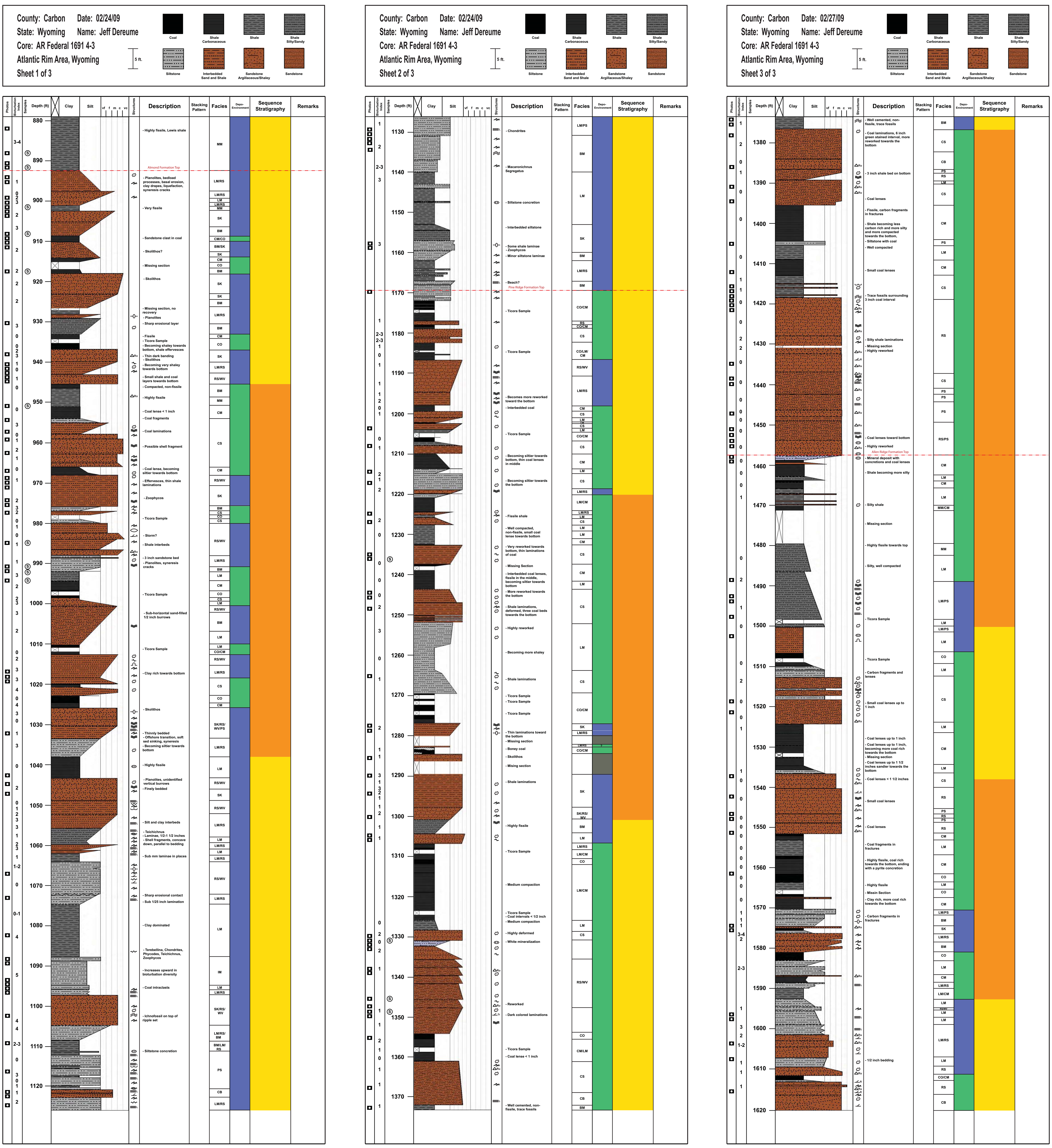


Figure 3. Stratigraphic description of core AR Federal 1691 4-3.

APPENDIX II

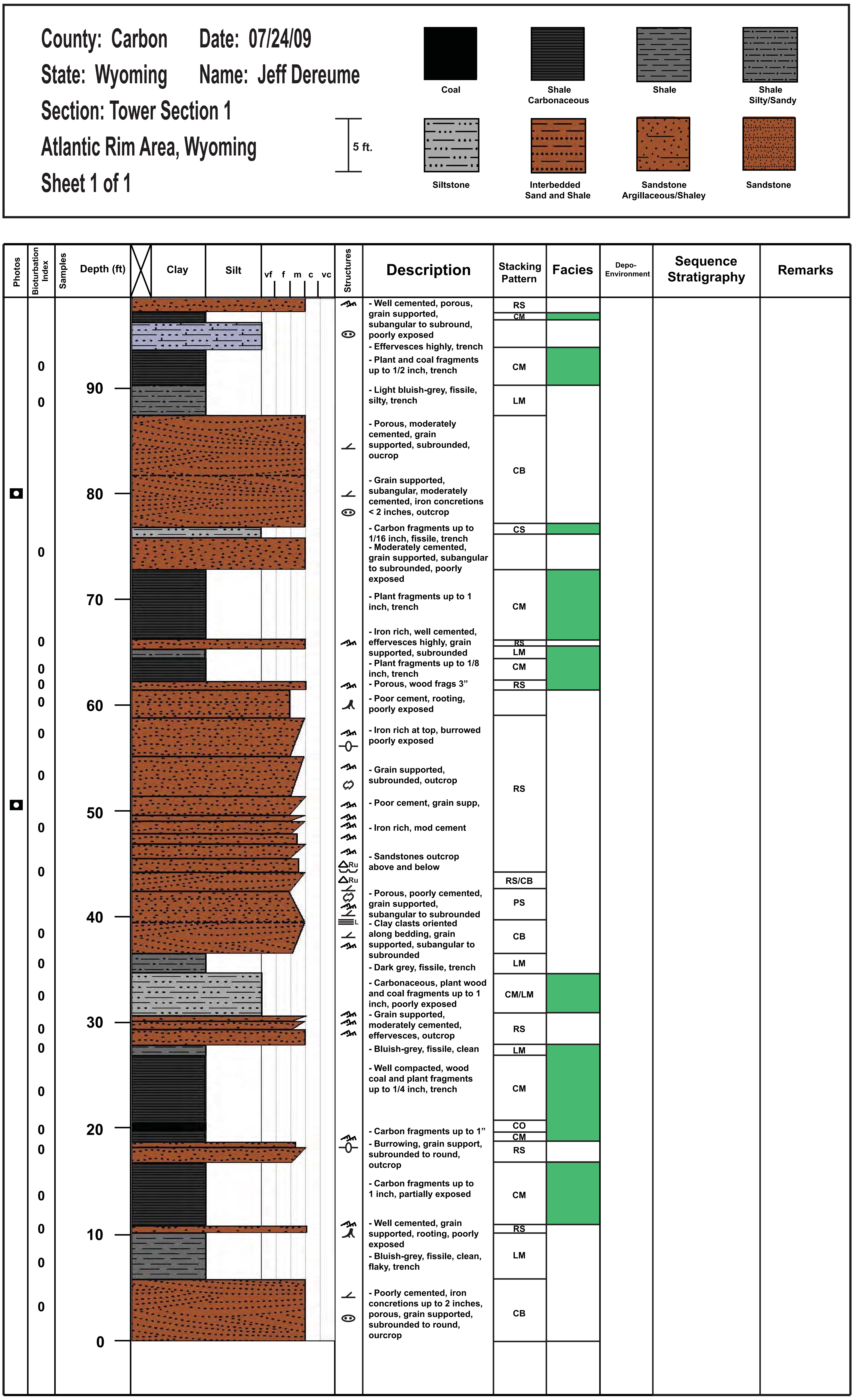


Figure 4. Stratigraphic section of outcrop Tower Section 1.

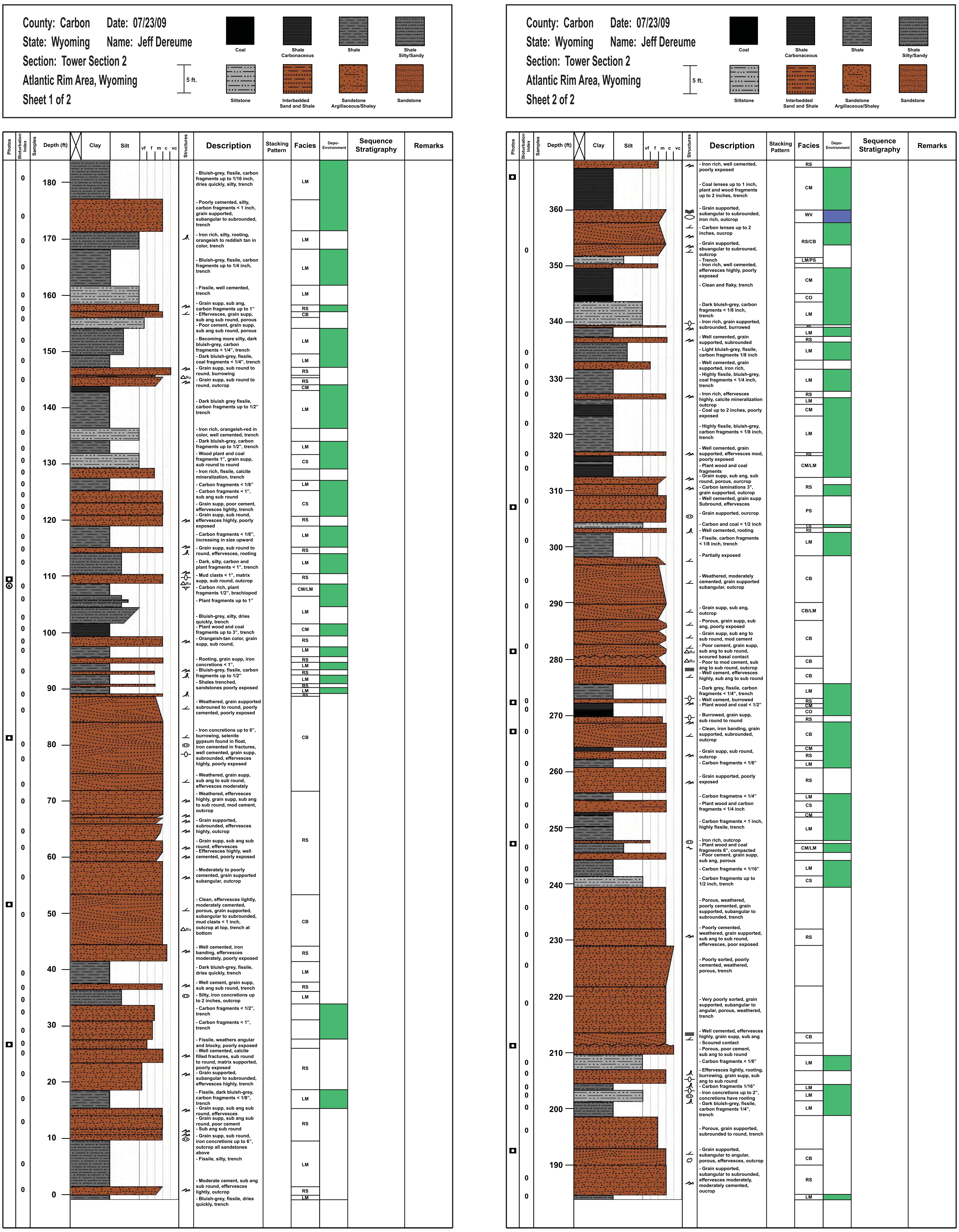
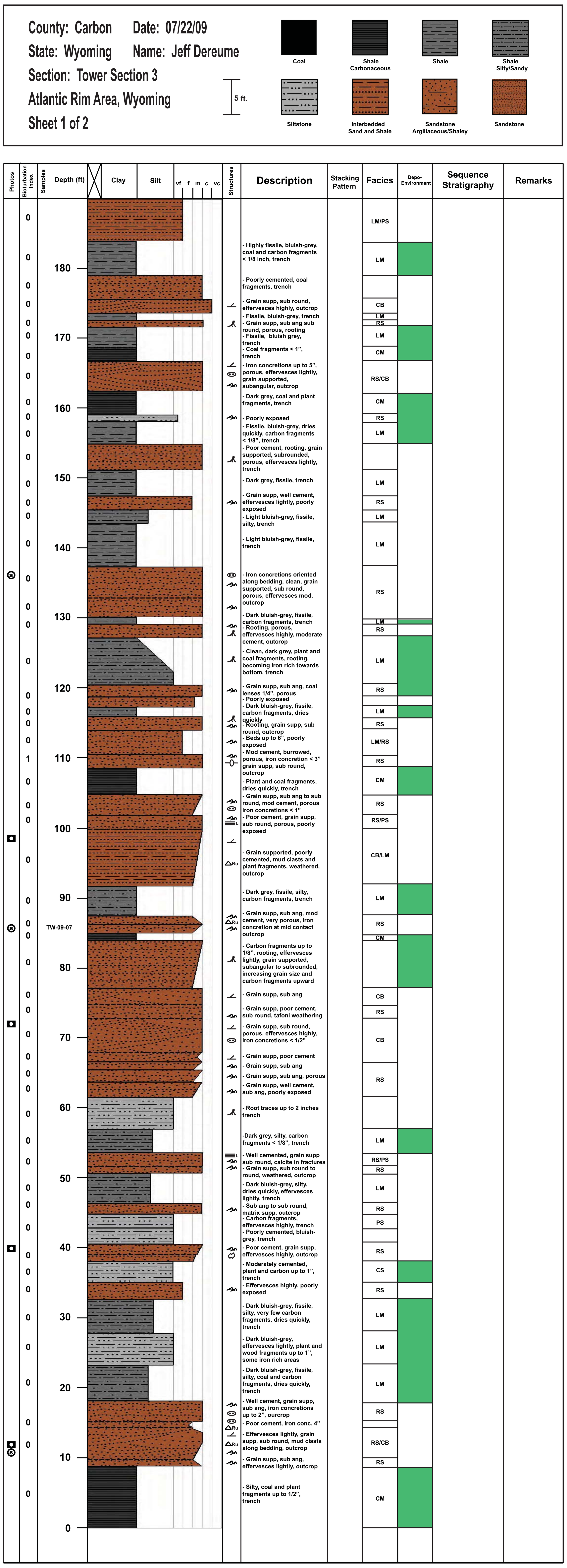


Figure 5. Stratigraphic section of outcrop Tower Section 2.



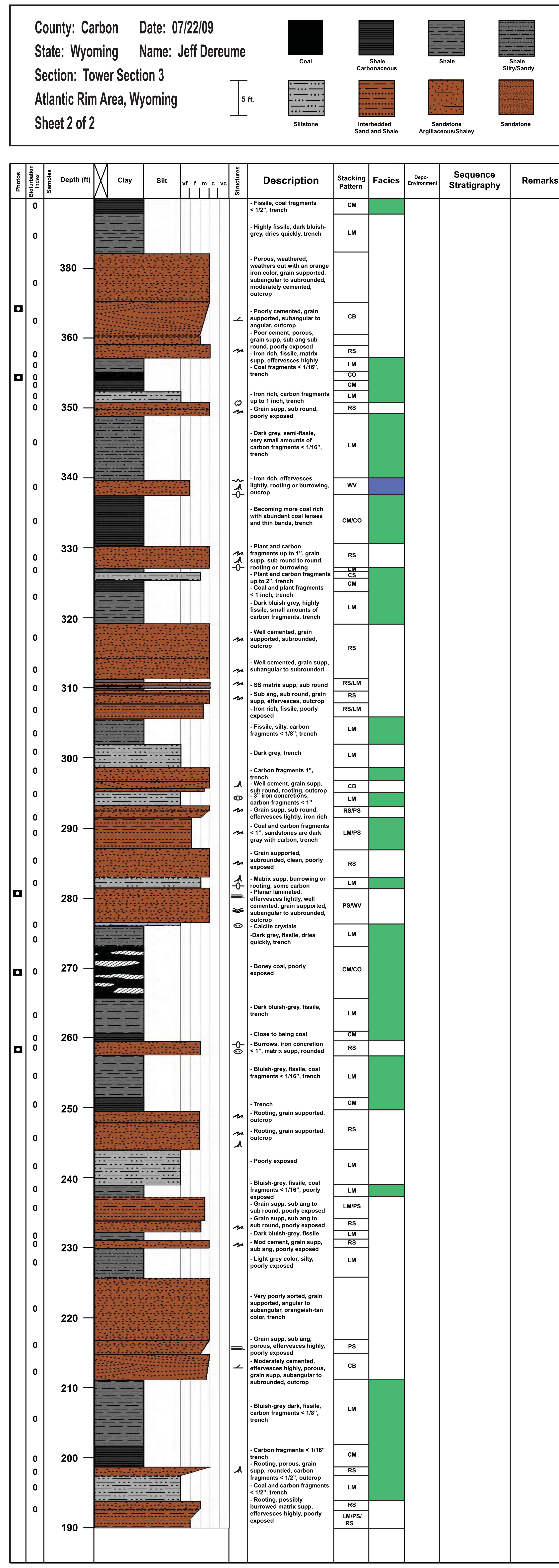


Figure 6. Stratigraphic section of outcrop Tower Section 3.

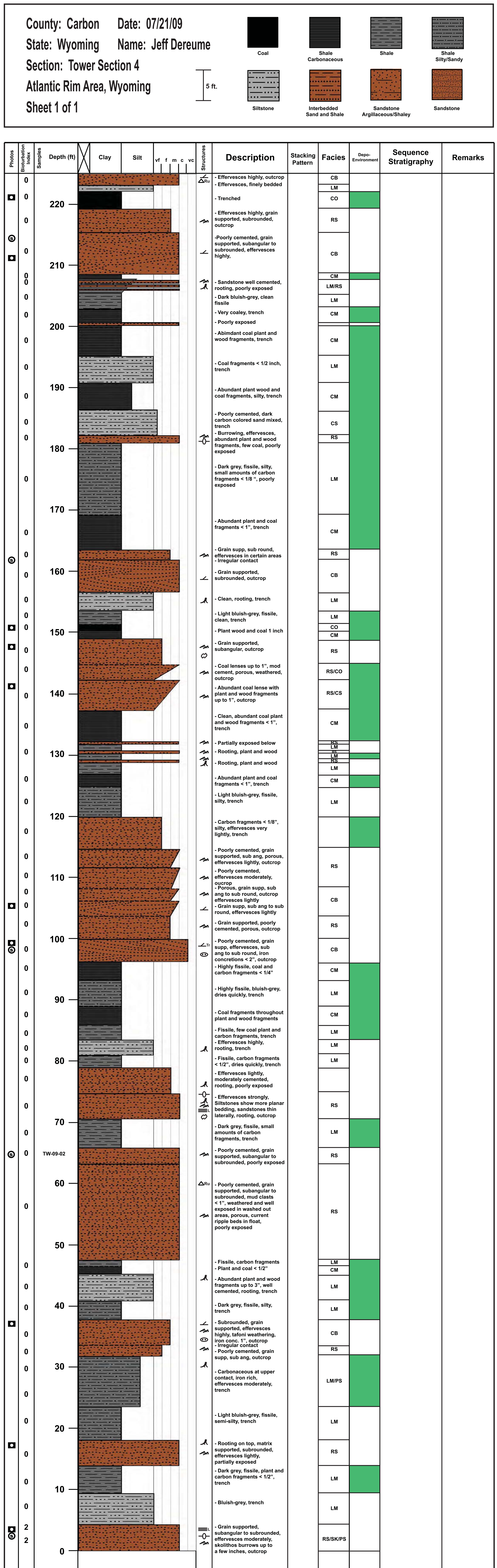


Figure 7. Stratigraphic section of outcrop Tower Section 4.

APPENDIX III

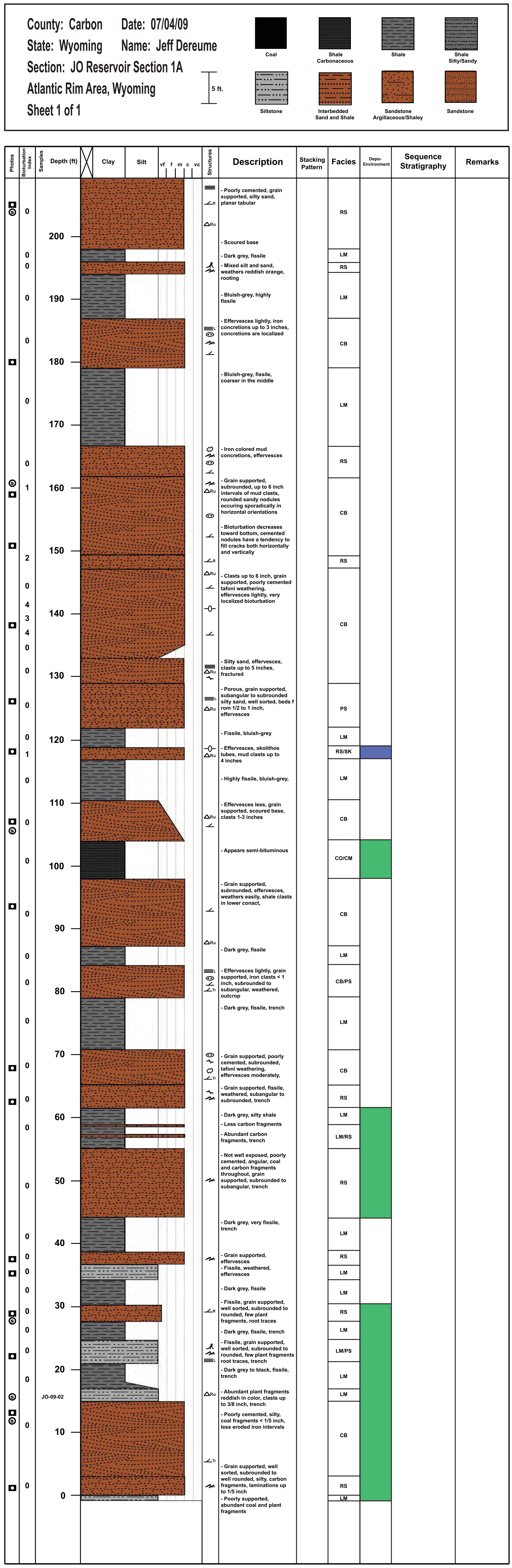


Figure 8. Stratigraphic section of outcrop JO Reservoir 1A.

Figure 9. Stratigraphic section of outcrop JO Reservoir 1B.

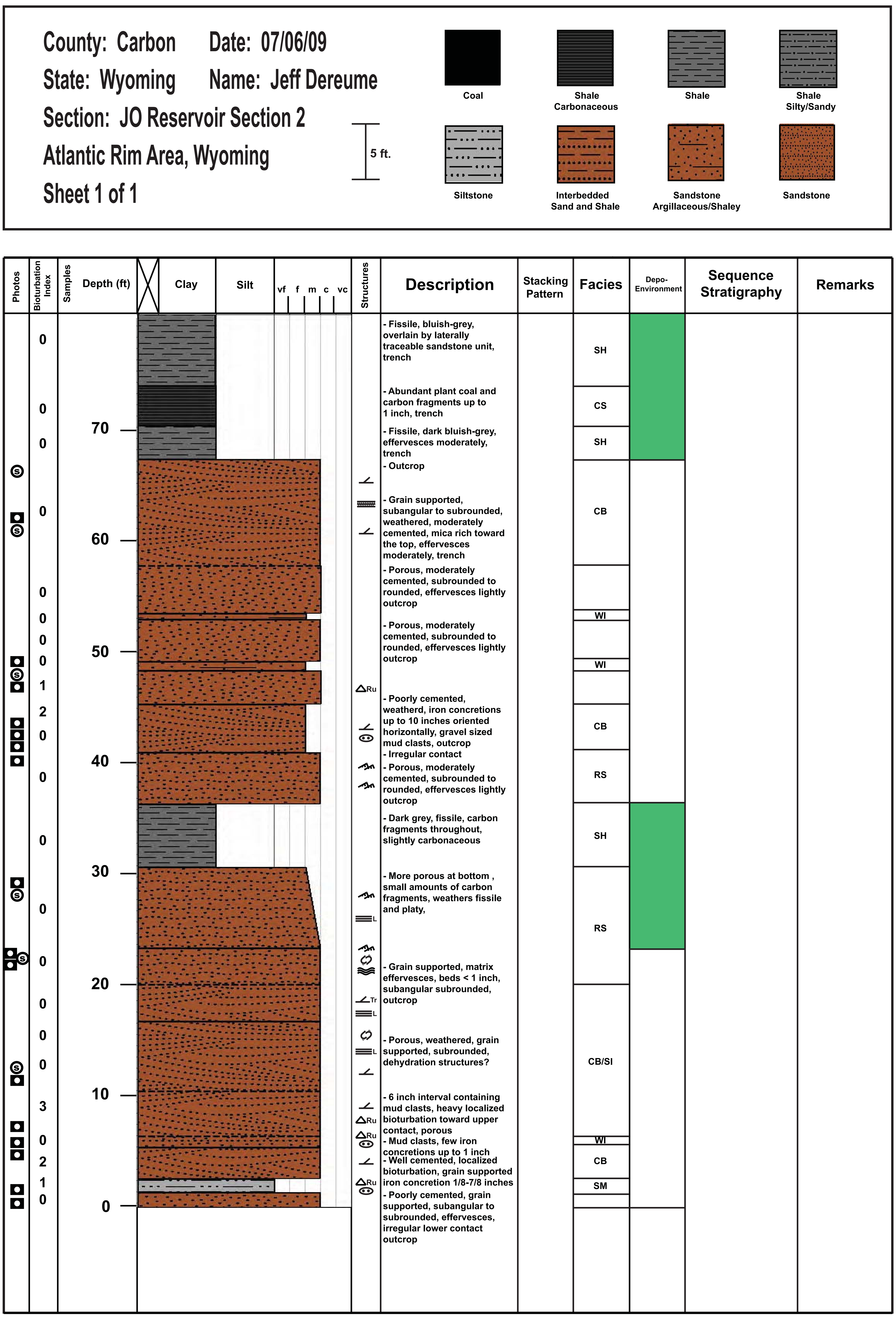


Figure 10. Stratigraphic section of outcrop JO Reservoir 2.

Figure 11. Stratigraphic section of outcrop JO Reservoir 3.

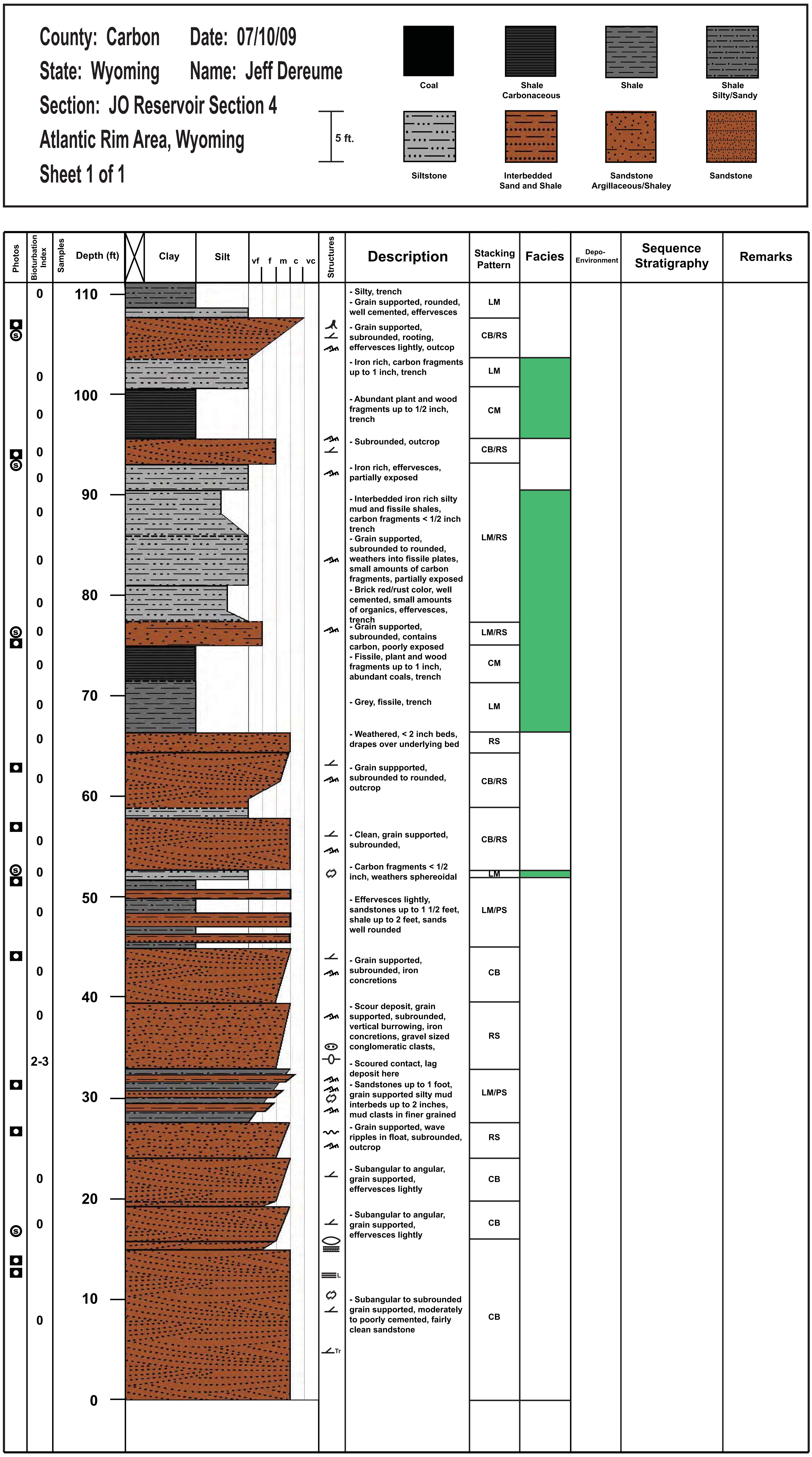


Figure 12. Stratigraphic section of outcrop JO Reservoir 4.

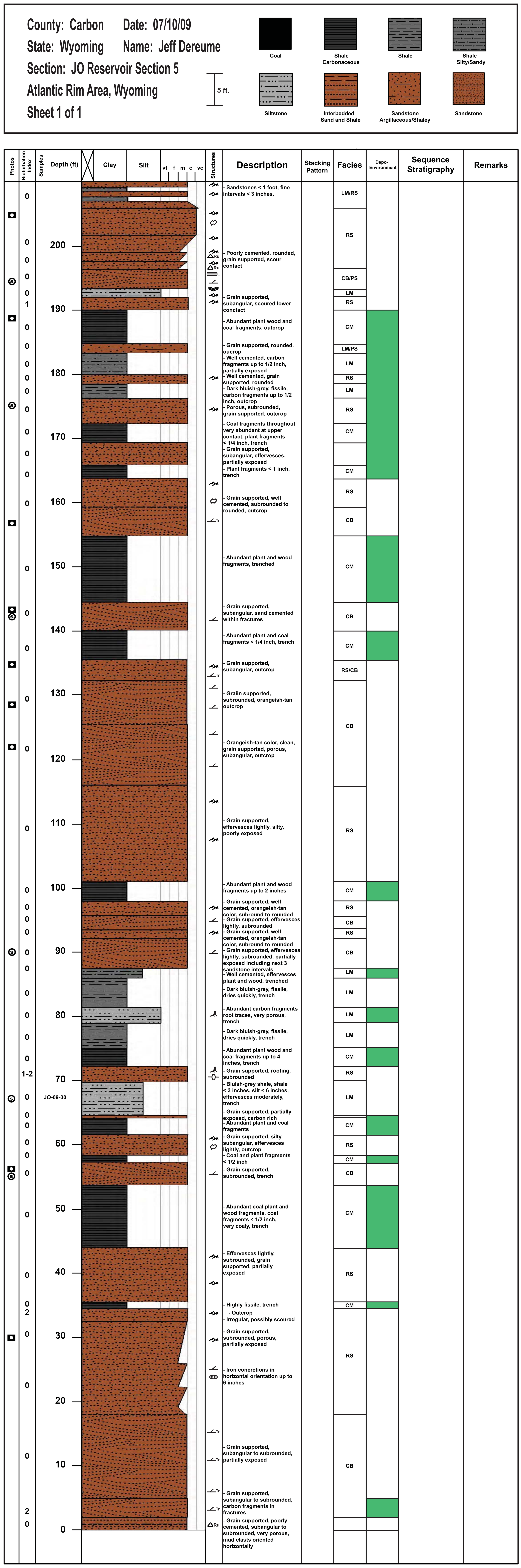


Figure 13. Stratigraphic section of outcrop JO Reservoir 5.

APPENDIX IV

Figure 14. Correlation of cores AR Federal 1491 3-14, 1591 13-15i, and 1691 4-3.

APPENDIX V

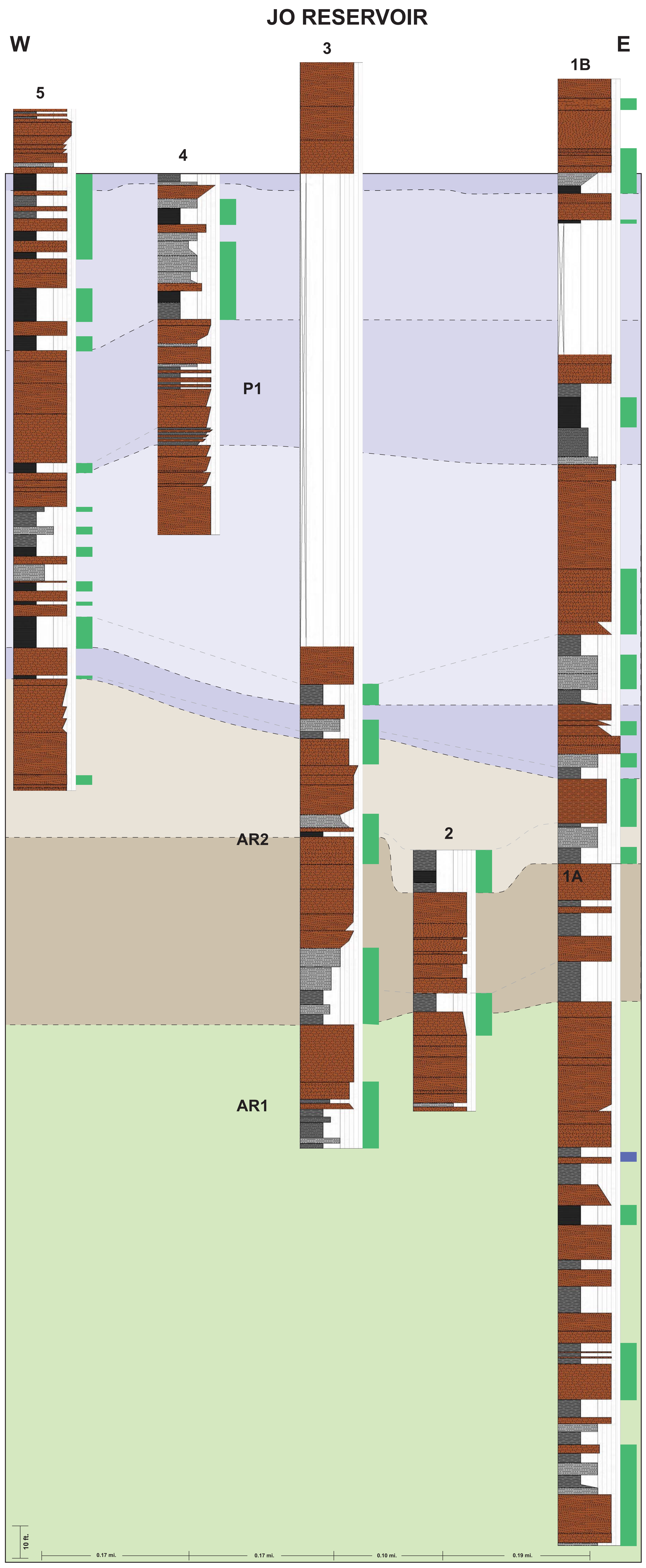


Figure 16. Correlation of stratigraphic sections from the JO Reservoir.

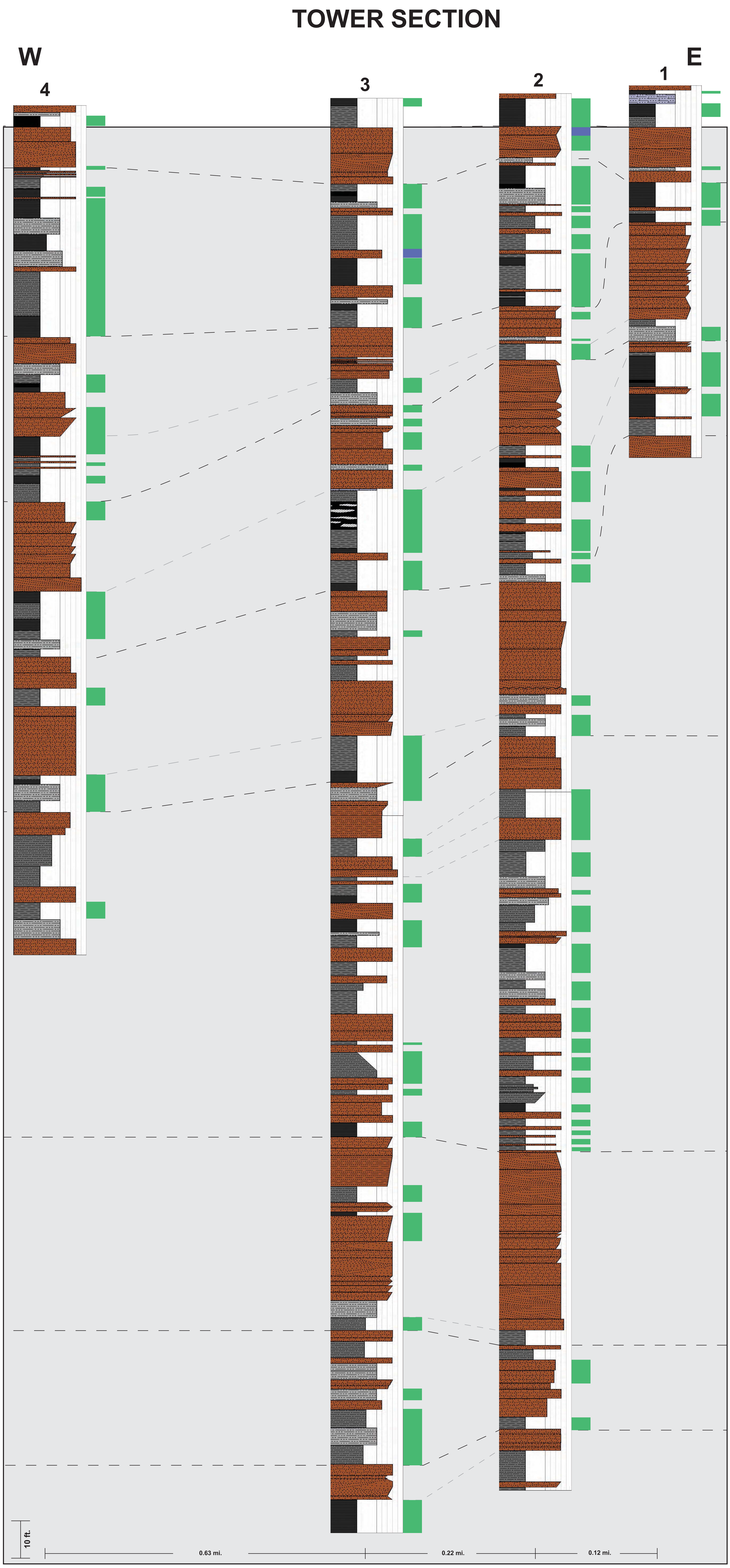


Figure 15. Correlation of stratigraphic sections from the Tower Section.